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The study of acoustic signals and the supposed spoken language of the dolphins

Vyacheslav A. Ryabov

T. I. Vyazemsky Karadag Scientific Station–Nature Reserve of RAS, 24 Nauki St., Kurortnoye, Feodosiya, 298188, Russian Federation

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Abstract

This paper continues studies in the problem of animal language by registering acoustic signals from two quasi-stationary Black Sea bottlenose dolphins (*Tursiops truncatus*) using a two-channel system in the frequency band up to 220 kHz with a dynamic range of 81 dB. The packs of mutually noncoherent pulses (NP) generated by the dolphins were matched to the animals. The waveforms and the spectra of these pulses changed from one pulse to another in each pack. In this connection, a suggestion was made that the set of spectral components of each pulse is a 'word' of the dolphin's spoken language and a pack of NPs is a sentence. The paper studied the NP peculiarities in the context of the characteristics of the human spoken language.

Keywords: Dolphin; Spoken language; Acoustics; Signal; Pack; Noncoherent pulse.

Introduction

Acoustic signals of toothed whales are diverse and serve as their primary means for mediating complex coordinated social behavior (foraging, defense against predators, etc.), navigation and communication among dispersed individuals, obtaining information on the environment [1]. We should specifically stress that these signals are the only source of sensory cues for the animals in poor visibility conditions.

To date, the general consensus in the scientific literature has been that the toothed whales (Odontoceti) possess a sonar. The sounding signals of the dolphin sonar are clicks lasting about 50 µs, with the maximum energy reached at frequencies around 120–130 kHz [2].

Most species of dolphins produce two types of sounds, which possibly play the role of communication signals in their social relationships. These are packs of broadband pulses and 'whistles' [3]. Several species of dolphins of the *Kogiidae*, *Physeteridae* and *Phocoenidae* families and the *Cephalorhynchinae* subfamily (Hector's dolphin) do not produce whistles and may communicate by pulsed sounds [4–6].

Pulse packs consist of a sequence of broadband pulses that are similar to echolocation clicks but unlike them have very short (0.5–10 ms) interpulse intervals [7] and significantly lower sound pressure levels (SPL) [2]. The presence and the function of these packs still remain unclear, even though the hypothesis that dolphins use them for communication has been discussed

E-mail address: ryabofff@inbox.ru.

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since the 1960s [6,8,9]. This hypothesis is based on the fact that the above-described signals are recorded when the dolphins are engaged in high social activity and at short distances (2–14 m) from them [1], and the interpulse intervals of these signals have a shorter processing time typical for echolocation (15–45 ms). It should be noted that the vast majority of the dolphin signals were recorded in the frequency band only up to 20 kHz (see, e.g., [8,10]), with few exceptions [6,7].

Many species of dolphins produce long frequency-modulated (FM) acoustic signals containing a large number of harmonics that occur at n-tuples of the fundamental frequency (n is an integer). Such signals have come to be called whistles because this is how humans perceive them.

The repertoire of context-specific whistles which vary according to the situation or to animal activity was studied and described almost immediately after the whistles were first recorded [11–13].

Most species of dolphins producing whistle signals are gregarious animals and live in large groups, so it was suggested that whistles play an important role in their social communication [14–16]. The manner in which such signals can be used for communications is the most common subject of discussion in the scientific literature. Recent studies have established that the fundamental frequency of the majority of whistles covers the frequency range of 2–35 kHz and up to 100 kHz for the harmonic frequencies [7,17–19]. However, both the necessity and the function of the harmonics which make up an integral part of the whistle are currently unexplained.

The signature-whistle hypothesis claiming that dolphins use these whistles to inform the community about their identity and about the location of other members of the social group [20,21] has been discussed recently and has found support in numerous papers (see, e.g., [16,22,23]).

It was also suggested that whistles have a communicative function, i.e., they are used for establishing connections, coordinating actions and maintaining cohesion in a group of animals scattered around the water area [16]. The maximum distance at which the dolphins can communicate with whistling signals was calculated based on the data on the maximum SPL of the whistle, the sensitivity of the dolphin's hearing, the level of ambient noise and sound attenuation with distance. It amounted to about 10.5 km. [24]

The material of the brief review presented above indicates the great interest of researchers in studying the acoustic signals of dolphins. At the same time, only echolocation clicks were the most extensively investigated in the frequency band up to 200 kHz, with a known position of the dolphin relative to the hydrophone. The vast majority of other types of dolphin signals were detected and described in the frequency band up to 20 kHz. Additionally, acoustic signals were recorded using equipment with insufficient dynamic range; the pulsed character of the sounds and the position of the dolphins relative to the hydrophone (the animals were swimming freely) were not taken into account. Perhaps that is why the authors of these studies failed to clearly identify which acoustic signals of the animals could be regarded as communication.

