Discrimination of the Signals with Identical Energy Spectra by the Bottlenose Dolphin

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Dolphins are capable of discriminating a small click followed by a large click from a time reversed pair of the same clicks. Because the time reverse of a signal does not change its energy spectrum it appeared that the dolphins discriminated the waveforms of the mirror image double clicks. A short-time spectral analysis with a 0.3-ms chi-square window has been suggested as an alternative to the time domain discrimination of the double clicks with identical energy spectra. The length of the analysis window was chosen based on the dolphin's auditory time resolution of around 0.3 ms and integration time of 0.265 ms. Dolphin's discrimination of three different types of time mirror image signals is discussed in this paper. Our experiments indicate that the dolphin's auditory analysis window is not bigger than around 0.1 ms. The dolphin's performance appeared to be more coherent with the time domain analysis of the mirror image stimuli than with the short-time frequency analysis.

I. INTRODUCTION

Target discrimination experiments have always been seen as a basic way to study auditory signal processing mechanisms in dolphins. Threshold differences in physical dimensions of targets can be precisely translated to the threshold differences in the target echo characteristics. A true problem, however, is to pinpoint the ones, which undergo the auditory analyses. A double representation of a target echo in the time and frequency domains seems to be a major obstacle to a plausible interpretation of target discrimination results.

Theoretical time resolution of the dolphin's clicks is as high as 0.012-0.015 ms (milliseconds). Combination of very short echolocation clicks with more than 100-kHz wide hearing frequency range from around 10 to 130 kHz suggests that the actual time resolution may be as high as the theoretical time resolution of the dolphin's echolocation clicks. However, it always seemed doubtful that the theoretical time resolution of the dolphin's clicks could be materialized in the relatively slow auditory system.

Some experimental results identify a time interval of around 0.3 ms as a fundamental constant of the dolphin's auditory system [1-4]. This interval named the "critical interval" is believed to be the time resolution and integration time of the dolphin's auditory system [5, 6]. As long as echo highlights are within the critical interval, a target echo is recognized by its frequency spectrum or time separation pitch (TSP) [3, 6].

There are, however, experimental results, which certainly suggest that dolphin's time resolution is almost as high as the theoretical time resolution of its echolocation clicks [7-12]. Particularly difficult to agree with the auditory time resolution of 0.3 ms is a dolphin's ability to discriminate mirror image double clicks at interclick intervals as short as 0.005 ms [5. 13, 15].

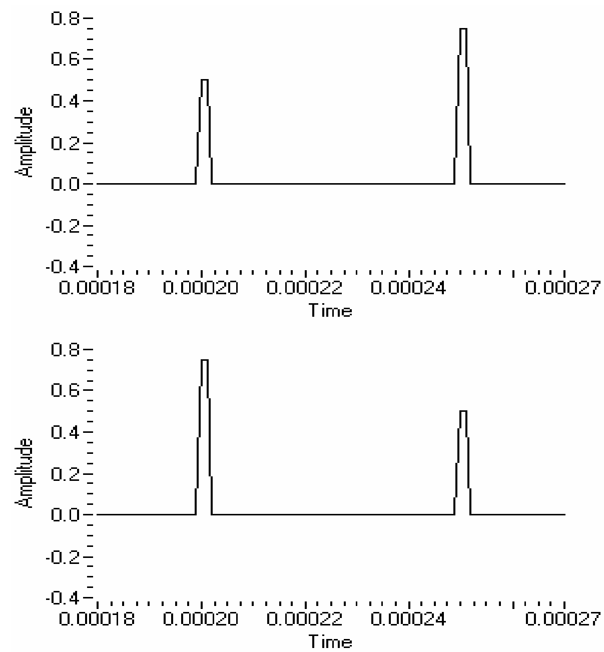

Fig. 1. Double pulses with the reversed order of a small and a large pulse. Time scale is in seconds.

The Black Sea dolphin was found capable of discriminating a small click followed by a large click from its time reverse replica (Fig. 1) [13]. The experiment was designed to investigate mechanisms of the auditory analysis within the critical interval. Despite differences in the waveform the mirror image double clicks have identical energy spectra. A minimum interclick interval of around 3 ms at which humans were able to discriminate between the double clicks [16], can be associated with the time resolution of the auditory system. Dubrovskiy [5] found, however, that when interclick interval was smaller than the critical interval of 0.3 ms, the difference in amplitude had to be more than 14 dB for the dolphin to be able discriminate the double

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clicks. As the interclick interval was increased to 0.25 ms, the threshold difference decreased to 8 dB and further to 1.6 dB at 0.5 ms. Dubrovskiy [5] concluded that within critical interval the dolphin could not discriminate the stimuli through their time profile or differences in the phase spectra. In subsequent experiments the dolphin was able to discriminate the stimuli at a 10-dB amplitude difference between the clicks for interclick intervals shorter than 0.1 ms as well, which led to a new inference that "time processing is quite valid within the critical interval". However, the decrease in threshold difference from 14 dB to 10 dB does not seem significant enough to draw contrary conclusion. It was clear from the paper that the reported results were preliminary and should experiments have been continued, threshold amplitude differences could be very much different.

We replicated experiments with the mirror image double clicks [5] and found very much different threshold values [15]. The dolphins were capable of discriminating the mirror image double clicks at the amplitude difference between the first and second click as small as 0.5-1 dB and as big as 30 dB. No indication of the critical interval of 0.3 ms was found in our experiments.

