Target Echo Processing in the Dolphin's Auditory System

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The dolphin's auditory time resolution and integration time constant are believed to be around 0.3 ms. As long as multiple highlights in a target echo fall within the 0.3-ms auditory integration window, they generate the echo spectral characteristics, which are used by dolphins for the target identification. On the other hand, theoretical time resolution of the dolphin's clicks is around 0.015 ms. Combination of very short echolocation clicks with a wide hearing frequency range from around 10 to 130 kHz suggests that the actual time resolution can 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. The echolocation clicks are usually associated with the auditory target echo analysis in the frequency domain. Many results of our behavioral experiments with dolphins do indicate the dolphin's auditory time resolution as high as 0.02-0.03 ms. This suggest that dolphins process target echoes with multiple highlights in the time domain. In this paper, some of our experimental results on temporal masking, temporal summation and double click discrimination in the bottlenose dolphin are presented.

I. INTRODUCTION

Numerous experiments have been conducted to investigate dolphins' ability to discriminate the material composition, size and shape of targets [1-4]. Dubrovskiy et al. [1, 2] suggested that dolphins discriminated spherical targets with different material composition and diameters by difference in average oscillation period of the target echo frequency spectra.

A time interval of around 0.3 ms is believed to be the auditory analysis window within which echo highlights merge for a dolphin into a single auditory image [5-11]. As long as echo highlights are within 0.3 ms, a target is recognized by its frequency spectrum or time separation pitch [8, 10]. The analysis window originated from the dolphin's auditory time resolution of around 0.3 ms and integration time constant of 0.265 ms [9].

The dolphin's time resolution was initially estimated in temporal masking experiments [5-7]. The backward masking results are frequently referred to as a basic proof of the dolphin's time resolution of around 0.3 ms obtained in behavioral experiments. Both a signal and a backward masker were clicks similar to dolphin's echolocation clicks. Dolphins discriminated between a single click and the pair comprised of a click and masker. The assumption was that at some masker delay the dolphin should switch from the time domain to frequency domain cues. Clearly, it would be only possible to identify this masker delay if there were some irregularities in the dolphin's performance. For the masker sensation level of 46 dB (above the dolphin's absolute threshold for a click) two different masking functions for two Black Sea bottlenose dolphins (Fig. 1) were obtained [5, 6].

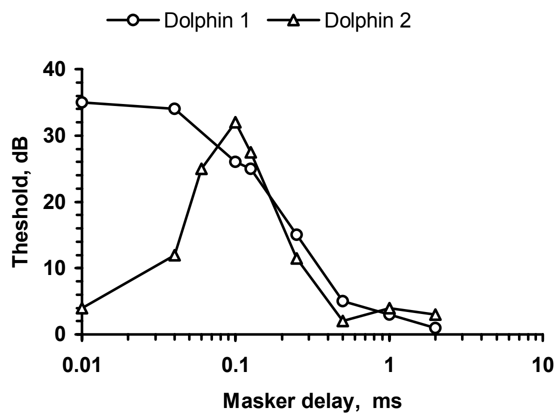

Fig. 1. Click masked thresholds as a function of the masker delay. The backward masker sensation level was 46 dB. From [5].

From Fig. 1, Velmin and Dubrovskiy [5] chose a masker delay between 0.25 and 0.5 ms to be a measure of the temporal resolving power of the dolphin sonar. They named this interval the "critical interval" of the dolphin sonar. However, the masking functions do not have any irregularities between 0.1 and 0.5 ms and the amount of masking changes steadily with the delay change. The backward masking functions produced a continuous sequence of the estimates as a function of the signal-to-noise ratio. A 0.3-ms estimate is only one of them, clearly not the best because it corresponds to very low signal-to-noise ratio of around –36 dB.

The time resolution of 0.2 to 0.26 ms were also estimated in target detection experiments but again for very low signal-to-noise ratios of -17 [8] and -50 dB [7]. No reasons were given for choosing -17, -36 or -50 dB signal-to-noise ratios to estimate the time resolution. However, it immediately follows from Fig. 1 that the smaller signal-to-noise ratio, the larger the threshold delay. By definition the time resolution is the shortest time interval between two highlights of equal amplitude which could be perceived as separate acoustic events. For the signal-to-noise ratios of – 10 and –20 dB for

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example, the time resolution estimates are 0.05 and 0.1 ms, respectively (Fig. 1, dolphin 1).

