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Object features extracted by an echolocating dolphin from acoustic echoes: computational models and behavioral data

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Theoretical time resolution of bottlenose dolphins echolocation clicks is as high as 15 -20 µs. Given a very broad frequency range of a bottlenose dolphin hearing extending from 5-10 kHz to as far as 130-135 kHz, the dolphin sonar time resolution could be as high as the theoretical time resolution of the echolocation clicks. Multi-highlight structure of a target echo in response to a brief echolocation click results in the echo frequency spectrum being rippled, with local maxima and minima at different frequencies. There are many computer simulated models of echo-processing in dolphins. Most of these models are based on the frequency domain analysis of target echoes. However as long as actual time resolution of the dolphin sonar is not known it is impossible to choose between the frequency and time domain analysis. Results of the behavioral experiment presented here indicate that bottlenose dolphins are capable of extracting time domain features of target echoes.

1 Introduction

Dolphins have acute echolocation ability to discriminate underwater targets that vary in dimension, shape, material composition. During echolocation dolphins typically emit series of very short 20-50 µs and broadband clicks with peak-to-peak pressure up to 220 dB re 1µPa. The clicks are transmitted within narrow beam around 10° at a 3 dB level.
In response to a single echolocation click, underwater objects produce multiple reflections, often called echo highlights. Difference in a number of highlights, their amplitudes and intervals between highlights can be used by dolphins to discriminate between targets as well as difference in the echo frequency spectrum. In other words, dolphins can potentially use both, the time domain and spectral profile informaiton for discrimination between objects. It is clear that the dolphin's ability to resolve time-frequency information wil be limited by the resolving qualities of the auditory system.

Computational models were developed to understand how multiple discrimination cues may be represented in the dolphin auditory system. Roitblat et al. [1] were the first to apply an artificial neural network to dolphin echolocation. The four layers counterpropagation network consisted of 20 input units corresponding to the 20 frequency bins equally spaced at 4.9 kHz between 63 and 162 kHz. They found that the network was able to classify the tested target echoes with 100% accuracy compare to 95% accuracy by the dolphin. In following study [2] Moore et al. used the frequency range from 31.3 to 146 kHz, which is similar to the frequency range of the bottlenose dolphin hearing, divided in 30 bins. Again, the network performance was almost as good (90% correct target classification) as the dolphin's performance (93%). Next, the constant-Q filters (frequency bins), within the range of experimentally determined Q values for dolphins, were used which provided better approach to the dolphin's auditory system [3].

Unlike the prior models, the model developed by Branstetter et al. [4] performs both the time and frequency domain analysis, and assumes that the relative saliency of each domain will determine a cue the dolphin likely uses for discrimination. The model consists of a bank of gammotone filters followed by half-wave rectification and lowpass filtering. The output of the model resembles a spectrogram however the model reflects temporal and spectral resolving properties of the dolphin auditory system. This model representation of sound provides a more accurate approximation to what the dolphin may hear compared to conventional spectrograms, time-amplitude, or spectral representations. Model outputs were organized to represent discrimination cues related to spectral, temporal and intensity information. The model decisions were determined by calculating the Euclidean distance between the sample and each alternative [4]. The model performance was compared to dolphins' performance in behavioural experiments. Although multiple discrimination cues were potentially available to the dolphin, simulation results suggest temporal and spectral information could be used in different discrimination tasks.

At least when discriminating the temporal order of a small and large click [5], the time domain discrimination model [4] yielded superior performance compare to the spectral model. For the first time the computational model has shown that at interval between the clicks of just 200 µs the bottlenose dolphin might be able to discriminate the temporal order of a small and a large click but not the difference in the short-time frequency spectra. Unfortunately, the authors did not test the model for shorter interclick intervals although there are a plenty of behavioral experimental data that show that a bottlenose dolphin are capable of temporal order discrimination at interclick intervals as small as 10 µs [6, 7]. As long as there were differences in the time domain waveforms, bottlenose dolphins were found capable of discriminating between different brief signals with identical energy spectra [8, 9]. The results of numerous behavioral experiments with bottlenose dolphins appear to be more consistent with the time domain discrimination cues rather than with frequency domain cues.

In this presentation we discuss results of a behavioural experiment with a Black Sea bottlenose dolphin on discrimination between brief signals with different as well as with identical energy spectra. We manipulated the stimuli energy spectra and time domain waveforms

2 Methods

The subject was adult Black Sea bottlenose dolphin (*Tursiops truncatus*). Experiments were conducted in a 28 × 13 × 4 m concrete pool of the Institute of Biology of the Southern Seas (Karadag Branch), NAS, Ukraine. The two-response forced-choice procedure was used. A vertical net partition between two transducers set the minimum distance of 5 m, from which the dolphin made its choice. The transducers were placed at 1m depth and 3 m apart. Prior to stimuli presentation, the dolphin positioned itself at the far (away from the transducers) end of the partition. The dolphin was required to approach the transducer transmitting the standard (reinforced) stimulus on any particular trial. The stimuli were transmitted simultaneously from the left and right transducers at a repetition rate of 5 Hz. The choice of the transducer to transmit a standard signal for a given trial was randomized. Spherical transducers of 1.2 cm in diameter were used. The transducers transmitting response had maximum at 110-130 kHz and dropped by 12 dB per octave toward lower frequencies. The threshold measurements were made using the method of constant stimuli.