The Atlantic bottlenose dolphin was also found capable of discriminating between mirror image double clicks [14]. The dolphin performed just slightly above the 75% correct response level. Johnson *et al*. [14] assumed that the dolphin could not temporally separate the clicks at the tested 0.2-ms interclick interval and chose to concentrate on the frequency domain cues. Windowed STFT analysis was used to generate the difference in the frequency spectra of a direct and a time-reversed double click. A chi-square window with 90 % decay by 0.3 ms was used for a short-time spectral analysis. The chi-square window simulated a real frequency analysis with the bandpass auditory filters characterized by a transient response with a rapid rise and exponential decay [14]. The size of the window was chosen based on the dolphin's critical interval of 0.3 ms [1-3] and the dolphin's integration time of 0.265 ms [4]. For a 0.2-ms interval and a 10-dB difference in the click amplitude, a 0.3-ms chi-square window strongly enlarges the ripples for one double click and diminishes the rippling in the reverse double click (Fig. 2). Au [6] suggested that the short-time frequency analysis seems more plausible than the use of phase difference cues and is also applicable to the experiment of Dubrovskiy et al. [5, 13].

The rippling, however, occurs at a very low energy level (Fig. 2) behind the large energy peak of the first click and might be difficult to detect. If the dolphin were able to separate the large peak and the following ripples, it might be able to detect a small energy peak before a large one in a comparison double click (Fig. 2).

Besides, although a 0.3-ms analysis window might work for the click amplitude difference of 10 dB, it would hardly produce enough difference in the frequency spectra for a click difference as small as 1 dB and interclick interval as short as 0.004 ms [15].

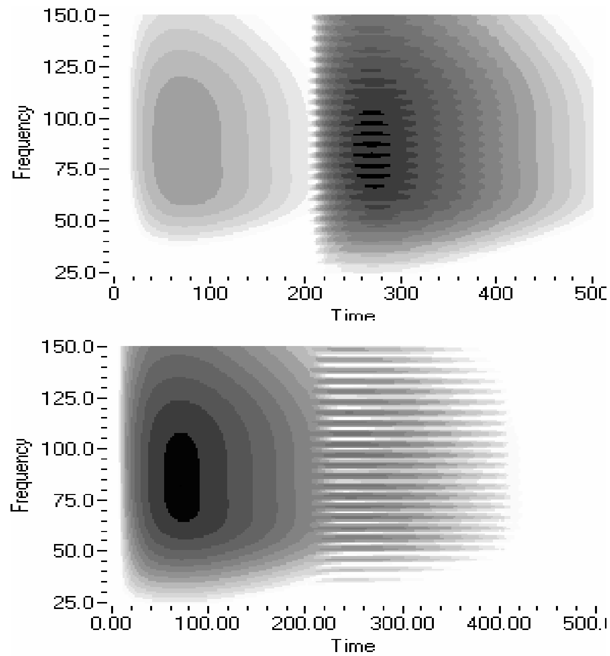

Fig. 2. STFT energy spectrograms generated for the double pulses in Fig. 1 using a 0.3-ms chi-square window (at the acoustical side of transducers). The amplitude difference between the first and second pulses was 10 dB; interpulse interval was 0.2 ms. Time scale is in microseconds.

Anyway, the differences in the short-time spectrum of the mirror image double clicks are caused by amplitude difference between the first and second clicks. With the auditory time resolution of 0.02-0.03 ms [7-12], the dolphin appears capable of discriminating the double clicks (Fig. 1) with interclick intervals of 0.2 ms [14] in the time domain, simply by a difference in the time order of a small and a large click.

The use of the mirror image double click allows narrowing our search for target discrimination cues by eliminating, at least the ones which stem purely from differences in the energy spectra. Using a broadband noise we also tried to mask for the dolphin the short-time spectra of the mirror image double clicks (Fig. 3). Threshold signal-to-noise ratios were measured as a function of the interclick intervals.

Two more types of the mirror image stimuli were also tested in experiments with dolphins. Although short-time spectra of mirror image stimuli are different, we seemed to find the way to reduce these differences beyond recognition for the dolphin. The double clicks with reversed order of a large and a small click were modified into double clicks with equal amplitude of the first and second clicks (Fig. 4, 5). The modified double clicks had identical energy spectra and practically the same short-time energy spectra. The difference in interclick intervals appeared to be the only time domain cue for the dolphin's discrimination of the modified double clicks. The third couple of mirror image stimuli were time reversed triplets of the clicks with identical interclick intervals and amplitudes (Fig. 12). It appeared that the triplets could only be distinguished in the frequency domain by difference in their short-time spectra. The results of the dolphin's discrimination of these three types of mirror image stimuli seemed to complement each other.

II. METHODS

The subjects were the Black Sea bottlenose dolphins. Experiments were conducted in a 28 × 13 × 4 m concrete pool. The two response forced-choice procedure was used. A vertical net partition between two transducers set a 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 stimulus on any particular trial. 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 110-120 kHz and dropped by 12 dB per octave toward lower frequencies. Calibrations were made using a B&K model 8103 hydrophone. The stimulus levels were 40-50 dB above the dolphin's absolute threshold for a click.

The threshold measurements were made with the method of constant stimuli. A stimuli parameter under consideration was gradually reduced until the dolphin's correct response dropped to around 50% level. Normally, a 3-6-dB increase in a stimulus parameter above the threshold was enough to restore performance to a 90-100% level. The difference was again decreased in 2-dB steps in 10-trails blocks. The threshold was reached 2 to 4 times during the session. The dolphins performed around 250 trials per session. A threshold estimate was completed when, over at least 2 consecutive sessions, threshold values were within 3 dB of each other. The threshold values from these sessions were averaged for the threshold estimate at the 75% correct response level.