Fortunately, dolphin 2 in [5, 6] appeared to indicate its time resolution capability more explicitly. For delays shorter than around 0.1 ms the amount of masking for the dolphin 2 decreased with the delay decrease up to 0.01 ms (Fig 1, dolphin 2). Sudden improvement in the dolphin's performance suggests that dolphin 2 have keyed in on the presence of the rippled spectrum of the double click whereas dolphin haven't [8, 10].

In any case, there was no reason to sort out from the backward masking function (Fig. 1) any delay between 0.25 and 0.5 ms as the estimate of the dolphin's time resolution. Even a pessimistic estimate could not be worse than around 0.1 ms, the delay at which the backward masking reversed for dolphin 2. The 0.1-ms delay might be the only clear indication of the time resolution because dolphin 2 obviously switched between different discrimination cues at this point.

Temporal summation phenomenon describes signal integration in an auditory system. Johnson [12] found that a tone pulse absolute threshold in the bottlenose dolphin decreased with the pulse duration increase in the same way as that in humans. He estimated the dolphin auditory integration time to be dozens of milliseconds. A much shorter integration time of 0.265 ms [9] was found for the Atlantic bottlenose dolphin in double click detection experiments. The dolphin's integration time proved to be of the same value as the critical interval [5-8]. Au [10] suggested that the critical interval might be the integration time of the auditory energy detector. Short-time spectral analysis with 0.3-ms chi-square window was suggested as the auditory mechanism of double click discrimination within the dolphin's critical interval [10, 11]. The auditory integrator with integration time constant of around 0.3 ms appeared to sufficiently describe the time and frequency domain click signal processing in the dolphin's auditory system [9, 13].

The problem is that even Velmin and Dubrovskiy experiments indicate that the dolphin's time resolution is not worse than at least 0.1 ms (Fig. 1, dolphin 2). Therefore, the auditory integration time seems to be longer that the time resolution. In fact, in experiments on a dolphin detection of double clicks we found the integration time of around 0.5 ms [14], which is twice as the integration time of 0.265 ms [9]. The backward masking for both dolphins in Fig. 1 could hardly be associated with the ideal 0.265-ms energy integrator [10] performance anyway. It describes an actual *temporal* masking of the small click masked by a large delayed click in the dolphin's auditory system.

Furthermore, the results of our experiments suggest that the dolphin's time resolution is almost as high as the theoretical time resolution of its echolocation clicks which is obviously at variance with the critical interval concept. It also seems difficult to agree the dolphin's time resolution of 0.02-0.03 ms estimated in our experiments with the auditory integration time of 0.265 ms [9] or 0.5 ms [14]. The dolphins in our experiments apparently used a very short auditory integration time otherwise the signal integration beyond 0.02-0.03 ms would have led to the dolphin failure to discriminate between tested signals [15-26].

The controversy could be resolved if a dolphin was found capable of adjusting the auditory integration time. In order to estimate the dolphin's auditory integration time, a double click detection threshold was measured as a function of an interclick interval [9, 14]. As long as the integration time is larger than the interclick interval, the masked threshold for the double click is lower than that for a single click. A dolphin gained in the signal detection using the largest possible integration time.

Instead of measuring masked thresholds as a function of a signal duration, which is normally being done in order to estimate an auditory integration time, we investigated how a click and a tone pulse masked threshold depended on the noise masker duration. It appeared advantageous for the dolphin to use integration time as short as possible in order to limit amount of masking that increased with the masker duration increase.

If backward masking experiments are used to estimate the dolphin's time resolution, it is essential to know how backward masking changes with the masker sensation level change. In this paper our results on the temporal masking in the dolphin for several masker sensation levels are presented. In a series of experiments instead of a click masker a 0.02-ms noise masker was used.

Additionally to the dolphin's auditory temporal masking and temporal summation we discuss here the dolphin's discrimination between double clicks with equal interclick intervals but different energy spectra (Fig. 3). The double clicks were designed to examine whether the backward masking decrease below 0.1 ms (Fig. 1, dolphin 2) was related to the frequency domain analysis of the click and the pair click-masker. The double clicks appeared to be indistinguishable for the dolphin in the time domain. The dolphin was expected to discriminate the double clicks as long as the first and second clicks merged into a single auditory pattern producing differences in the frequency spectra. At some big enough interclick interval, the double click should disintegrate for the dolphin into two separate acoustic events. This threshold interclick interval might be close to 0.1 ms where the backward masking reverse was found for dolphin 2 [5].

It took us many more experiments than discussed here to get accustomed with an idea of the dolphin's auditory time resolution as high as 0.02-0.03 ms. In this paper we concentrated on the experimental results one way or another related to the temporal masking results which are considered to be a basic proof of the 0.3-ms critical interval. Our results of temporal masking, temporal summation and even frequency analysis of the double clicks appear to be consistent with the dolphin's auditory time resolution of 0.02-0.03 ms.