At the same time, a promising new technique for studying the functions of the acoustic signals of dolphins by registering the signals of two quasi-stationary dolphins using a two-channel recording system was described in Refs. [25–27]. This technique has allowed for the first time to ascribe each signal to a specific animal, to record the sequence for the exchange of different types of signals between the dolphins, the dynamics of the changes in the characteristic of the radiation pattern and the signal waveform, to classify and interpret the functionality of the signals in view of the theory of signals and echolocation. Dolphins signals were divided into the following classes:

- a sequence of ultrashort sequence ultra-wideband coherent pulses (clicks);
- packs of mutually noncoherent pulses (NP);
- pack of mutually coherent pulses (CP);
- packs of versatile pulses (VP);
- FM-simultons with evenly distributed tones (whistles).

The results of the studies give reason to regard all acoustic signals of dolphins as sounding signals of not one sonar (as discussed earlier) but at least six different sonar types. At the same time, it was suggested in Refs. [25–27] that NPs are the signals of a highly advanced spoken language of dolphins.

The goal of this study is to reliably measure and analyze the noncoherent pulses as the most likely acoustic signals of the hypothetic spoken language of the dolphins.

Experimental subjects and procedures

The experiments were performed on two adult Black Sea bottlenose dolphins (*Tursips truncatus*), named Yasha (male) and Yana (female), in a closed concrete pool with the dimensions 27 m × 9.5 m × 4.5 m, located at the T.I. Vyazemsky Karadag Scientific Station – Nature Reserve of RAS.

