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Recognition and Classification of Noise Signals by Dolphins (*Tursiops truncatus*) Under Conditions of Noise Interference and Spatial Uncertainty of Their Simultaneous Presentation

A. V. Akhi*

Sechenov Institute of Evolutionary Physiology and Biochemistry, St. Petersburg, 194223 Russia

**e-mail: andrey.akhi@gmail.com*

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Abstract—The ability of the dolphin auditory system to recognize and classify noise signals according to certain invariant characteristics under the influence of noise interference and in conditions of spatial uncertainty of the simultaneous presentation of positive and negative signals was investigated. Bottlenose dolphins trained to differentiate such signals had to solve this problem in conditions simulating real sea conditions, when the perception of a useful noise signal occurs against a background of similar signals and against a noise interference background. First, noise signals were sequentially presented to the animal against a background of white masking noise. Subsequently, the dolphin had to identify a signal of a positive class from several simultaneously sounding sound sources. The animal's performance was assessed at several specified noise interference levels. In this case, the actual noise interference was both white noise and simultaneously sounding negative signals. It has been shown that the efficiency and noise immunity of the dolphin's auditory system depends on the degree of alternativeness of the spatial uncertainty of the simultaneous presentation of signals.

Keywords: dolphin, noise signals, noise interference, classification of signals by dolphins, spatial uncertainty

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INTRODUCTION

The principles and mechanisms that demonstrate how the auditory system of echolocating marine animals can analyze acoustic signals are an extremely important topic. Acoustic perception of the environment plays an extremely important role in the life of marine mammals, such as bottlenose dolphins. With the help of the organ of hearing, direction is localized and the properties of a sound source are distinguished. This occurs both in the passive and active modes of acoustic perception, when objects are probed by the animal's location signals and reflect echoes that carry information about the objects. The operation of dolphin sonar in active mode when perceiving broadband ultrasonic signals has been studied quite well in a large number of experimental works [1–4]. When the sonar is operating in active mode, the direction of arrival of the echo signal and the distance to the source of reflection, determined from the time of arrival of the echo and its intensity, are known. The frequency range of the echo signal, as a rule, coincides with the frequencies of the location signal. Information about the location object is contained in the fine spectral–temporal structure of the echo signals received from it. During operation in passive auditory mode, the animal faces the more complex problem of analyzing acoustic information, when the direction and moment of sound arrival, as well as its properties (spectral-temporal characteristics), are unknown in advance. Efficient perception of a low-frequency signal coming from a previously unknown direction requires that passive hearing be omnidirectional. This is confirmed by studies of the directivity of perception of dolphins in the low frequency range [1–3, 5]. This omnidirectional reception is combined with the ability of dolphins to tune out spatially distant interference. Low-frequency hearing provides dolphins with the ability to detect and recognize sources of useful signals at long distances, due to the low attenuation of sound in water at low frequencies, and this is important because the most important biogenic sounds for them are low-frequency sounds of fish. In passive mode, the organ of hearing operates by a method, known in sonar as direction finding. Signal sources are detected, direction to it is determined, and it is recognized by studying the spatial structure of the sound field created by the objects of the search. Current knowledge about the basic mechanisms of dolphin hearing, which underlie their highly developed echolocation system, is still far from complete. In particular, the mechanisms that determine the high noise immunity of sonar, which in many respects exceeds similar properties of technical acoustic systems, remain largely unclear.

A dolphin in a marine environment constantly faces the need to perceive a useful signal in the presence of biogenic, abiogenic, and anthropogenic acoustic interference, as well as interference associated with echolocation signals from obstacles that are not currently location objects. Multiple sources of unusual sounds reduce the reliability of the sonar. Dolphin has to solve the problem of ensuring noise immunity of the acoustic communication channel. In the course of evolutionary development and ecological specialization, dolphin hearing has adapted to functioning under conditions of constant exposure to various types of acoustic interference and extracts the necessary information from a complex of various sounds.