II. METHODS

The subjects were adult bottlenose dolphins (*Tursiops truncatus*). 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 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 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. Calibrations were made using a B&K model 8103 hydrophone.

The threshold measurements were made with the method of constant stimuli. A signal parameter under consideration (click amplitude, interclick interval, noise pulse duration and so on) was gradually reduced until a dolphin's correct response dropped to around 50% level. Normally, 3-4 dB increase in a signal parameter above the threshold was enough to restore performance to a 90-100% level. The parameter 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. The threshold measurement 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 a threshold estimate at a 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 stimuli were generated using a chi-square window and a time increment of 1 microsecond. The darkness of a spectrogram is in direct proportion to the spectrogram energy.

A. Temporal masking

The backward masking of a click signal by a click masker was measured for the masker sensation levels of 27, 39 and 47 dB. The click signal and click masker were produced by impulse excitation of the transducer with a 0.002-ms square pulses. The transducer acoustic reaction to the square pulse had duration of around 0.025 ms with a peak frequency at 110-130 kHz. The maskers were transmitted simultaneously through the left and right transducers at a repetition rate of 3-5 Hz. The signal was mixed with the masker at one of the randomly chosen transducers. Throughout experiment, the amplitude of the masker was constant. The masked thresholds were determined by varying the signal amplitude.

In order to deter the dolphin from discriminating the masker and the pair click-masker in frequency domain, a click masker was replaced with a 0.02-ms noise masker (Fig. 2).

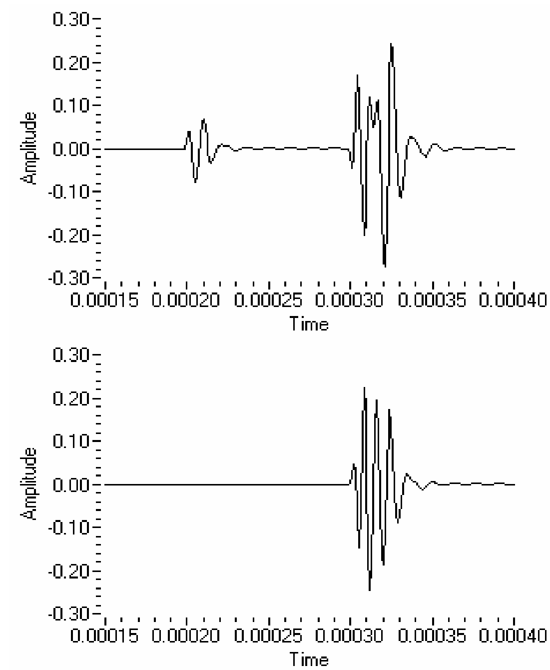

Fig. 2. Waveforms of the click signal and noise maskers at the acoustical side of the transducers.

As long as the dolphin perceives the click and the masker as separate acoustic events, the replacement of a click masker with a noise masker should not affect the click detection. Otherwise, if the dolphin discriminate the stimuli frequency spectra, it would be difficult for him to detect the presence of the click in the random frequency spectrum of the pair click-masker. Both forward and backward masking functions were obtained for the noise masker. In some experiments, a 0.01-ms noise pulse was also used as a signal instead of a click.

B. Double clicks with different energy spectra

Dolphins could not discriminate the double clicks with different interclick intervals if both intervals were larger than around 0.3 ms [6, 15]. It was suggested that at interclick interval shorter than 0.3 ms, the double click merged for the dolphin into a single auditory image and the dolphin discriminated the double clicks by difference in the double click energy spectra [13]. However, dolphins discriminated the intervals between noise pulses with almost the same accuracy as that between correlated clicks [22]. As long as the double clicks with different intervals are used it is difficult to separate the time and frequency domain cues. In order to eliminate for the dolphin the time domain cues, we used the double pulses with equal interclick intervals (Fig. 3). The pairs of square pulses in Fig. 3 differ in the polarity of the first square pulses. At the acoustical side of transducers the pairs of square pulses were transformed into double clicks with equal interclick intervals and the same amplitude difference between the first and second clicks. Dolphins are unable to distinguish between the transducer reactions to a positive and negative square pulse. Therefore, the time domain waveforms of the double clicks appeared to be indistinguishable for the dolphin.

