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RESUME – On rapporte les derniers succes à la compréhension du mécanisme d'écholocation chez les dauphins. On fait une essentielle attention au povoir des dauphins de détection et de discrimination dans les condition acoustiques differentes. On examine aussi l'adaptation des paramètres du signal d'écholocation aux changements des bruits et de la réverbération exterieurs. On discusse le pouvoir des dauphins de discrimination d'un obstacle selon les dimension, la nature et la forme géométrique à l'aide des signaux utilisés.

ABSTRACT – Latest achievments in understanding of mechanisms underlying dolphin echolocation are discussed. Main attention is drawn to dolphin detection and recognition in different acoustic conditions. Adaptation of echolocation signal parameters to changing ambient noise and reverberation are also considered. The results on target discrimination by size, shape and material composition are discussed with emphasis to main cues used by the dolphin.

1. INTRODUCTION

The dolphin echolocation system is drawing attention of the engineers–acousticians, engaged in technical sonars research and development. They are attracted by its high efficiency in different acoustical condition. The dolphin biosonar advantages over technical sonars are especially pronounced while detection and recognition of slowly moving or motionless targets in shallow water, where reverberation are predominant interference. So, what is the reason for such efficiency of the dolphin biosonar? The main one is, that dolphin is actively adjusting itself to constantly changing acoustical conditions varying its ongoing pulses intensity, repetition rate, spectral content of pulses, the position from which the object insonification is done, lifting to the sea surface or descending to the sea-bottom.

The experimental and computer simulation results achieved by now enable understanding the mechanism of the dolphin biosonar functioning in objects detection and recognition.

In this paper we discuss the experimental data and the basic mechanisms of underwater objects detection and recognition by dolphins.

2. TARGET DETECTION

The echolocation abilities of dolphins for target detection have been investigated under different acoustical conditions: in pools[1,10,25], in sea bay [5,7], in open waters [2-4], on the ambient noise background and with specially radiated continous noise [1], pulse [6] and reverberation [12,28]. There have been used spherical and cylindrical targets of different sizes and made of different materials, and also disks, fishes and other objects.

The ability of Phocoena phocoena was studied [18] to detect thin threads made of different materials, and that of inia [29], which was able to detect the wire 1.4 mm in diameter, while the Phocoena phocoena detected the wire 0.2 mm, twisted perlon thread 0.8 mm and nylon thread 1.0 mm in diameter. The detection range has not been estimated in these studies.

The experiments made in the pool showed, that the minimal metal sphere size, detected by the bottlenose dolphin at the distance 4.5 m was 0.3 cm [1]. According to Au and his co-author's data [2] the utmost distance of target detection in the very noisy sea bay ranged 55-73 m, the target being 2.5-7.6 cm in diameter. In another place of the same bay where the reverberation was weaker, the distance of the same targets detection reached 113 m [3].

According to [5,7] the maximum distances of target detection with equivalent radii a=5 cm and a=9 cm have been 140 and 200 m in conditions of sea bay. For the target with a=14 cm the maximum distance of detection exceeded 250 m.

The hydrolocation equation for stationary signals and noises is expressed this way [19]

$$DT = SL - 2TL + TS - (NL-DI), \qquad (1)$$

where DT is the threshold of detection, SL is a source level, 2TL are propagation losses, TS is a target strength, NL is ambient noise level and DI is receptional directivity index.

Still, for nonstationary signals this equation should be transformed in such a way, that energy flux density should be used. The equation suitable for dolphin biosonar derived by Au [13] looks like

$$DT_E = DT - 10 \log T_i = SE - 2TL + TS - (NL-DI) \qquad (2)$$

where DT_E corresponds to signal/noise (SNR) 10 log Ee/No, Ee is echo energy flux density, T_i is time of echo integration, No is spectral density of noise power.

In experimental condition the peak sound pressure SPL_{pp} is usually estimated instead of the energy flux density, that is why the equation (2) may be expressed like that [13]

$$E = SPL_{pp} + 10 \log \int_0^T S^2(t)dt - 6 \ , \qquad (3)$$

where S(t) is the acoustic signal time profile [13].

The receptional directivity index estimates DI for bottlenose dolphins were obtained by Au and Moore [20]. For the frequencies 30, 60 and 120 kHz the DI values correspond to the following equation

$$DI = 16.9 \log f - 14.5 \ , \qquad (4)$$

where f is in kHz.

The estimations of the relation echo-signal/noise DT_E achieved by Au and Snyder [3] show the values between 7.2 and 12.7 dB.

The dolphin echolocator can be considered as an energy detector with integration time 264 *m*s [13]. This time coincides well with the value of the critical interval (265 *m*s) which we have found for bottlenose dolphin as a time interval, within which echo highlights merge into acoustic whole [21,22].