Observations of dolphins in their natural habitat and experimental studies indicate the high efficiency of these animals' echolocator in detecting obstacles and recognizing targets in a noisy environment. In recent years, researchers have studied the effect of noise on the functioning of dolphins' auditory system [6–8] or changes in animal behavior when exposed to acoustic noise [9]. When studying the influence of artificially created noise on the functioning of a dolphin's sonar, it was shown [2, 10, 11] that the animal does not lose the ability to detect and distinguish objects (spherical targets differed in material and size) if the sound pressure of white noise reaches 900 N/m^2 in the 1–150 kHz frequency range. A dolphin's ability to detect fish is observed at noise levels for which it is impossible to isolate a useful signal from noise by conventional hydroacoustic means. This might suggest that dolphins have mechanisms that efficiently reduce the effect of ambient noise on sonar. Among the possible adaptive mechanisms that allow dolphins to reduce the masking effect of interference, the literature indicates an increase in the level of probing signals [2, 3, 9], a change in the discrete frequencies of the spectral characteristics of pulses [2, 3, 11], a change in their repetition rate [2], mechanisms of temporal selection of echo signals [2, 3], expedient change in behavior [2], and the presence of acute spatial directivity of radiation [2].

In many experimental studies on the immunity of the dolphin's auditory system to interference, tones of a wide range of frequencies and pulses of various durations were employed as useful signals. Dolphins' perception of a useful tone and noise signal from noise interference and the influence of noise on the echolocation process of detecting and recognizing targets have been studied quite well [1–3]. In this case, noise was an element of methodologies that made it possible to assess the functional capabilities of dolphins' hearing. In the natural habitat of an animal, a useful signal is always either noisy or is a noise signal itself . The noise existing in the ocean is not only an obstacle to hydroacoustic reception. Frequently, received noise is a useful signal that carries useful information about hydrological, meteorological, biological, and other important components of the acoustic field of the water area. For marine mammals, the noise of schools of fish makes it possible to detect efficient fishing areas, and signals from sources of danger allow it to be avoided in advance.

There are not many studies of the capabilities of the auditory system of dolphins devoted to perception of broadband noise signals with changing parameters, as well as their classification according to certain invariant characteristics. The interest in how they are perceived is due to the fact that most of the actual sounds in a marine environment are broadband noise and that these signals carry many informational features in their spectra that a dolphin could use in recognizing and identifying them. Studying how and what features are used in identifying signals would allow a better understanding the mechanism underlying operation of the auditory system. N.A. Dubrovsky et al. [12] demonstrated for the first time how dolphin's auditory system identifies in the signal spectrum information features containing the invariance of belonging to a certain class. They also presented a hierarchically organized system of independent spectral features that can be used as invariants in signal classification. In order of importance these are:

(1) the macrostructure of the spectrum (shape of the envelope);

(2) the microstructure of the spectrum (discrete components);

(3) the signal energy.

Our studies [13–17] demonstrated the possibility and efficiency of dolphins' identification and classification of low-frequency noiselike signals, as well as possible information features in the signal spectrum necessary and sufficient for their discrimination. However, some issues on the dolphin's perception of noise signals remain unstudied.

The objective of this study is to elucidate the functional capabilities of the bottlenose dolphin's auditory system when perceiving, distinguishing and classifying noise as a useful signal, under exposure to noise interference and spatial uncertainty of signal arrival during their simultaneous presentation with varying degrees of alternativeness, i.e., in conditions similar to natural.

MATERIALS AND METHODS

The signals used in this study were noise simulations or noiselike signals that we used in previous studies [13–17] (Fig. 1). Noise simulation was carried out by generating broadband signals, which are pseudorandom sequences of rectangular pulses with different polarities, filled with a carrier frequency of 125 kHz. Such sequences differ from random ones in that the output voltage changes at a frequency that is a multiple of the clock pulse frequency, and the sequence has a period. Such simulated pseudorandom continuous pulse sequences result in a noise-like process. If its time pattern represents various sequences of rectangular pulses, then the signal spectrum is a set of discrete components (spectrum microstructure) and the shape of the envelope characteristic of this set (spectral macrostructure). Both the set of discrete components and shape of their envelope are periodically repeated along the frequency axis with increasing frequency, each time with a smaller amplitude. Therefore, the effective frequency range of the generated signals, determined by the timing parameters of the pulses and interpulse intervals, had a low-frequency character and was concentrated in the 150 Hz–5 kHz band. The time coding of pulse sequences made it possible to generate and simulate a variety of broadband noiselike signals. To form them, three sequences of pulses were selected, defining a certain class of signals (first class, 10 100 000; second class, 10 100 110; third class, 11 110 000). Sequences of pulses could be stretched or compressed, which was carried out by setting different durations of a single pulse τ—92, 260 and 560 μs. Three signals of the same frequency-time structure, but different frequency-time scales represented one class of signals, and two other structures of different scales—two other classes of signals. For one of the dolphins participating in the experiments, the first class was positive; for the other, third class.