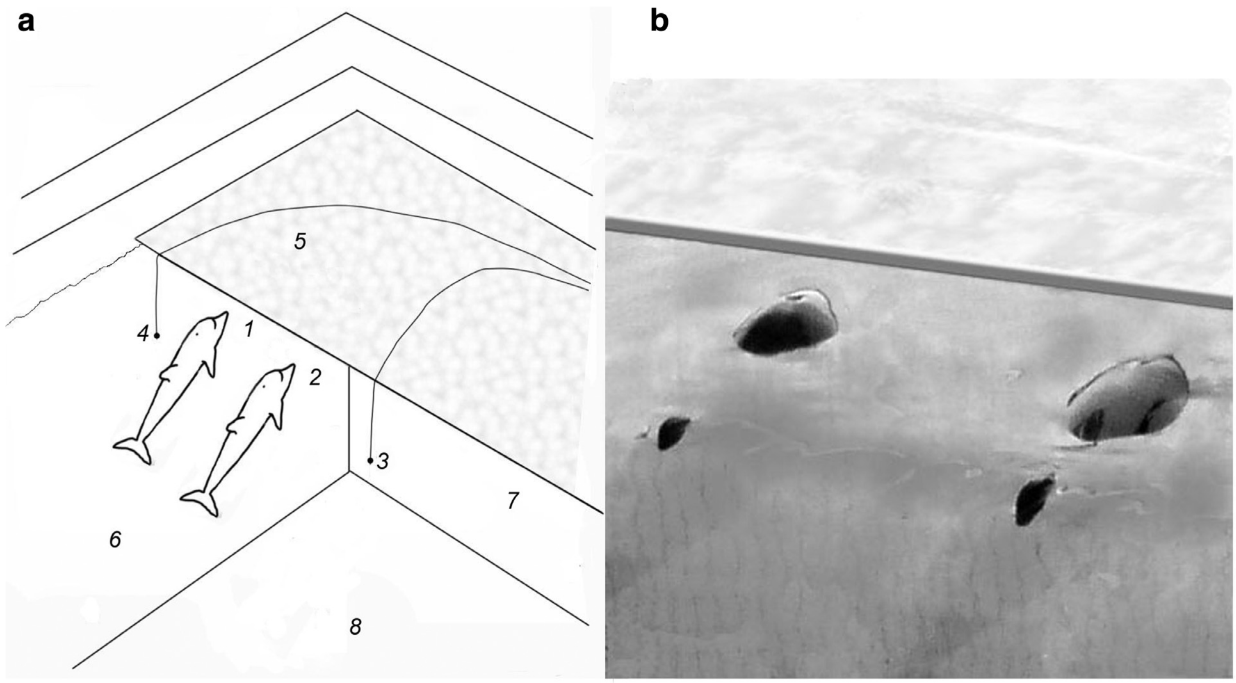

Fig. 1. Configuration of the experiment (a) and photograph of the quasi-stationary position of the dolphins during the recording of sounds (b). Positions *1* and *2* are dolphins Yana and Yasha, respectively; 3 and 4 are the hydrophones of the first (I) and the second (II) channels; 5 is the walkway; 6 and 7 are the long and the short sides of the pool; 8 is the pool bottom.

The dolphins have lived in the pool for about 20 years and have normal hearing. The water level in the pool is 4 m. The configuration of the experiment is shown in Fig. 1a.

The acoustic signals produced by dolphins Yana (*1*) and Yasha (*2*) were recorded with no special training and no food reward for the dolphins. The periods of time used was when the dolphins habitually swam to walkway *5* (located 0.1 m above the water level), and remained afloat at the water surface with almost no motion (quasi-stationary) (Fig. 1b). The signals were registered by a two-channel recording system, which detected the moment when each signal arrived at the hydrophone of its channel. Each signal was ascribed to the specific dolphin and NPs were identified during the analysis of the two-channel recording, taking into account the inter-channel time delays for each signal, the inter-channel amplitude difference for the sound pressure of the given signal, as well as the known distances between the hydrophones, the dolphins and the borders of the pool.

The distance between the hydrophones of channel I and channel II (a recording base of 3.5 m) has been chosen so as to obtain the inter-channel difference of the time delays and the SPL amplitudes of each acoustic signal at the hydrophones that was required for subsequent analysis. The distance between the dolphins was about 1 m. The hydrophones were located in the far acoustic field of the dolphins at ∼1.5 m. The hydrophones were immersed to a depth of 1 m in order to, as far as possible, reduce the probability that the signals going toward the hydrophones located further from each dolphin would be shielded by the body of the other animal. Moreover, to assess the effect of pool reverberation on the recorded signals, hydrophones were positioned so that one of them (*4*) was located near the pool wall, and the other (*3*) in the center of the pool (see Fig. 1a). The distance from wall 4 to hydrophone 6 was 0.45 m, and 3 m from hydrophones 3 and 4 to wall 7. The specifications of the equipment used are listed in Table. 1.

We used spherical hydrophones made of piezoelectric ceramics. Each channel of the signal recording consisted of a hydrophone, a voltage amplifier, and one of the multichannel analog-to-digital converter (ADC). The digitized dolphin signals from the ADC were continuously recorded to the hard drive of a laptop. The recording and processing of the signals were carried out in the PowerGraph 3.3.8 and Adobe Audition 3.0 software packages. Signal spectra were

Table 1
Equipment specifications.

Parameter	Unit	Value
Hydrophones		
Diameter	mm	14
Calibrated sensitivity		
channel I hydrophone	dB relative to 1 V/μPa	–203.5 (66.5)
channel II hydrophone	(μV/Pa)	–206.0 (50.0)
Uneven frequency response	dB	
up to 160 kHz		±3
up to 220 kHz		±10
Recording channels		
High-pass filter	kHz	0.1
Voltage amplifier	dB	40
ADC resolution (USB-3000)	bit	14
ADC dynamic range	dB	81
Sampling frequency for each channel	MHz	1

calculated using the 4096-point fast Fourier transform with the Hamming window function. There were no other animals in the pool during signal recording.

Experimental results

One of the typical recordings that display a sequence of mutually noncoherent pulses produced by Yana and Yasha is shown in Fig. 2. The dolphins emitted pulsed sounds in packs with time intervals between the packs greatly exceeding the interpulse intervals in a pack. Pulse duration in packs varied from 0.08 to 0.60 ms and its average value was about 0.25 ms. The slight difference in the inter-channel SPLs of each signal (less than 16 dB) indicates the absence of a high directivity for NP radiation. Each pulse in the pack has a characteristically complex shape which varies from one pulse to another in the NP pack. Because of this, the spectrum of each pulse also varied from one pulse to another.