The comparison of the dolphin echolocator with an optimal detector, which completely uses all available information about the signal and the noise [20] showed, that the dolphin detects signals with SNR on average 7.4 dB above the level of the optimal detector.

As it was already noted, the most peculiar in dolphin target detection underwater is its flexible reaction on the changing acoustic situation, which displays itself in all the main radiation characteristics: intensity, time interval between the pulses, echolocation series duration, and, consequently, the numbers of pulses in series, variation of time intervals and emited pulse spectrum.

The ongoing pulse level depends on the distance from the target and on ambient noise level. For the bottlenose dolphin, in conditions of shallow water sea bay with considerable noise background the value of SPL_{pp} changed from 100 dB to 104 dB [2].

When detecting the target in quiet pool [1] the clicks level of the bottlenose dolphin varied from 33 to 62 dB depending on the level of noise radiated into the water.

Au et al.[31,32] revealed different echolocation signals from dolphins (the bottlenose dolphin and beluga) kept in a biologically quiet environment as compared with dolphins kept in a biologically noisy place. Echolocation clicks emited in noisy surrounding shifted in peak frequency to higher values, as did the click's sound pressure level (SPL).

It should be noted, that the different species of dolphins use different radiation levels. For example, Phocoena phocoena have weaker echolocation pulses, that is from 5÷6 to 10÷12 dB (see the review [10]).

Analysing series of echolocation clicks authors [5,7] discovered, that beginning from a certain distance, instead of single clicks there are clearly observed bursts of clicks with an interval between the bursts, exceeding the doubled time of click propagation to the target. Within the bursts, the time intervals are considerably shorter than the time interval between the bursts. Thus, we may speak about two ways of clicks radiation of the bottlenose dolphin - the single pulses and the bursts of pulses. The latter increases speed of information entry in the distant objects echolocation. Similar results were gained in experiments with a false killer whale (Pseudorca crassidens) [14]. The number of clicks par trial increased as a function of distance between the animal and the target. The variance of click number reflected degree of incertainty in the target detection. The more certain was the animal the fewer number of clicks was emited.

There are considerable changes in echolocation signals when periodic pulses were radiated in experimental pool [6]. When the number of interference pulses increased from 40 to 1200 per second the click number increased from 25 (in case of interference absence) to 61 per second, the mean duration of clicks series grew from 0.8 to 2.7 s; (at that the number of clicks in series changed from 20 to 170) and the peak sound pressure at 1 m distance from the dolphin head increased from 4.5 to 27000 Pa. At that, there has not been registrated such an adjustment of the click emission moments at which the echo would be at a maximum distance (along the time scale) from the neighbouring interference pulses.

We believe that the reason for this phenomenon is the inertia of neural control over the clicks radiation mechanism. Really, the sudden switching on the interference pulses resulted in changing echolocation click repetition rate only in 300 ms. The dolphin exibits the ability to change the frequency content of its clicks and can produce echolocation signals with dual energy peaks well separated in a frequency scale [1,9,31,32].Dolphins also can control both the frequency and amplitude of their echolocation clicks. Moore and Pawloski [9] observed three types of clicks: (1) predominantly low frequency (30-60 kHz);(2) wideband bimodal clicks (30-100 kHz); and (3) high frequency clicks (100-130 kHz). Romanenko [33] recorded stereotyped and oscillatory pulses, using hydrophones located in vicinity of dolphin head. Oscillatory pulses were longer in duration and had narrower power spectra.

As it was stated above, the dolphin biosonar efficiency reveals in shallow water conditions, when the reverberation noise, causelly related with emited clicks, is rather strong.

Special experiments [12,28] have been done to investigate such an interference influence on echolocation abilities of the dolphin. In experiments made by Titov [12] the smooth bottom of the pool was covered with shingle, having size from 5 to 30 mm. Shingle was evenly distributed on two circles area 40 cm in diameter. The target was lowered in a random order in the middle of one of the circles and then it was lifted at such a height over the middle of the circle, that a dolphin was able to detect it. The bottlenose dolphin detected a lead sphere 50 mm in diameter on the bottom of the pool at 5 m distance in 75% of the trials. The 33 mm steal sphere was detected with the same percentage of correct decision in case the lower part of the sphere was lifted over the bottom by 1.7 cm. Thus, targets detection seemed possible only in case they protruded over the largest stones not less than by 2 cm. In our experiment the dolphin went in deep water from the very start and moved to the targets very slowly, locating them at small grazing angles to the bottom for diminishing the bottom reverberation.

This observations led to believing that cetacean have specific mechanisms of tuning out the reverberation, for example, a mechanism of time gating, which is working as follows: when strong pulses of reverberation are arriving, it blocks the auditory system and, on the contrary, it raises the auditory sensitivity in the moments of weak echo reception [23].