Computer simulation was used to illustrate stimulus waveforms and energy spectra at the electrical and acoustical sides of a transducer. Short Time Fourier Transform (STFT) spectrograms of the stimuli were generated using a chi-square window with different lengths and a time increment of 1 microsecond. The darkness of a spectrogram is in direct proportion to energy.

A. Double clicks with a reverse order of a small and a large click

In the first series of experiments the dolphin's discrimination between the double pulses with a reverse order of a small and a large click (Fig. 2) was investigated. In order to mask the differences in the short-time spectra, the gap between the first and second square pulses was filled with the broadband white noise (Fig. 3).

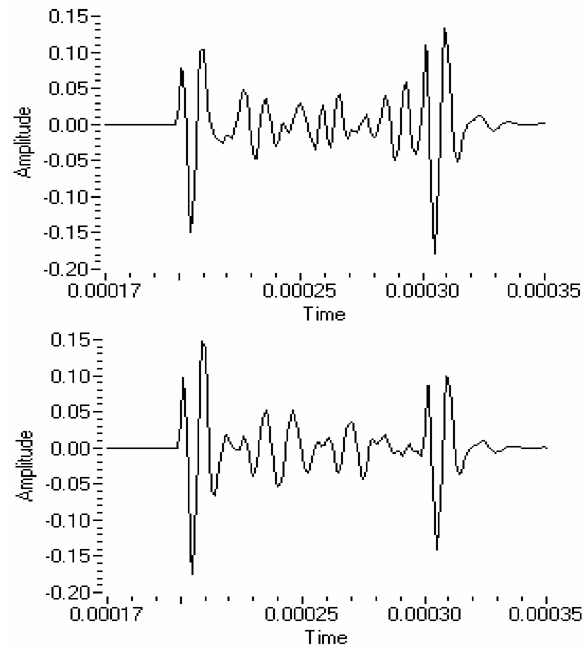

Fig. 3. Waveforms of the mirror image double clicks mixed with the noise (at the acoustical side of the transducers). Time scale is in seconds.

The amplitude difference between the first and second clicks was 2 dB. The noise amplitude was gradually increased until the double click discrimination dropped to a 50% level. The masked threshold was measured for several interclick intervals from 0.02 to 0.2 ms. As the interclick interval was increased the noise duration was also increased to fill the gap between the clicks.

B. Double clicks with different interclick intervals

A dolphin's discrimination between the double click with different intervals was studied to estimate the dolphin's auditory frequency resolution [1, 2]. However, the interpretation of the dolphin's discrimination between the double clicks with different interval is as problematic as that between the real targets. Whenever the threshold differences in the echo frequency spectra were measured, there were always the differences in the interclick intervals that could be used by the dolphin.

The negative pulses symmetrically added to the double pulses shown in Fig. 1 do not obliterate stimuli property to be time mirror image, yet transform them into the double clicks with different interclick intervals (Fig. 4).

Because at a 0.005-ms interpulse interval the pair of the negative and adjacent positive electrical pulses is transformed at the acoustical side of the transducer into a single click, the triplets of electrical pulses in Fig. 4 produced the pairs of acoustic clicks (Fig. 5). However, the negative pulses changed the double clicks with identical interclick interval into the double clicks with different interclick intervals. The interclick interval in the double click produced by the bottom triplet in Fig. 4 was 0.005 ms shorter than that produced by the top triplet.

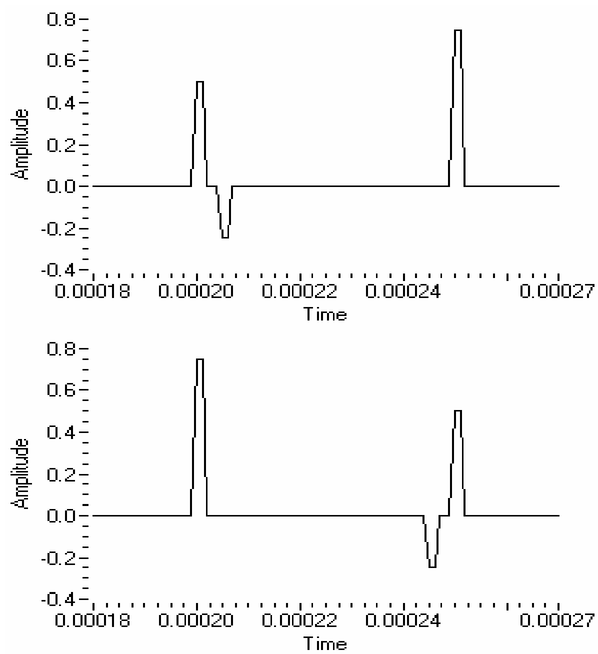

Fig. 4. Mirror image triplets of 0.002-ms square pulses formed from the double pulses shown in Fig.1 by adding negative pulses. Time scale is in seconds.

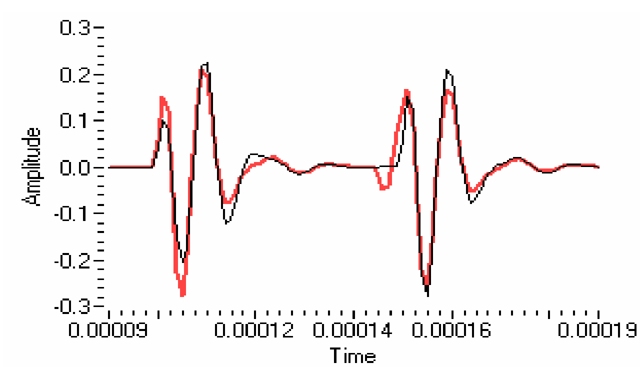

Fig. 5. Superimposed waveforms of the mirror image triplets shown in Fig. 4 at the acoustical side of the transducers. Time scale is in seconds.