The experiments were carried out in a pile-net enclosure 7 × 9 × 6 m, located in a sea bay. The study involved two adult bottlenose dolphins, who had previously taken part in acoustic studies on the discrimination of noise signals, using the method of behavioral reactions with food reinforcement during free-swimming animals. In response to a positive signal presented by the experimenter, the dolphin had to approach a plastic manipulator located in front of a hydrophone (piezoceramic sphere with a diameter of 20 mm) emitting a useful noise signal and touch it, for which it received a fish. The animal's approach to the negative signal was not reinforced. At the first stage, the dolphin was tasked with identifying a positive class of signals with a minimum single pulse duration of 92 μs from a negative class signal with pulses of the same duration, but with a different sequence. Signals of one positive and two negative classes were sequentially emitted in random order from one hydrophone located 6 m from the animal. Next, signals of other single pulse durations of 260 and 560 μs were introduced, i.e., the same signals on different time–frequency scales. The experimental training program consisted of 20 signals of the positive and 20 signals of each of the negative classes. Based on the results of initial training, dolphins successfully classified the signals presented to them with a probability of P = 0.95–1.00.

In their natural habitat, a dolphin is more often faced with the need to isolate and identify a useful signal, which in our experiments was a positive noise signal against a background of interference of various origin. Therefore, at the next stage, the ability of the dolphin's hearing to identify a class of useful noise signals against the background of noise interference was determined. To noise the useful signal, a hydrophone (piezoceramic sphere with a diameter of 30 mm) emitting white noise in a band up to 50 kHz was located 20 cm behind the signal hydrophone. To estimate the signal-to-noise ratio, the sound pressure levels of the useful signal and sound pressure of noise interference were measured at the starting position of the animal. To estimate the threshold signal-to-noise ratio at which effective signal recognition is possible, several gradations of the noise level were selected.

The experimental conditions of the next stage were even closer to natural ones. Most often, an animal needs to isolate a useful signal against the background of the simultaneous presence of different signals, including those of similar origin, but which are currently an interference. Moreover, the direction to the source of the useful signal is unknown or it may change. Therefore, to create a situation similar to the natural one, a second signal hydrophone, identical to the first, and a hydrophone emitting white noise, the same as in the first case, were placed in the experimental enclosure. The offset between the first and second pairs of hydrophones was 3.5 m, and the angular offset relative to the dolphin's starting position was ~45° (Fig. 2a). With this experimental setup, the efficiency of the animal's correct recognition of the necessary signal also depends on the angular offset of the hydrophones. The greater the offset angle (up to 180°), the easier the task for the dolphin and the higher the correct result. The more acute the angle, the more difficult the task. Therefore, in the experiments, the case of average angular offset was taken (45°). Thus, simultaneously and in random order, a signal of a positive class was emitted alternately from one of the hydrophones spaced in the enclosure, and one of two signals of negative classes was emitted from the other. There were 18 different combinations of positive and negative signals of three durations emitted from the two hydrophones. The experimental program presented 20 repetitions of all possible combinations, 360 in total

At the next stage of the study, after the animals adapted to the complexity of the problem and assessed the efficiency of their work in conditions of alternative spatial choice against the noise interference background, spatial uncertainty was increased by introducing a third pair of signal and interference hydrophones located at the same distance and with the same offset relative to the previous pairs of hydrophones (Fig. 2b). The dolphin had to identify the source of signals of a positive class, which could be sent in a random order to any of the three signal hydrophones located in the enclosure, while noise of negative classes was simultaneously sent to other signal hydrophones.