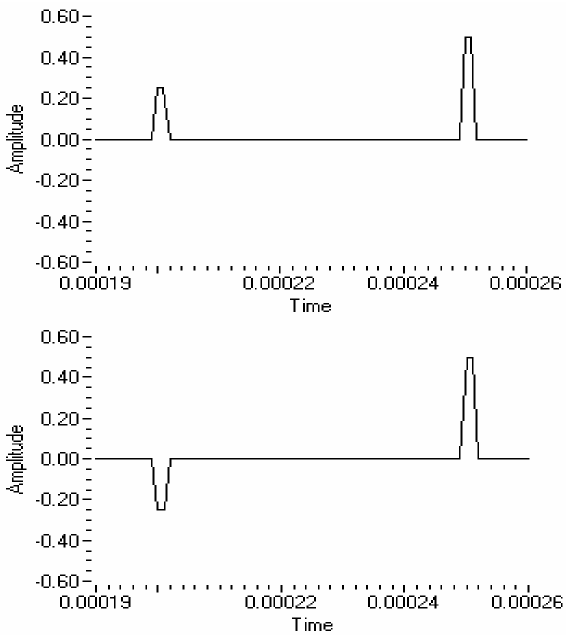

Fig. 3. The pairs of 0.002-ms square pulses at the electrical side of transducers. Time scale is in microseconds.

On the other hand, the frequency spectra of the double clicks in Fig 3 are very much different. Although the energy spectra of the double clicks are rippled with the same period, maxima of one spectrum correspond to minima of the other (Fig. 4).

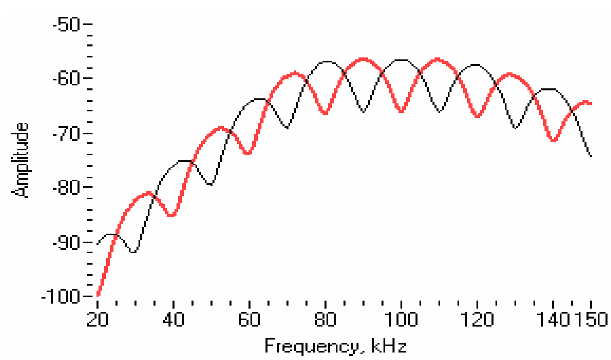

Fig. 4. Amplitude spectra of the double pulses shown in Fig. 3 (at the acoustical side of the transducers).

It is clear that the frequency spectra differences could only be generated if the first and the second clicks interfere with each other in the dolphin's auditory system. It was expected that dolphin would be able to discriminate the double clicks as long as interclick interval was shorter than some threshold interval, determined by the auditory frequency resolution, beyond which the double click should disintegrate for the dolphin into two separate acoustic events.

The differences in the frequency spectra of the double clicks are the biggest if the first and second clicks have equal amplitude. The largest interclick interval between the first and the second clicks of the double click was measured as a function of the difference in the click amplitudes. The thresholds were measured for the double clicks with large clicks followed small clicks (Fig. 3) as well as for the double clicks with reversed order of the clicks. The maximum interclick intervals measured for the double clicks in Fig 3, appeared to be a limit for the dolphin's frequency analysis of target echoes with multiple highlights.

C. Temporal summation

Masked thresholds for a click were measured as a function of the duration of a masking noise pulse (Fig. 5).

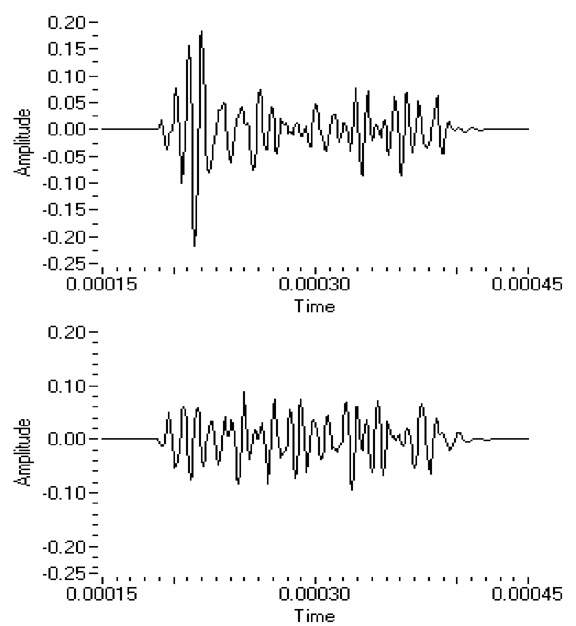

Fig. 5. Waveforms of the click mixed with a noise masker (top block) and noise masker alone (bottom block) at the acoustical side of transducers. Time scale is in microseconds.