To verify such a suggestion special experiments have been conducted, in which the bottlenose dolphins detected the steel sphere 40 mm in diameter on the background of artificial reverberation [21,22]. The latter was made by radiating pulses, simulating in its time profile the ongoing click of the dolphin.

Time locking for the reverberation pulse, echolocation click of the dolphin and echo from the sphere was done by triggering the generator for an interference pulse by the ongoing click of the dolphin. Changing the delay between dolphin click and interference pulse, it was possible to "move" the "source of reverberation" location relative to the echo source.

It has been found,that at echo-signal/reverberation being.- -50 dB the sphere detection percentage was close to 100 so far as T>200-300 *m*s for two bottlenose dolphins.

Thus, high level of dolphin biosonar resistance to reverberation is mostly a result of high time resolution (~250 *m*s).

3. TARGET RECOGNITION

Numerous experiments on dolphin abilities to recongnize and identify targets differing in shape, size and material composition have been done lately [4,10,13,24,28]. The thresholds of targets identification by these parameters have been defined. The role of spectral, temporal and amplitude differences in target recognition has been revealed. Several models for echolocation target recognition has been also developed [8,15-17].

A great number of experiments with spheric targets proved, that threshold discrimination by size is as small as 2% (reliable recognition of steel solid spheres with diameters 5.1 and 5.2 cm).Characterizing the targets distinctions by target strength differences, we shall see that the threshold values for a large file of data will be close to 1 dB. The dolphin abilities to differenciate the material of underwater objects seems to be very impressive [10]. In the great number of cases the dolphins differenciate the material of the objects with the same size and shape. Analysis of spheric targets identification by its size and material led us to understanding of some regularities and let to develope a number of echolocation identification models.

One of the first models [8] was based on the fact, that the energy spectrum of echo, born by a short click and containing a number of echo highlights has a periodic component with a mean period Df. It was shown [8], that target identification by the dolphin takes place in case when difference in mean periods of power spectrum oscillation for compared targets exceeds a certain threshold.

The identification rule was formulated as follows: if $df = (Df_1-Df_2) > df_0$, the decision is made that targets to be compared are different;if $df < df_0$ the opposite decision is adapted. Here Df_1 and Df_2 are mean periods of power spectrum oscillations of the compared targets, df_0 is the threshold constant.

This model made possible to predict the discrimination of spheric targets having different both in size and material composition [11]. The target discrimination is reliable when $df > 2$ kHz and $df < -3$ kHz. Within the interval 2 kHz $< df <$ -3 kHz the percentage of correct discrimination is from 55 to 65.

This model of solid spheres differenciation may be also expressed in time domain. Echo from the solid sphere caused by an echolocation click consists of two main components: the primary echo, which is similar to ongoing click in time profile, especially for acoustically rigid materials (steel,glass etc.) and the secondary echo, which has time delay from the primary one $Dt \sim 1/Df$. While passing to acoustically less rigid materials the duration and peak value of the secondary echo is increasing relative to duration and peak value of the primary echo. To the value df, determining solid spheres discrimination in the spectral domain , the value of dt can be brought in correspondence describing the targets discrimination in the time domain.

The limits of the spectral discrimination mechanism application have been defined. With either secondary echo (when the target of the given material composition gets smaller or when the material stiffness growth with the given size) or primary echo (when the material stiffness lessens) disappearance, the very notion of the mean period of oscillation in the target power spectrum or the time interval between the primary and secondary echo is also disappearing.

This model of the recognition mechanism has been developed for solid spherical targets though,it may be applied to every targets echoes from which consist of at least two well pronounced highlights.

In number of papers [25-28] the dolphin echolocation abilities to detect metallic plates and cylinders have been investigated. The authors discuss different parameters characterizing the object recognition. It was indicated, that the main parameters are echo duration, the differences in highlights appearance and peak amplitudes of the highlights in echo. In particular, the presence of time interval between the correlated highlights may be perceived by dolphins as time separation pitch (TSP).

The question of cues, used by bottlenose dolphins in object detection and recognition was studied using synthesized sound pulses, simulating echo-signals from the complex targets [15-17]. An hierarchy system of independent cues has been determined, containing three features: "macrostructure of power spectrum" MaPS, which is determined by large scale deformations of power spectrum (about 10 kHz and more), "microstructure of power spectrum" MiPS, which is determined by small-scale power spectrum oscillations with period between 5 and 10 kHz and a pair of pulses energy (E). The dominant cues is MaPS, then goes MiPS and E. In auditory stimuli identification the bottlenose dolphin successively estimates the cues from the dominant cue to the minor one, interrupting on the cue containing suprathreshold cues differences in the compared stimuli.

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