Moreover, for the pulse amplitudes in Fig. 4, the negative pulses equalized for the dolphin the energies of the first and the second acoustic clicks (Fig. 6). Although within a broad frequency range the energy spectra of the single electrical pulse and the pair of the electrical pulses of opposite polarity were different, within the frequency range of the dolphin hearing the energy spectra of the first and the second acoustic clicks were practically the same (Fig. 6).

Whenever presented with the acoustic click produced by a single electrical pulse and the click produced by the pair of electrical pulses, the dolphin was unable to discriminate between them. In contrast to the original double clicks of Fig. 2, the short-time energy spectra of the mirror image triplets are also practically indistinguishable (Fig. 7).

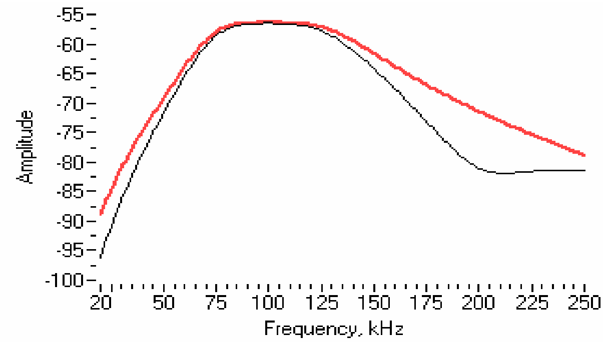

Fig. 6. Energy spectra of the first and second clicks of the double clicks shown in Fig. 5.

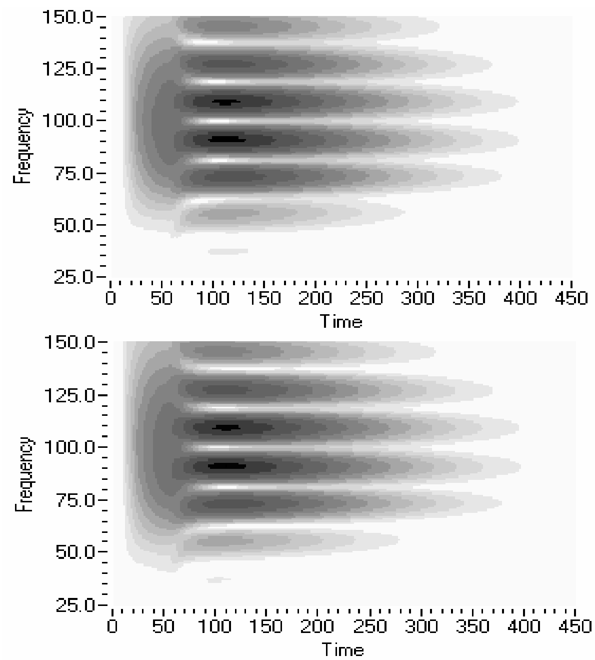

Fig. 7. STFT spectrograms generated for the mirror image double clicks (Fig. 5) using a 0.3-ms chi-square window. Time scale is in microseconds.

It appeared that the difference in the interclick intervals was the only discrimination cue for the mirror image double clicks. The largest interclick interval at which the dolphin would be able to discriminate the double clicks was measured. The interval between the negative and adjacent positive pulses (Fig. 4) was kept 0.005 ms throughout the experiment. Interclick intervals were varied by changing the triplet durations (from onset of the first pulse to the offset of the third pulse) so that they remained mirror image. It was expected that the dolphin would fail to discriminate the double clicks if the interclick interval difference was decreased below the dolphin's difference limen on interval [5. 8].

It seemed essential whether the threshold interval difference for the mirror image double clicks (Fig. 5) would be the same as that for non-mirror image double clicks [5, 8]. If the threshold interval differences proved to be the same it would signify that the dolphins in [5, 8] also discriminated the double clicks in the time domain but not by differences in the double click frequency spectra.

C. Triplets with identical interclick intervals and amplitudes.

The third couple of mirror image stimuli were time reversed triplets of the 0.002-ms square pulses with identical interpulse intervals and amplitudes (Fig. 8). It appeared that these triplets could only be distinguished in the frequency domain despite that they too had identical energy spectra.

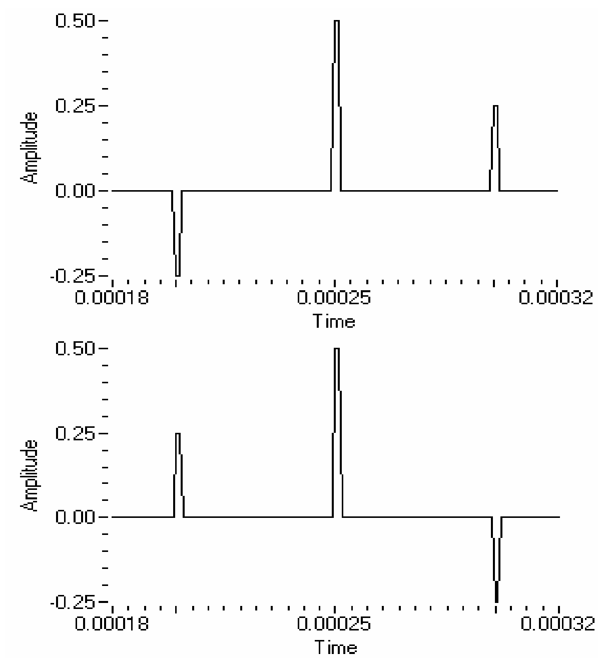

Fig. 8. Mirror image triplets of the square pulses with identical interpulse intervals and amplitudes at the electrical side of the transducers. Time scale is in seconds.