As an example, Fig. 3 shows the forms and the spectra of the first four NP from pack *5* (see Fig. 2), produced by Yana. These signals were classified in accordance with the theory of signals and echolocation as mutually noncoherent pulses (NP) [25–27]. The amplitude spectrum of these pulses had many maxima and minima and covered the entire frequency range of the dolphin's hearing, from 6–15 to 160–200 kHz. However, the amplitude spectra of the signals (see Fig. 3) are only shown up to 160 kHz, since the auditory thresholds of the bottlenose dolphin start to increase significantly at frequencies above 135 kHz. The SPL of the pulses (Fig. 2) ranged from 15 to 330 Pa; NP packs contained from 4 to 27 pulses; interpulse intervals ranged from 19 to 300 ms.

Discussion of the results

The analysis of numerous NPs registered in our experiments showed that the dolphins took turns in producing pulse packs and did not interrupt each other, which gives reason to believe that each of the dolphins listened to the other's NPs before producing its own. In this case, the directions of the arrows next to the numbers in Fig. 2 indicating the number of each NP pack mark the direction of message transfer (from Yasha to Yana or vice versa), i.e., an exchange of NPs. Essentially, this exchange resembles a conversation between two people. The fundamental difference between the dolphin exchange of information and the human conversation is in the characteristics of the acoustic signals of their spoken language. Each pulse in the NP packs that is produced by dolphins is different from another by its appearance in the time domain and by the set of spectral components in the frequency domain. In this regard, we can assume that each pulse represents a phoneme or a word of the dolphin's spoken language.

To determine the role of NPs, we analyzed the form and the spectrum of 50 pulses. The number of extrema in the pulse spectra that varied in level by more than 3 dB was 20–30. However, no identical pulses were discovered among them. This suggests that, most likely, each pulse in the NP packs is a word of the dolphin's spoken language, and a pulse pack is a sentence, i.e., some kind of message.

Mutually noncoherent pulses occur at frequencies up to 200–250 kHz, but the energy of the pulses constituting the spectra quickly starts to fall at frequencies below 10 and above 140 kHz (see Fig. 3). The NP characteristics are similar to those described in [25–27].

Assuming that these pulses are none other than dolphin speech, it seems interesting to compare it to the human speech. The spectrum of each pulse occupies almost the entire frequency range of the dolphin's hearing, from 6–15 to 160 kHz. Notably, the lack of spectral components below 6–15 kHz improves the noise immunity of speech, as the absolute auditory thresholds of the dolphin and the ambient noise level start to growrapidly at frequencies below about 10 kHz.

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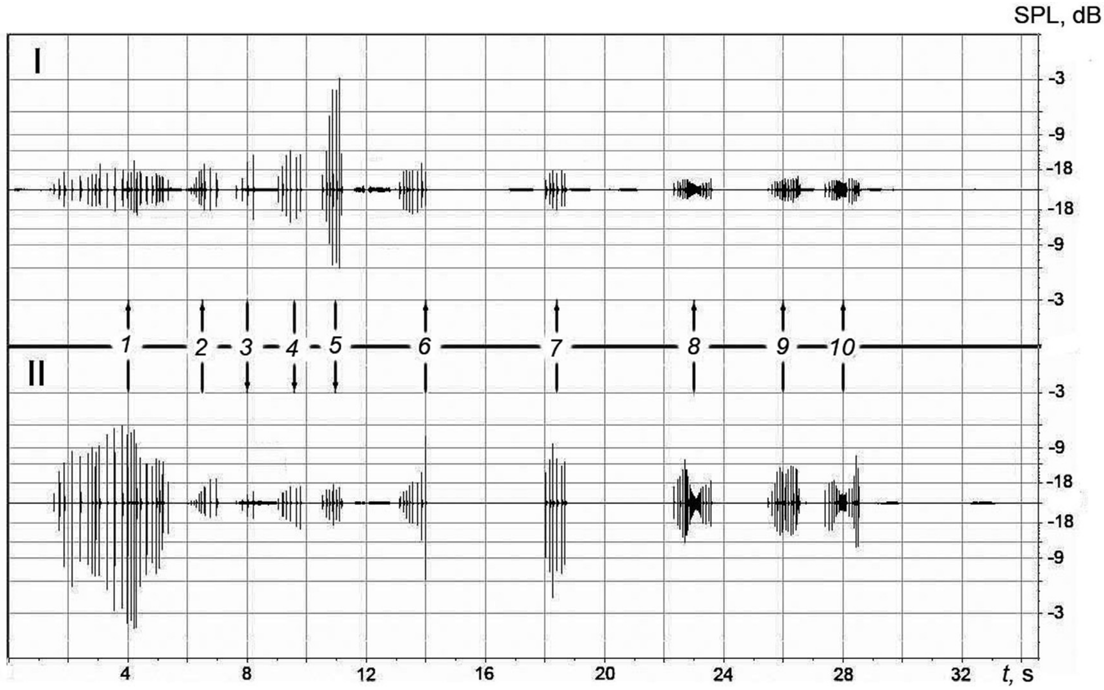