Each combination of simultaneously presented signals included one positive-class signal and two negative-class signals with different time–frequency modes. The experimental program ensured that all

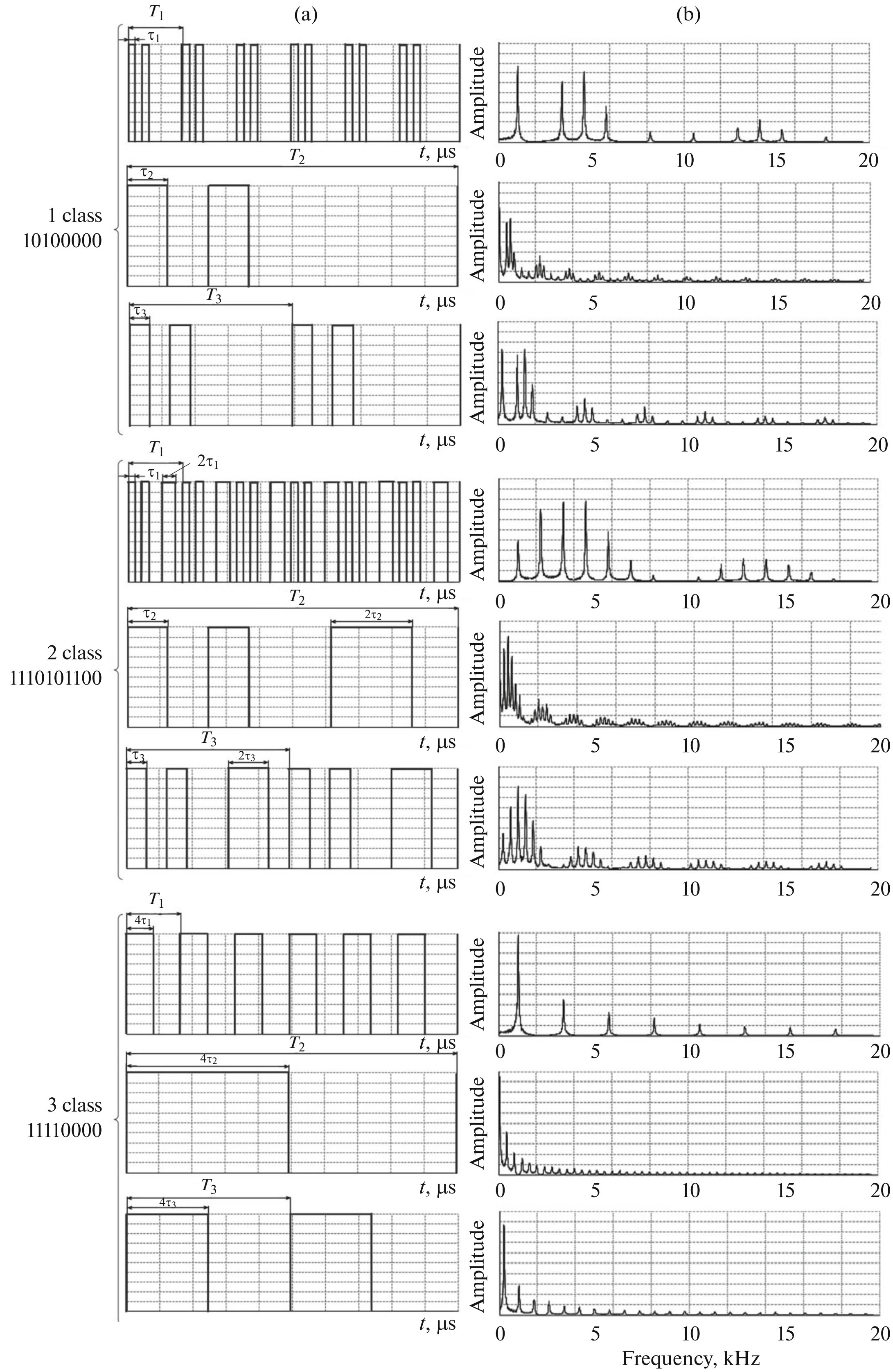

Fig. 1. Temporal and spectral structures of signals. (a) Temporal structure of signals. T, period of repetition of group of pulses in a sequence. $T_1 = 736$ μs, $T_2 = 4480$ μs, $T_3 = 2080$ μs. τ, minimum duration of one pulse in each operating mode: $\tau_1 = 92$ μs, $\tau_2 = 560$ μs, $\tau_3 = 260$ μs ($T = 8\tau$). (b) Spectral structure of signals. X axis, frequency; Y axis, amplitude of spectral components.