The idea of using such stimuli came after series of experiments with the pairs comprised from the first and second pulses of the top and bottom triplets [17] (this volume). At equal interpulse intervals, the energy spectra of the pairs are rippled with the same period, however maxima of one spectrum correspond to minima of the other. Because the pulse amplitudes and interpulse intervals were the same in comparison pairs, there were no discrimination cues for the dolphin except for the differences in the frequency spectra. However, the frequency spectra differences could only be generated if the first and the second clicks interfered with each other in the dolphin's auditory system. It was found that the dolphin was able to discriminate the double clicks produced by such pairs of the square pulses as long as interclick interval was shorter than around 0.1 ms [11, 17]. This threshold interval appeared to be a largest interval for which the first and the second clicks merged for the dolphin into a single auditory pattern producing the differences in the double click frequency spectra.

The third pulses were added to the first two pulses in order to equalize the stimuli energy spectra. It was expected that equalizing the spectra would lead to the dolphin's failure to discriminate the triplets. However, it did not. As long as the dolphin discriminated the double clicks it was able to discriminate the triplets as well.

Although the energy spectra of the triplets are identical, the short-time windowed spectral analysis reveals clear differences between the triplets. Wherever there is an energy maximum for one triplet, there is an energy minimum for the other (Fig. 9).

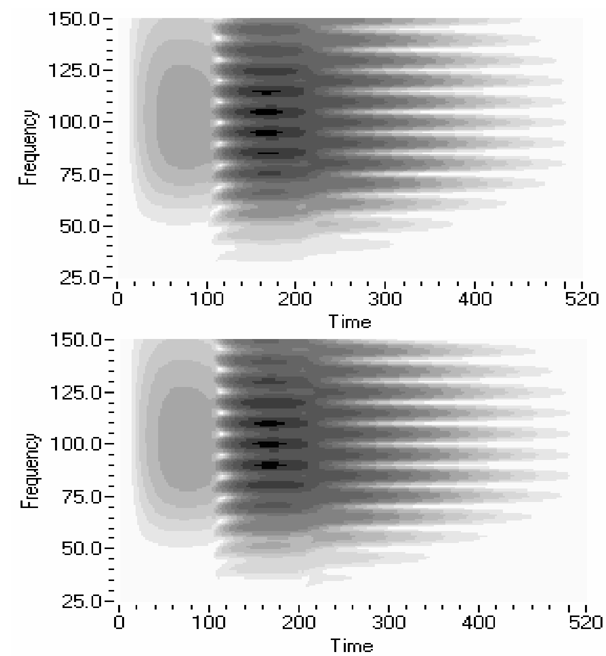

Fig. 9. STFT spectrograms generated for the direct and reverse triplets of Fig. 8 (at the acoustical side of the transducers) using a 0.3-ms chi-square window. Interclick intervals were 0.1 ms. The middle click was 10-dB larger than the first and the second clicks. Time scale is in microseconds.

The energy spectra differences will only occur if the spectral analysis window is longer than the interclick interval. Therefore, the largest interclick interval at which the triplets are distinguishable for the dolphin can be taken as an estimate of the dolphin's auditory spectral analysis window. The threshold interclick interval was measured as a function of the amplitude difference between the middle and margin clicks.

The mirror image double clicks in Fig. 1 could be identified both in the time and frequency domains by the difference in the click amplitude or by a short-time energy spectra. The mirror image double clicks in Fig. 5 have practically the same short-time energy spectra. They only could be discriminated in the time domain by difference in the interclick intervals. The mirror image triplets (Fig. 8) have identical interclick intervals as well as the pulse amplitudes. Therefore the only cue that could be used by the dolphin to discriminate the triplets appeared to be a short-time spectral analysis. The results of the dolphin's discrimination of three different stimuli types seemed to be complementary regarding the auditory analysis of the click signals in the time and frequency domains.

III. RESULTS

A. Double clicks with a reverse order of a small and a large click

In the absence of the noise the dolphin's discrimination of the double clicks (Fig.1) with a 2-dB amplitude difference between the clicks was 100% correct for all tested interclick intervals from 0.02 to 0.2 ms.

For a small amplitude difference between the first and second clicks, the STFT spectrograms generated for the direct and reverse double clicks using 0.3-ms chi-square window appear to be very similar (Fig. 10).

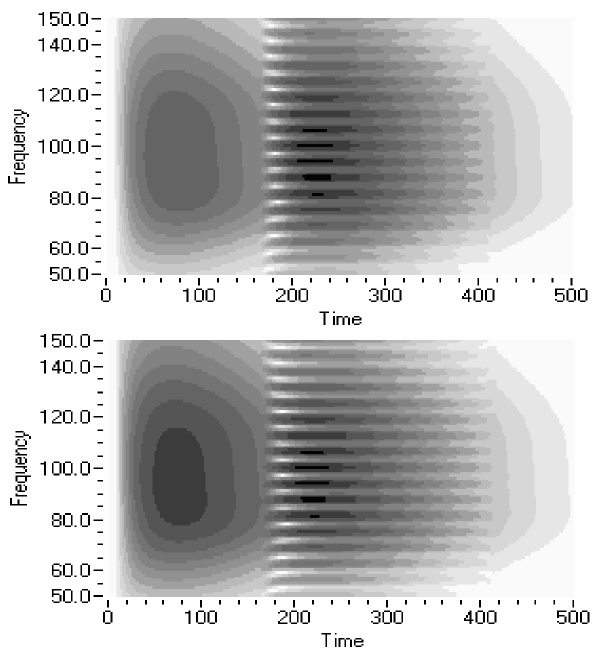

Fig. 10. STFT spectrograms generated for the direct and reversed double clicks in the absence of the noise using a 0.3-ms chi-square window. Interclick interval was 0.16 ms. Time scale is in microseconds.