Two types of stimuli were used. First, the dolphin was required to discriminate between the stimuli shown in Figure 1. At the electrical side of the transducers the stimuli were double-pulses. One double-pulse consisted of two pulses with the same polarity separated by 5 µs. In the other, the pulses were of opposite polarity and were separated by 10 µs. Because of very short time intervals between the pulses, at the acoustical side of the transducers, the double-pulses appeared as single clicks. Within frequency range of the bottlenose dolphin hearing, the stimuli have only one trough in the energy spectrum at the same frequency of 100 kHz.

Although the difference in the stimuli energy spectra were obviously big enough to be discriminated by any of the abovementioned computational model, it was not clear whether the energy spectra having a single trough at the same frequency would yield difference in the dolphin's auditory perception. Moreover, because the phase spectra of the double-clicks were almost identical within the frequency range of the dolphin hearing, the stimuli had very similar time waveforms at the acoustical side of the transducers. On the other hand, the differences in the stimuli energy (amplitude) at the acoustical side of the transducers of around 2 dB could be used by the dolphin for discrimination.

Next, by adding the double clicks to each other as shown in Figure 2 we created time-reversed quadruples with identical energy spectra. The short-time energy spectra of the quadruples also appeared to be very similar. At the same time because of considerable difference in a direct and reversed quadruple phase spectra (B iii), the time waveforms at the acoustical side of the transducers were also different. Thus, we compared the dolphin discrimination between the brief signals having different energy spectra but very similar time waveforms with discrimination between brief signals having identical energy spectra and very similar short-time energy spectra but different time domain waveforms.

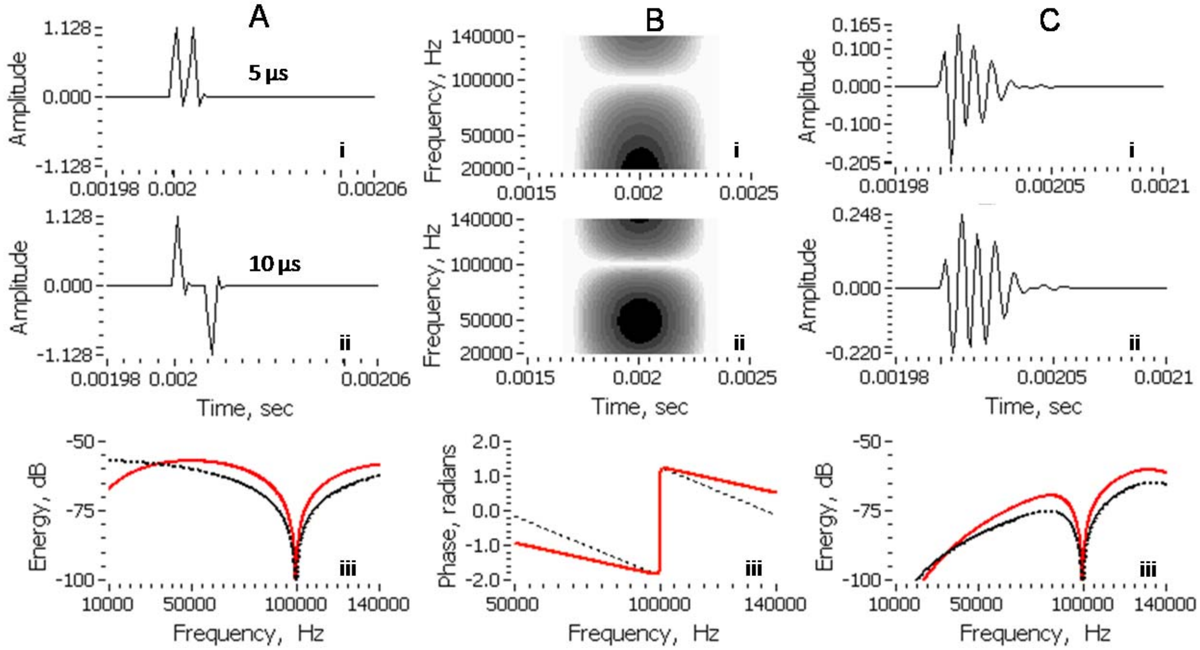

Figure 1: A – Double-pulses comprised of two identical 2-µs pulses with the same (i) and opposite (ii) polarity separated by 5 and 10 µs respectively and their energy spectra (iii). B (iii) - Phase spectra of the double-clicks at the electrical side of the transducers. B (i and ii) – STFT spectrograms of the double-pulses generated using 700-µs Hanning analysis window and 10-µs time increment. C –Waveforms (i and ii) and energy spectra (iii) of the double-pulses at the acoustical side of the transducers.