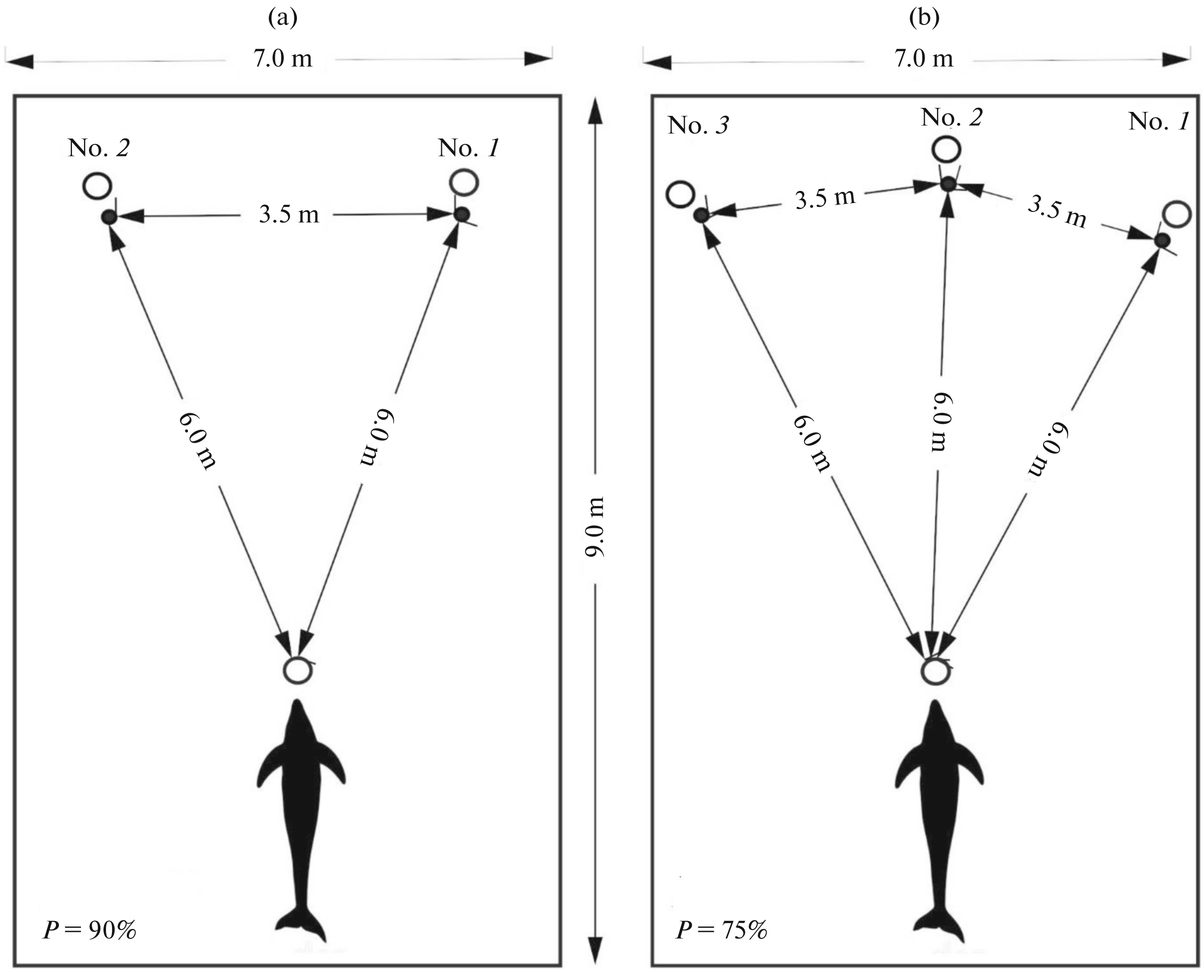

Fig. 2. Scheme of experiments: (a) alternative (of two) spatial choice of positive-class signal. Nos. *1* and *2*, signal hydrophones (black dots) and noise interference hydrophones (white circles). White circle below is starting position manipulator. (b) Multialternative (out of three) spatial selection of positive class signal. Nos. *1*, *2*, *3*, hydrophones similar to Fig. 2a.

possible combinations of signals, were presented in random order to three signal hydrophones, of which there were 81. With a similar 20-fold repetition, the total number of presentations was 1620.