The 0.3-ms chi-square window produced very shallow ripples in both short-time spectra with slightly different ripple depths. These short-time spectra are much more difficult to differentiate than the spectra for a 10-dB amplitude difference between clicks (Fig. 2) [14]. In contrast to the spectrograms in Fig. 2, comparison spectrograms in Fig. 10 can not be considered as the one with and the other without ripples at all [6, 14].

With the noise filled the gap between the clicks (Fig. 3), the short-time spectra became practically indistinguishable (Fig. 11) whereas the dolphin was able to discriminate the double clicks even at a higher noise level. The integration of the noise within a 0.3-ms analysis window completely masked differences in the short time spectra hardly noticeable even in absence of the noise (Fig. 10). In order to discriminate the double clicks masked with the noise, the integration window should be shorter than interclick interval. As soon as most of the noise is left outside an integration window, the clicks can be separated and their energies can be measured.

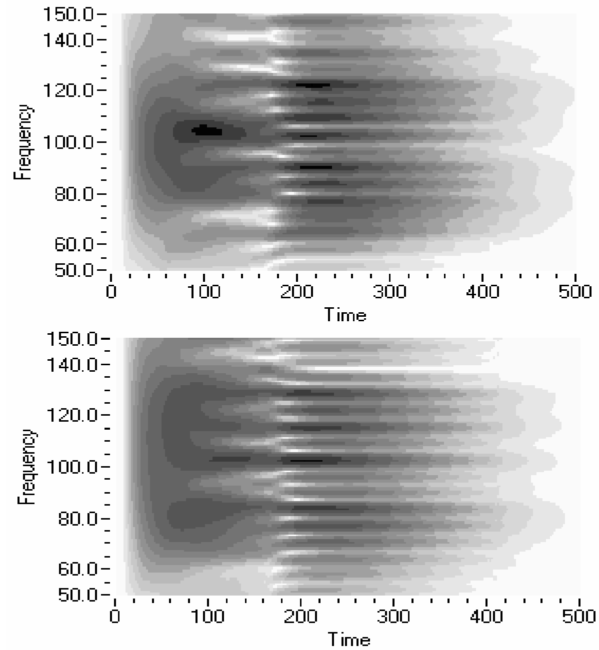

Fig. 11. STFT spectrograms generated for the direct and reversed double clicks mixed with the noise (Fig. 3). The signal-to-noise ratio was around 6 dB above the threshold. A 0.3-ms chi-square window was used. Time scale is in microseconds.

The independence of the masked threshold from the interclick interval indicates that the integration time was shorter than at least 0.05 ms (Fig. 13).

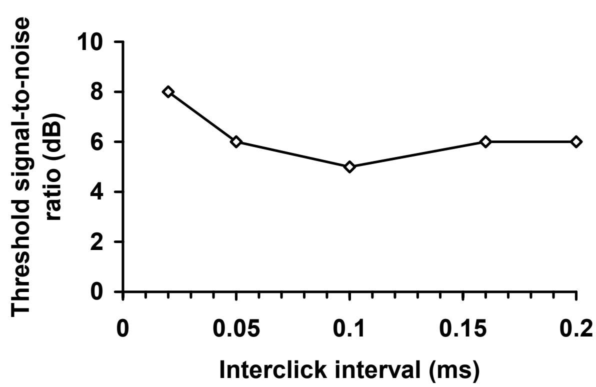

Fig. 12. Threshold ratio of the amplitude difference between the first and second clicks to the root-mean-square value of the noise as a function of the interclick interval.

The masked thresholds in Fig. 12 are linked to the amplitude difference between the first and second clicks because what is matter for the double click discrimination, both in time and in frequency domains, is the click amplitude difference but not the absolute amplitudes of the clicks. The dolphin discriminated the double clicks as long as the root-mean-square value of the masking noise was around 6 dB below the difference in the peak amplitude of the clicks. However, with the integration window shorter than 0.05 ms, the dolphin could hardly generate any meaningful short-time spectra differences between the double clicks. The time domain analysis of the double clicks seems to account well for the dolphin's discrimination of the double clicks.

Even with the integration window smaller than 0.05 ms, the dolphin would hardly be able to separate the clicks at interclick interval of 0.02 ms, not to mention interclick intervals of 0.004 ms [15]. At the acoustical side of the transducer the double pulse (Fig.2) with that short interclick interval are transformed into a single click. We found that in order to discriminate between the double clicks at very short interclick intervals the dolphin used the auditory filter with a bandwidth of 15-20 kHz centered at one of the minimum in the amplitude spectrum of the double clicks [15, 18]. Due to characteristic changes in the phase spectra at the amplitude minimum, the filter reactions to the direct and reversed double clicks can be very much different even for a very short interclick interval. The dolphin's ability to discriminate between the mirror image double clicks at very small interclick intervals might require even more precise time domain analysis than can be described by the auditory time resolution of 0.02-0.03 ms [15, 18].

B. Double clicks with different intervals

The dolphin proved to be capable of discriminating the double clicks with identical energy spectra and practically the same short-time energy spectra within the frequency range of the dolphin's hearing (Fig 7). The dolphin discriminated the double clicks of Fig. 5 as long as the interclick interval was smaller than 0.05 ms (Fig. 13).