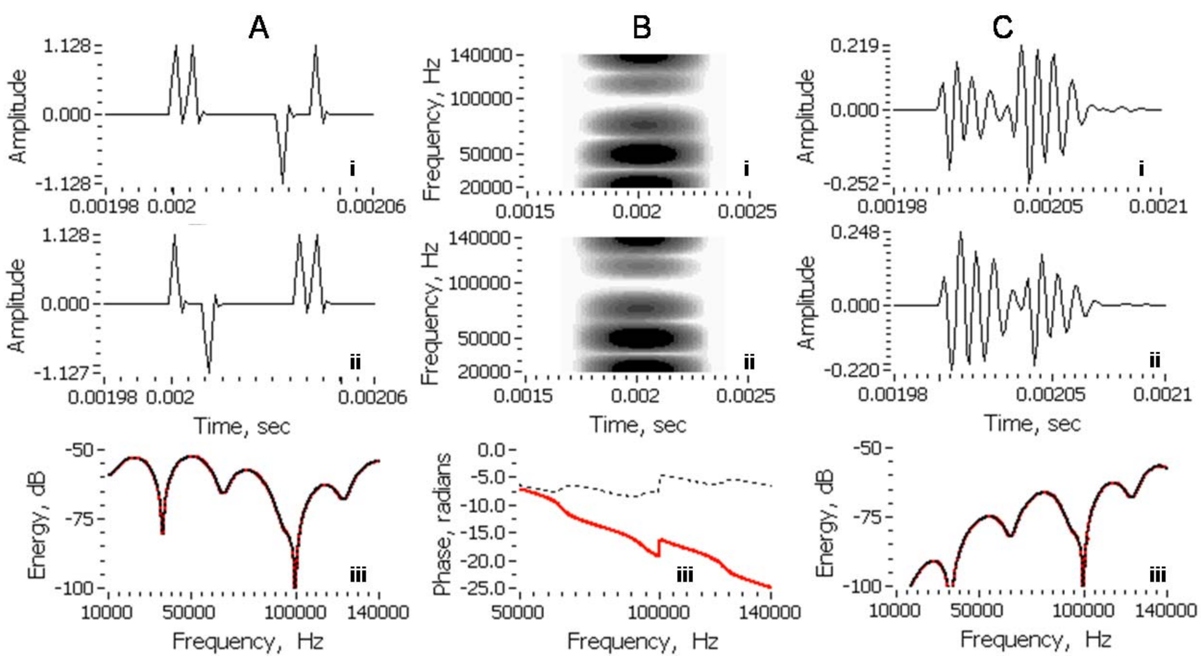

Figure 2: A – Mirror image quadruples (i and ii) and their energy spectra (iii) at the electrical side of the transducers. B (iii) – Phase spectra of the quadruples. B (i and ii) – STFT spectrograms of the quadruples generated using 700-µs Hanning analysis window and 10-µs time increment. C – Waveforms (i and ii) and energy spectra (iii) of the quadruples at the acoustical side of the transducers.

3 Results

Despite repeated effort, the dolphin was unable to discriminate between the double pulses shown in Figure 1. It appeared that the differences in both the time waveforms and energy spectra were below discrimination threshold for the dolphin. At the same time the discrimination of the time-reversed quadruples with identical energy spectra (Figure 2) was at a near 100% correct response level even for the overall quadruple duration (from beginning of the first pulse to the end of the fourth pulse) as short as 35 µs. Given the fact that position of the peaks and troughs in the short-time energy spectra of the quadruples was also identical (though there were some differences in the trough depths) the dolphin appeared to discriminate between the time domain waveforms of the quadruples (Figure 2C i and ii).
The dolphin appeared to discriminate the stimuli based on difference in temporal order of a small and large click (Figure 2C i and ii) because it was possible to disrupt discrimination by equalizing amplitude (by manipulating the pulse amplitudes at the electrical side of transducers retaining the identical energy spectra of the quadruples) of the first and second clicks.

To follow the quadruple envelope differences, the dolphin's auditory time resolution should be better than at least 30 µs. The results appear to be consistent with the time domain discrimination cues rather than with frequency domain cues and agree well with the bottlenose dolphin auditory time resolution of 20-30 µs measured in behavioural experiments [8-12]. As far as a computational model of the dolphin sonar is concerned, more attention should be given to an extremely high temporal acuity of the bottlenose dolphin auditory system.

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