Fig. 2. Example of the recordings displaying the sequence of the NP packs produced by Yana (down arrows) and Yasha (up arrows). The numbering of the packs corresponds to their sequence; I and II are the numbers of the recording channels. The sound pressure level (SPL) of the acoustic pulses was normalized to 350 Pa.

The spectrum of the human speech also covers almost the entire frequency range of the human hearing, but the frequency range of 0.3–3 kHz is enough for normal intelligibility of human speech. It is known that every word in the human language is created by various arrangements (with repetition) of several different phonemes pronounced together, one after another. Phonemes are formed by the spectral components of the corresponding sounds. A virtually infinite number of words can be created from a finite number of phonemes (e.g., 40 in Russian).

We can assume that, unlike humans, dolphins create every word by combining (with repetition) the corresponding spectral extrema (see Fig. 3), i.e., by combining several spectral extrema, different in frequency and level, that they can reliably distinguish, in a wider (by about 40 times) frequency range. Consequently, the spectral extrema of the ‘words’ in the spoken language of the dolphin play the role of phonemes in the human speech. Also unlike the human, the dolphin pronounces all the phonemes of a word simultaneously. Because of this, the duration of an noncoherent pulse is only 0.08–0.60 ms, and its average duration, i.e., the dolphin word, is about 0.25 ms, which is two to three orders of magnitude less than the duration of the phoneme in the human speech. Such a short duration of a word determines the high temporal and spatial (about 37 cm) resolution of the dolphin’s speech. On the other hand, this result indicates a definite advantage of the dolphin hearing over the human one, as dolphins can analyze complex acoustic pulses of shorter duration (by at least 2–3 orders of magnitude) than humans. Thus the NP interpulse intervals substantially longer than the dolphin words (19–300 ms) also vary within a wide range, which apparently improves the robustness of the dolphin’s speech against reverberation. In other words, the dolphin ‘says’ each following word after the reflections from the previous one have attenuated. However, the dolphin’s speech unfortunately lies beyond the time and frequency characteristics of the human hearing, and is thus unavailable to humans. In contrast to the human perception, dolphins hear human speech, as it falls in the low-frequency limit of their hearing but is weakened due to a substantial reflection of the sound energy at the air–water interface.

It is interesting to estimate the extent to which the hypothetical spoken language of the dolphin possesses