To estimate the signal-to-noise ratio, the sound pressure levels of the useful signal and sound pressure of noise interference were measured. The latter was measured as the total sound pressure created by three hydrophones, which were supplied with white noise of a certain amplitude, emitted by noise interference hydrophones, and the sound pressure of two signal hydrophones, which were supplied with signals of negative classes, perceived by the dolphin as interference. In the experiment, we determined the level of interference (signal-to-noise ratio) at which the animal distinguishes the positive class of signals with a probability higher than 0.7. The experiments were carried out according to a program that included all combinations of presented signals, given in random order. For each of the selected noise levels (total noise of noise interference and simultaneously sounding signals of negative classes); 80 combinations of signals were presented. The experimental data were statistically processed. Statistical analysis was carried out in the data processing package SPSS for Windows v. 13.

RESULTS AND DISCUSSION

The results of experiments assessing the efficiency of animal classification of noise signals under conditions of noise interference and various spatial uncertainties are presented in the table.

There were no statistically significant differences between the performance of the two animals, so only average values are reported. The confidence interval is within 1–2%. As can be seen, the dolphin quite confidently identifies and classifies presented signals in cases of sequential selection of signals and is not much worse in the case of an alternative choice from two simultaneously sounding signals with an intensity of noise interference four times greater than the intensity of the useful signal. Multialternative selection of a sig-

Table 1. Efficiency of dolphins' classification of noise signals under conditions of noise interference and varying spatial uncertainty

	Sequential choice				Choice of two				Choice of three			
SNR	6.7	0.33	0.27	0.17	6.7	0.33	0.27	0.2	2.7	2	1.3	0.7
Detection efficiency, %	97.5	80	75	70	93	75	70	65	80	75	70	40

nal source from three simultaneously sounding ones turned out to be a more difficult problem. In this case, reliable work of the animal was possible if the intensity of the useful signal exceeded the intensity of the interference. Therefore, at this stage of the experiment, other signal-to-noise ratios more adequate to this case were chosen.

An attempt was made to conduct an experiment with a further increase in spatial alternativeness. However, when choosing from four simultaneously sounding signal sources, the probability of the dolphin working correctly even in the absence of noise interference proved unreliable (below 0.7) [17]. Apparently, this was too difficult a problem for the animal, so it was decided to abandon this complication.

The experimental data indicate a high degree of noise immunity of the dolphin's auditory system when distinguishing and classifying useful noise signals. Previous studies [13] have shown that the dolphin's auditory system is capable of distinguishing and classifying low-frequency noises as useful signals if their structure contains invariant features in the form of a certain rhythmic sequence of pulses. This ability is preserved even when the time–frequency scale within the class changes, when it is stretched/compressed. The present study shows that the dolphin's auditory system retains a high probability of detecting and classifying these signals under conditions of alternative choice and spatial uncertainty in the appearance of the useful signal in the presence of noise interference, i.e., in conditions as close as possible to natural. The energy characteristics obtained under these conditions for the efficiency of a dolphin's detection of a useful noise signal against a background of interference of various intensity levels indicate a high degree of noise immunity of the animal's auditory system when isolating a useful noise signal from noise, which is preserved under difficult conditions of alternative choice and spatial uncertainty of the signal's appearance. Dolphins' ability to spatially localize the arrival of a signal is also highly developed and has extremely high accuracy for both active and passive hearing [18].

Comparison of our data on the noise immunity of the auditory system of dolphins with the noise immunity of the hearing of other animals, as well as with the noise immunity of hydroacoustic systems, indicates a significant advantage on the part of dolphin sonar in isolating a useful noise signal from noise interference. A dolphin is capable of identifying a noise signal in the presence of interference five times larger than the signal. In this parameter, the auditory systems of both humans and many animals are inferior to the auditory system of the dolphin. The energy characteristics of the signal/interference ratio, ensuring reliable selection of a useful signal, in humans are 1/1 [19], and in bats, which, like dolphins, are echolocating animals, are 3/2 [20]. And, although absolutely identical experimental studies on the noise immunity of hearing of dolphins, bats and humans have not been carried out due to their different frequency hearing range, habitat and other conditions, the order of the signal/interference ratio indicates better noise immunity of the auditory system of dolphins.

Technical hydroacoustic systems are also inferior to dolphin sonar in terms of noise immunity. Simple small-sized hydroacoustic systems can operate when the signal exceeds the interference by two to four times. Complex computerized and large-scale systems that can accumulate and process a useful signal can operate with a superior level of interference, but even in this case, performing the task in conditions of multialternative spatial uncertainty becomes problematic. A correct quantitative comparison of the capabilities of a technical and a living system is even more problematic, but within the framework of the discussion, it is only possible to mention the qualitative superiority of a live sonar over a technical one.