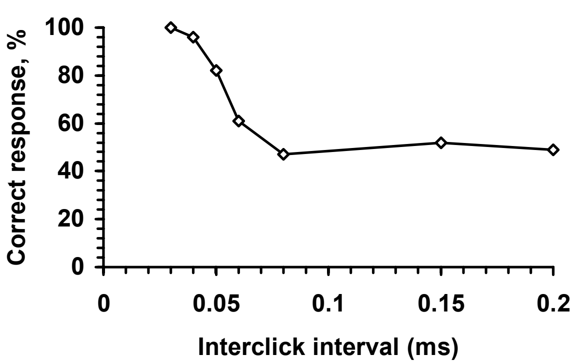

Fig. 13. Dolphin's discrimination of the mirror image double clicks (Fig. 5) as a function of the interclick interval.

For the absolute interval difference of 0.005 ms (Fig. 4), the threshold relative interclick interval difference was around 10%. Approximately the same threshold differences in the interclick intervals were found for non-mirror image double clicks with different interclick intervals [1, 8, and 12]. Although there were some differences in the short-time spectra, they appeared to be beyond recognition for the dolphin if a 0.3-ms integration window was used (Fig. 7). The short-time spectra shown in Fig. 14 are obviously different at any frequency and yet they correspond to the double clicks with the same threshold interclick intervals of 0.050 and 0.055 ms [5, 8] as the spectra in Fig 7.

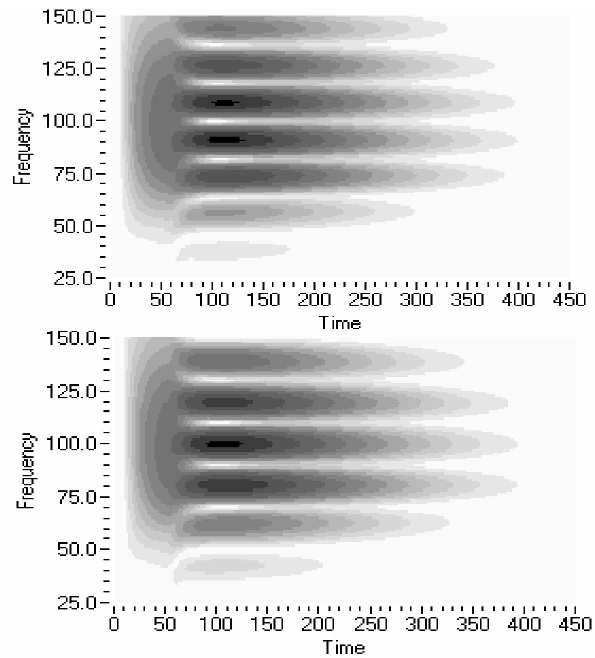

Fig. 14. STFT spectrograms generated for the non-mirror image double clicks with 0.055 and 0.050 ms interclick intervals using a 0.3-ms chi-square window.

The short-time spectra in Fig. 14 were generated for the non-mirror image double clicks produced by the pairs of identical square pulses with different interpulse intervals [5, 8]. In contrast to Fig. 7, the short-time spectra in Fig. 14 have different ripple separation with some maxima of one spectrum situated against the minima of the other. The threshold difference between interclick intervals, proved to be the same for the mirror image double clicks with practically the same short-time spectra (Fig. 7) and the non-mirror image double clicks with considerable difference in the short-time spectra (Fig. 16). This signifies that the dolphins in [5, 8] paid no attention to the differences in the frequency spectra of the double clicks and discriminated them in the time domain. The dolphins failed to discriminate the double clicks when the relative interclick interval difference clicks was decreased below the dolphin's difference limen on interval.

The dolphin was able to discriminate the mirror image double clicks at the interclick intervals as short as 0.03 ms (Fig. 13) which suggests the auditory time resolution even better than 0.03 ms.

C. Triplets with identical interclick intervals and amplitudes

The dolphin was capable of discriminating the mirror image triplets (Fig. 8) as long as interclick intervals were within 0.005 ms to around 0.1 ms.

The largest interclick interval for which the dolphin was able to discriminate the triplets changed in inverse proportion to the amplitude difference between the middle and periphery clicks (Fig. 8). At a 0.1-ms interclick interval the clicks had to be of the same amplitude for the dolphin to discriminate the triplets. As the amplitude difference was increased to 20 dB, the threshold interclick interval decreased to 0.04-0.05 ms.

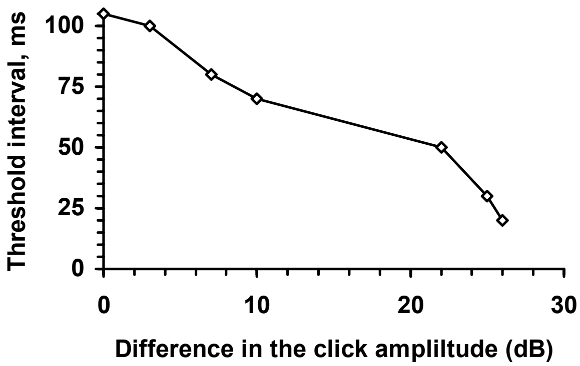

Fig. 15. The largest interval between the clicks of the mirror image triplets (Fig. 8) as a function of the amplitude difference between the middle click and preceding and following clicks.

Despite the clear differences in the short-time energy spectra generated with 0.3-ms chi-square window (Fig. 9), the dolphin failed to discriminate the triplets for interclick intervals longer than 0.1 ms. This time interval appears to be the dolphin's auditory analysis window. As long as interclick intervals were longer than the 0.1-ms auditory integration window, the interference between the clicks was not strong enough to produce tangible for the dolphin differences in the short-time spectra.