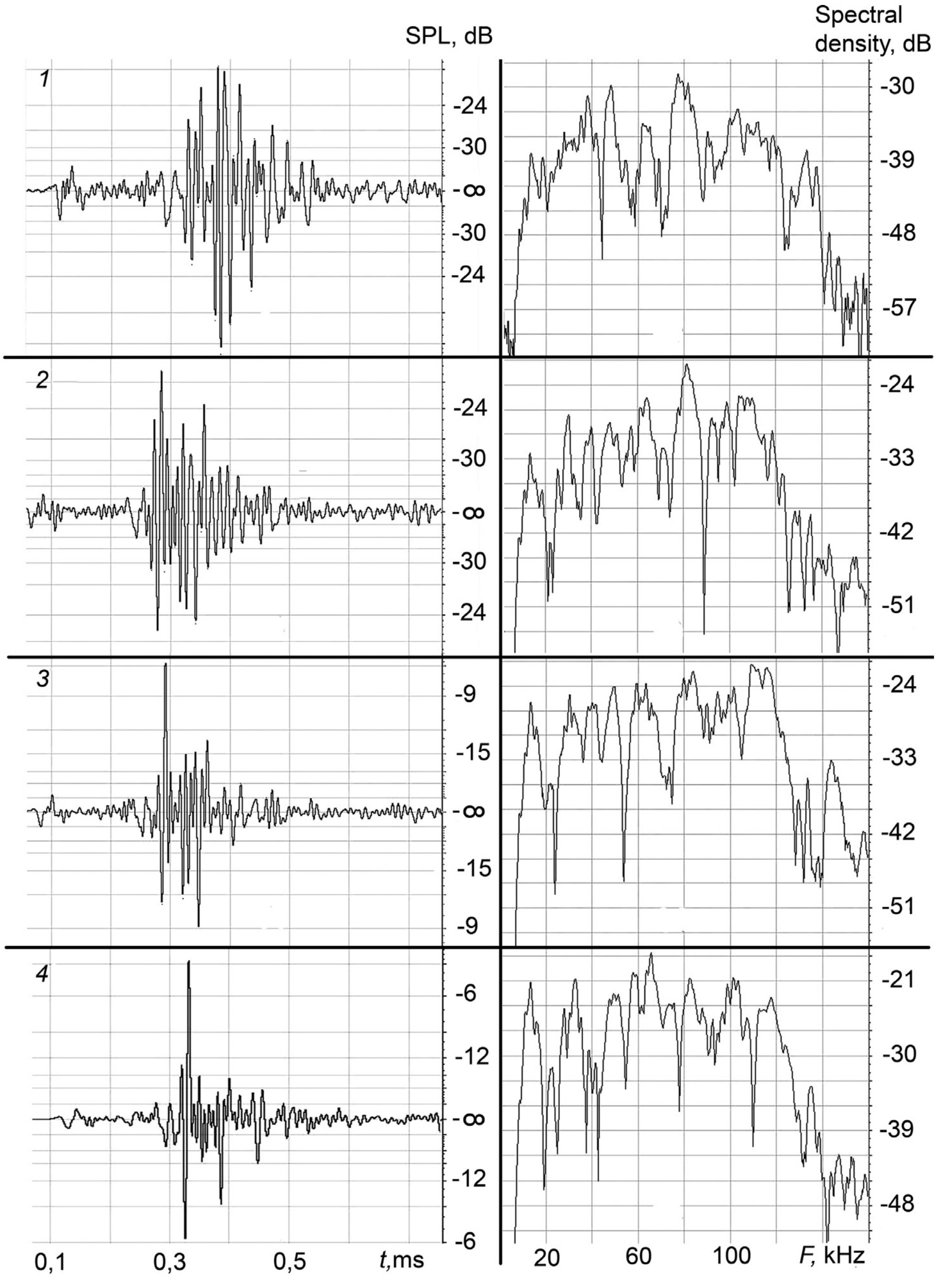

Fig. 3. Shape of the first 4 NPs (1–4) from pack 5 (see Fig. 2) produced by the dolphin Yana, and their corresponding amplitude spectra (to the right). The sound pressure level (SPL) of the acoustic pulses was normalized to 350 Pa.

the basic design features of the human language described by Hockett [28]. Let us discuss them in the same order as they were considered in Hockett's study (Table 2).

The first six features identified by the author are evidently inherent to the dolphin language and do not require additional discussion. It is of interest to discuss the remaining features that are to a greater degree determined by the level of the animal's intelligence and consciousness [26,29,30].

Semanticity. Experiments have revealed [31,32] that the dolphin understands new commands issued within artificial sign or sound language systems which use five-word-long sentences and interpreting which requires processing both the semantic and the syntactic rules of the language. These results, in our

Table 2
Presence (or absence) of the design features of the spoken human language in languages of other animals.

Hockett's design feature	Animal language			
	Bee dancing	Lark song	Gibbon call	Grey parrot's onomatopoeia
Vocal-auditory channel	–	+	+	+
Broadcast transmission and directional reception	+	+	+	+
Rapid fading	?	+	+	+
Interchangeability	limited	?	+	+
Total feedback	?	+	+	+
Specialization	?	+	+	+
Semanticity	+	in part	+	+
Arbitrariness	–	if semantic,+	+	+
Discreteness	–	?	+	+
Displacement	always +	?	–	–
Productivity	+	?	–	limited
Traditional transition	–	?	?	limited
Duality of patterning	–	?	–	+

All of these design features (i.e., all the pluses) are characteristic for the dolphin (and the human) spoken language, which is substantiated below.

opinion, indirectly confirm the hypothesis that each NP in the natural spoken language of the dolphin is a word with a specific meaning.

Arbitrariness. Conceptual learning within artificial sign or sound language systems, within several paradigms including learning to recognize a set of images and to compare images, has been demonstrated experimentally [33]. This indirectly proves that there is no direct link between the number of spectral extrema of a word and what the words mean in the hypothetical natural spoken language of the dolphin.