What are the possible physiological mechanisms that ensure efficient selection of a useful signal from a background of noise? In any receiving acoustic system, this can be accomplished by reducing the intensity of interference during the passage of the signal in the receiving path via optimal processing of all information (useful signal and interference). Suppression of the penetration of interference in living systems is possible due to the mechanisms of spatial selectivity of auditory reception. The formation of the spatial characteristics of auditory reception is undoubtedly based on the physiological mechanisms of binaural hearing, which ensure directed selective perception of acoustic information from the surrounding space, and the peculiarities of the orientational behavior of the species [19]. For locating animals, directional perception of signals becomes especially important, because these animals are constantly faced with the need to distinguish a useful signal from extraneous interfering noise by a small angular difference in sound arrival. The ability of the auditory system to tune out interference when detecting a useful signal in noise conditions depends on the degree of spatial offset of signal and noise sources, and it is characteristic of a number of animal species, including dolphins and humans, as well as bats [19–21]. In human studies conducted using the spatial signal shift technique, it was shown that spatial offset of signal and interference sources leads to a drop in the masking effect of interference by up to 10 dB [22, 23]. In a dolphin, offset of signal and noise sources in the horizontal plane leads to a decrease in the masking effect of noise by 30 dB [11, 22]. The same drop in the masking value was obtained for bats [24]. When the sources of the useful signal and interference are spatially offset due to interaural differences in the signal, the masking effect is reduced and the signal is heard better. In the case of spatial combination of signal and interference sources, there are no interaural differences in the parameters of the signals at the system input and the masking value is greatest. In this case, other mechanisms may come into force to facilitate the offset of the useful signal from the interference. One of them may be pretuning of the auditory system when corresponding signals are received. Tuning of the system to receive initially presented signals is similar to sensory dominance and is explained by trace processes in auditory centers (trace excitation in neural networks) selectively excited by the signal and trace inhibition in competing neural groups that selectively respond to masking noise. As a result of the active tuning of hearing to a perceived useful signal, a gradual increase in the response of auditory receptors is possible [25]. Another mechanism may be optimization of the signal filling frequency (selection of frequencies optimal for perception from the signal). The importance of the signal frequency for the noise immunity of the system is explained by the frequency response of its input and the characteristics of its neural networks, which result in preference for frequencies in a certain range.

Optimal processing of all information (signal and noise) entering the receiving path is based on the use of complex signals. The best resolution is achieved with short duration signals. As the results of this work have shown, one of the mechanisms for increasing the noise immunity of the dolphin receiving system may be selection by pulse duration. Its use allows the animal to solve the problem of isolating a pulse signal, the duration of which lies within specified limits. In our experiments, the artificially determined difference between the signal and the noise is created using temporal coding of a sequence of pulses, which creates the signal's own rhythm and spectrum with a spectral set of discrete components inherent only to it. Pretraining of the animal ensured that only signals with specified time–frequency parameters were received and perceived by its auditory system as positive (for which it is given a reward). In negative signals, which are interference, the time–frequency parameters are different. In white noise, especially since the noise is distributed evenly in frequency and time. Based on the analogy with hydroacoustic systems that isolate similar signals from interference, it can be assumed that the dolphin's auditory system, when distinguishing a useful signal from an array of positive and negative signals and noise interference, works as a cross-correlation type receiver, a matched and optimal filter, at the output of which the signal represents is a function of cross-correlation between the useful signal and all information arriving at its input. Perhaps this is achieved by constructing the impulse response of the filter in the form of a mirror image of the useful signal.

CONCLUSIONS

The study showed that a dolphin's auditory system retains a high probability of recognizing and classifying noiselike signals under conditions of an alternative choice and spatial uncertainty of their appearance in the presence of noise interference, i.e., in conditions as close as possible to natural. The physiological mechanisms used by dolphins to isolate a useful signal from noise are of direct interest not only to biologists, but also to engineers and signal detection theorists. The study of these mechanisms should contribute to a deeper understanding of the adaptive capabilities of specialized biological analyzer systems and to solving the most important hydroacoustic problems.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

All applicable international, national and/or institutional guidelines for the care and use of animals are followed in accordance with the principles of the Basel Declaration and ARRIVE Guidelines. The experimental methodology complied with the recommendations of the bioethics commission of the Sechenov Institute of Evolutionary Physiology and Biochemistry, Russian Academy of Sciences (Protocol № 1-2 dated January 26, 2023). This article does not contain any studies involving human subjects.

CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

REFERENCES

1. W. W. L. Au, *The Sonar of Dolphins* (Springer, New York, 1993).
2. V. M. Bel'kovich and N. A. Dubrovskii, *Sensor Foundations of Cetacea Space Orientation* (Nauka, Leningrad, 1976) [in Russian].
3. N. A. Dubrovskii, in *Black Sea Bottlenose Dolphin Tursiops truncatus ponticus. Morphology. Physiology. Acous-*

tics. Hydrodynamics, Ed. by V. E. Sokolov and E. V. Romanenko (Moscow, 1997) [in Russian].

4. E. V. Romanenko, Acoust. Phys. **65** (1), 103 (2019).
5. V. V. Popov and A. Ya. Supin, *Hearing of Cetacean and Dolphins* (KMK Sci. Press, 2013) [in Russian].
6. V. V. Popov, V. O. Klishin, D. I. Nechaev, M. G. Pletenko, V. V. Rozhnov, V. Ya. Supin, E. V. Sysueva, and M. B. Tarakonov, Dokl. Biol. Sci. **440** (4), 332 (2011).
7. A. Ya. Popov, V. V. Supin, E. V. Rozhnov, V. O. Sysueva, D. I. Klishin, M. G. Nechaev, and M. B. Pletenko, Mar. Mamm. Holarctic **2**, 191 (2012).
8. O. I. Lyamin, S. M. Korneva, V. V. Rozhnov, and L. M. Mukhametov, Mar. Mamm. Holarctic **2**, 41 (2012).
9. B. L. Southall, A. E. Bowies, W. T. Ellison, J. J. Finneran, R. Z. Gentry, C. R. Greence, K. D. Kasta, D. R. Ketlen, J. H. Miller, P. E. Nachtigal, W. J. Richardson, J. A. Tomas, and P. L. Tyack, Aquat. Mamm. **33** (4), 1 (2007).
10. V. P. Babkin and N. A. Dubrovskii, Tr. Akust. Inst., No. 17, 29 (1971).
11. A. P. Abramov, A. G. Golubkov, V. I. Korolev, and V. B. Fradkin, Tr. Akust. Inst., No. 17, 24 (1971).
12. N. A. Dubrovskii, T. V. Zorikov, O. Sh. Kvizhinadze, and M. M. Kuratashvili, Sov. Phys. Acoust. **37** (5), 485 (1991).
13. K. A. Zaitseva, V. I. Korolev, and A. V. Akhi, J. Evol. Biochem. Physiol. **44** (2), 230 (2008).
14. K. A. Zaitseva, V. I. Korolev, and A. V. Akhi, J. Evol. Biochem. Physiol. **49** (3), 353 (2013).
15. K. A. Zaitseva, V. I. Korolev, and A. V. Akhi, J. Evol. Biochem. Physiol. **51** (2), 152 (2015).
16. K. A. Zaitseva, V. I. Korolev, A. V. Akhi, and E. Y. Butyrskiy, J. Evol. Biochem. Physiol. **53** (3), 241 (2017).
17. A. V. Akhi, Fundam. Prikl. Gidrofiz. **16** (1), 90 (2023).
18. V. A. Ryabov, Acoust. Phys. **69** (1), 119 (2023).
19. Ya. A. Al'tman, *Spatial Hearing* (Pavlov Institute of Physiology RAS, St. Petersburg, 2011) [in Russian].
20. A. D. Grinnell, in *Animal Sonar System. Biology and Bionics,* Ed. by R. G. Busnel (Laboratoire de Physiologie Acoustique, Jouy-en-Josas, 1967), **Vol. 1**, p. 451.
21. S. M. D'yachenko, L. D. Korolev, R. N. Rezervov, and B. K. Chemodanov, Tr. Akust. Inst., No. 17, 43 (1971).
22. K. A. Zaitseva, A. I. Akopian, and V. P. Morozov, Biofizika, No. 3, 519 (1975).
23. Yu. M. Mamakin, Biofizika **19** (6), 1 (1974).
24. E. Sh. Airapetyants and A. I. Konstantinov, *Echolocation in Nature* (Nauka, Leningrad, 1974) [in Russian].
25. D. N. Lapshim, Sens. Sist. **28** (3), 52 (2014).