At a 0.1-ms interclick interval, the ripples in the short-time energy spectrum of the triplets are separated by 10 kHz (Fig. 9), which can be considered as the frequency resolution of the dolphin's auditory system. The dolphin's frequency resolution for click signals similar to the dolphin's sonar clicks proved to be worse than the frequency resolution of around 2 kHz found for continuous rippled noise [19].

Although the dolphin was unable to discriminate the triplets with considerable differences in the short-time spectra (Fig. 9), it readily discriminated the triplets with 0.01-ms interclick intervals (Fig. 16), which had very similar short-time spectra (Fig.17). Clearly, the 0.3-ms chi-square integration window does not justify the dolphin's performance in both cases.

The time domain analysis appeared to be a better option for the triplet discrimination at very short interclick intervals when a triplet transforms into a single click at the acoustical side of a transducer (Fig. 16).

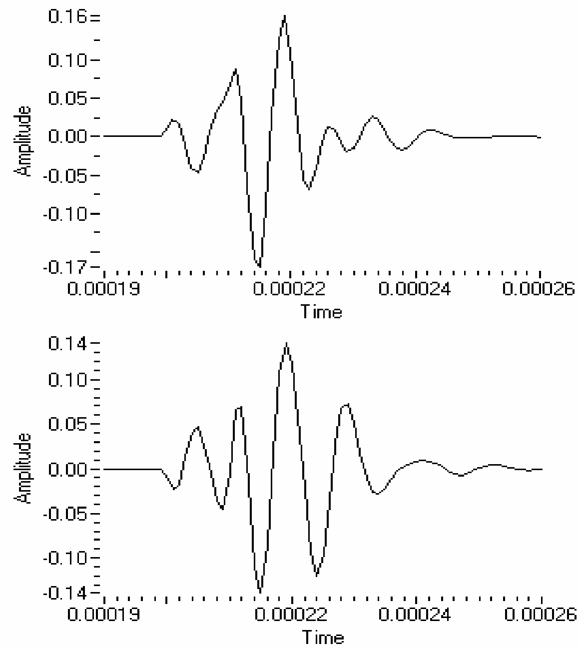

Fig. 16. Waveforms of the mirror image triplets (Fig. 8) at the acoustical side of transducers. Interclick interval was 0.01 ms. The middle click was 10-dB larger than the first and third clicks. Time scale is in seconds.

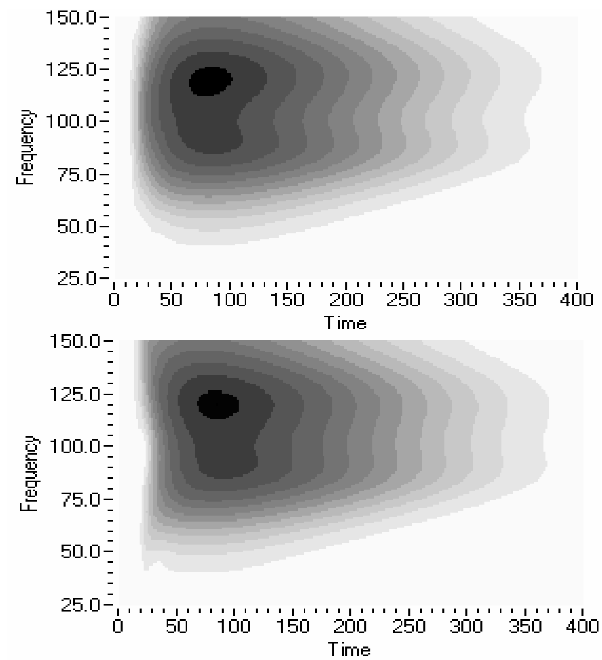

Fig. 17. STFT spectrograms generated for the direct and reversed triplets for 0.01-ms interclick interval using a 0.3-ms chi-square analysis window. The middle click was 10-dB larger than the first and third clicks. Time scale is in microseconds.

In fact, as long as the click interference in the auditory filters produces the differences in the triplets short-time spectra, the waveforms of an auditory filter reaction to the direct and reversed triplets are also different. It might be that the dolphin discriminated the time domain waveforms of triplets at the output of an auditory filter as it likely did when discriminating the double clicks with time reversed order of a small and a large click [15, 18].

Given the fact that the dolphin was able to discriminate the mirror image double clicks (Fig. 5) with the same short-time spectra (Fig 7), we should think of the time domain discrimination model that could be applicable to all mirror image stimuli tested in our experiments. Even if differences in the mirror image triplets could only be produced by narrowband frequency filtration, the triplets could be discriminated by differences in the time domain waveforms of an auditory filter reaction.

As to the double clicks with time reversed order or a small and a large clicks (Fig. 1), it follows from Fig. 15 that the bigger amplitude difference between the first and second clicks, the shorter interclick interval beyond which the short-time frequency spectra of the double clicks become indistinguishable for the dolphin. For the click amplitude differences as big as 10 dB [14] a dolphin would be able to discriminate the short-time spectra of the time reversed double clicks (Fig. 1) only if the interclick interval was shorter than around 0.06 ms.

The 0.3-ms chi-square analysis window [14] originated from the 0.3-ms critical interval [1, 2] and 0.265-ms integration time constant [4] appears too big to account for the dolphin's discrimination of the mirror image signals. The length of the dolphin's auditory analysis window is likely not greater than 0.1 ms. However only the time domain analysis with the time resolution better than 0.03 ms allows accounting for the dolphin's discrimination of at least two out of three tested couples of the mirror image stimuli.

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