Discreteness. The discreteness of words in the dolphin language under consideration is likely determined by their different distributions over the frequency and the level of the maxima and minima of the spectral components of the acoustic pulses (see Fig. 3). These differences are apparently easily recognized by the dolphin because they exceed its differential hearing thresholds by frequency 0.2–0.8%) in the range of 10–130 kHz [34–36] and by intensity (10%) [37,38].

Displacement. It has been demonstrated that the dolphin correctly understood the commands of the artificial sign language system when they were transmitted as a televised image of the trainer as reliably as when the trainer directly issued them. The words of this language were referentially understood by the dolphin, including the ability to show the presence or absence of the referential object in the pool [33,39]. These facts indirectly prove that dolphins can refer to objects in space and time in their natural spoken communication and to 'discuss' things that are currently absent. This implicitly points to the presence of a high level of consciousness and a highly developed language in dolphins.

Productivity. By analyzing different combinations of individual spectral extrema in the dolphin language, it is possible to roughly estimate the number of words that the dolphin can create. If the dolphin uses the mechanism of critical bands with the width of about 10% of the central frequency of the auditory filter [40–43] in analyzing the spectrum of the word, about 26 frequency bands can fit into the 10–120 kHz frequency band. In this case, the maximum number of individual words that can differ by at least one spectral extremum is equal to the sum of the number of combinations with repetitions of 26 elements taken $1+2+...+26$ at a time, which adds up to about $5 \cdot 10^{14}$. This value is very high and obviously excessive, and may be even higher when taking into account the differences in the levels of the spectral extrema of the spectrum. Without a doubt, this quantity characterizes the potential for applying this method to encoding words. The actual number of words used by dolphins is apparently much lower and can be comparable to the human language. This number is reached as early as at seven spectral extrema, the number of combinations with repetitions of 26 elements taken 7 at a time increases to $3.4 \cdot 10^6$ words, i.e., a number comparable to the number of the known words of the human language, which does not exceed $(1–2) \cdot 10^6$. In this regard, we can assume that the spoken language of the dolphin is open.

Traditional transition. Non-genetic transmission of social behavior from generation to generation was observed in Cetaceans [44,45]. This indicates that these species of slow-growing, socially complex animals with a large brain [46] have highly advanced and effective mechanisms of social learning. Several potential scenarios and mechanisms, observed in a group of spotted dolphins (*Stenella frontalis*) freely swimming in the waters of the Atlantic, include vertical, horizontal and oblique directions of social transmission of information in different behavioral contexts [47]. Learning in this case may be an important means for transmitting social knowledge and, perhaps, a cetacean 'culture' from one generation to the next [48]. These results indicate that, along with some inborn aspects of the spoken language, dolphins evidently obtain words and natural language from their kin.

Duality. Since the spoken language of the dolphin consists of spectral extrema that act as phonemes, we can hypothesize that it has both phonological and grammatical structures, so dolphins can create an infinite number of words from a finite number of spectral extrema, which can in turn create an infinite number of sentences.

The analysis of the dolphin spoken language in this study has revealed that it either directly or indirectly possesses all the known design features of the human spoken language. For comparison and illustration of the obtained results, let us consider again the table from Hockett's study [28] (see Table 2). The first column of the table lists the design features of the human spoken language first established by Hockett [28], and the other columns list the presence of these features in the communication systems of various animals. We should emphasize that all of these design features are present in the spoken language of the dolphin (and of the human).

Conclusion

In this study, we carried out a reliable measurement of the mutually noncoherent pulses and their subsequent analysis as the most probable acoustic signals of the hypothetic spoken language of dolphins.

As this language exhibits all the design features present in the human spoken language, this indicates a high level of intelligence and consciousness in dolphins, and their language can be ostensibly considered a highly developed spoken language, akin to the human language. This claim is supported by the fact that dolphins have possessed brains that are somewhat larger and more complex than human ones for more than 25 million years [49]. Due to this, for further research in this direction, humans must take the first step to establish relationships with the first intelligent inhabitants of the planet Earth by creating devices capable of overcoming the barriers that stand in the way of using languages and in the way of communications between dolphins and people.

The results obtained in this study suggest the existence of a similar highly developed spoken language in toothed whales (Odontoceti), based on the similarity of their acoustic signals and morphology. However, the problems of studying acoustic signals of dolphins and toothed whales considered in the study undoubtedly present an interesting field for further research.

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