If a click and a noise pulse start simultaneously, the auditory integration beyond the click should increase the click masked threshold. However, if the dolphin was able to control auditory integration time, the masked threshold could be independent of the masker duration. The absence of the temporal summation of the noise masker would be an indication of a very short integration time and high auditory time resolution.

Throughout experiment, the amplitude of the noise masker was constant. For a given duration of the noise pulse, the masked threshold was determined by varying the click amplitude. The masked thresholds were measured for a zero and 0.01-ms delay of the click relative to the onset of the noise pulse. The noise pulses were transmitted through both transducers at a repetition rate of 3-4 Hz. The click was randomly mixed with the noise pulse at one of the transducers. The broadband noise was produced using standard analog noise generators. Two noise generators of the same model were used for the left and right transducers so that the noises were uncorrelated.

Masked thresholds for a 100-kHz tone pulse in a 10-ms and 55-ms noise pulse as well as in continuous noise as a function of the tone pulse duration were also measured. The tone pulse was delayed by 0.01 ms relative to the onset of the noise pulse.

III. RESULTS

A. Temporal masking

The backward masking of the click signal by the click masker strongly depended on the masker sensation level for both tested animals. A 27-dB masker did not affect the click detection for all tested masker delays larger than 0.02 ms (Fig. 6).

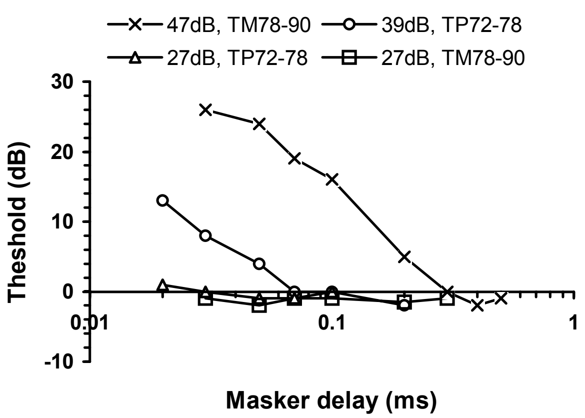

Fig.6. Masked thresholds as a function of the click masker delay. The masker level and the dolphin's names are shown in the legend.

It is difficult to single out from Fig. 6 any specific masker delay to represent the dolphin's auditory time resolution. The backward masking results produced an infinite sequence of the time resolution estimates as a function of the masker delay with the masker sensation level as a parameter.

As long as the delay was longer than around 0.05 ms, the 0.02-ms backward noise masker with SL of 38 dB did not affect click detection. Positive delays in Fig. 7 correspond to the click preceding the masker (backward masking); negative delays correspond to the click following the masker (forward masking). The 20-dB noise masker begun to interfere with the click detection when it was delayed by less than 0.02 ms or led the click by less than 0.04 ms. Forward masking with the 38-dB noise masker almost vanished for the click delay longer than 0.1 ms.

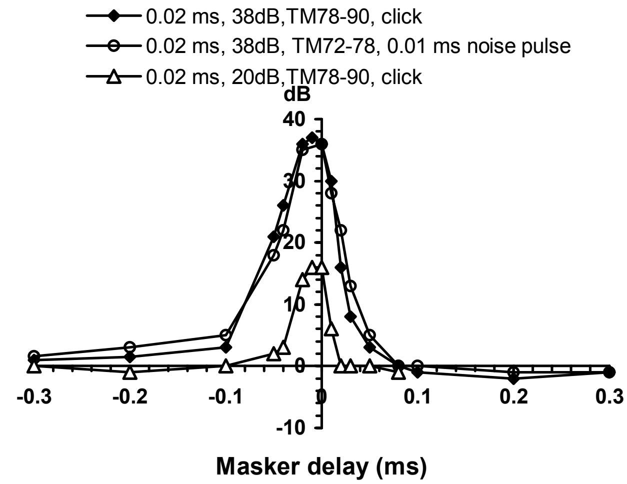

Fig 7. Masked thresholds as a function of the noise masker delay. Positive delays are for a backward masking; negative delays are for a forward masking. Noise masker duration, masker level, dolphin's name, type of the signal (click or 0.001-ms noise pulse) are shown in the legend.

It could be assumed that when backward masked threshold reaches the click absolute threshold, the dolphin perceives the click and masker as two separate acoustic events. The shortest masker delay for which that condition is met can be taken as an estimate of the dolphin's time resolution. Depending on the masker level this delay varies from 0.01 to 0.2 ms (Fig. 6, 7).

The dolphin's time resolution estimated this way is an assured, though pessimistic estimate because it is taken at a very low signal-to-noise ratio of –20 to –46 dB (Fig. 8).

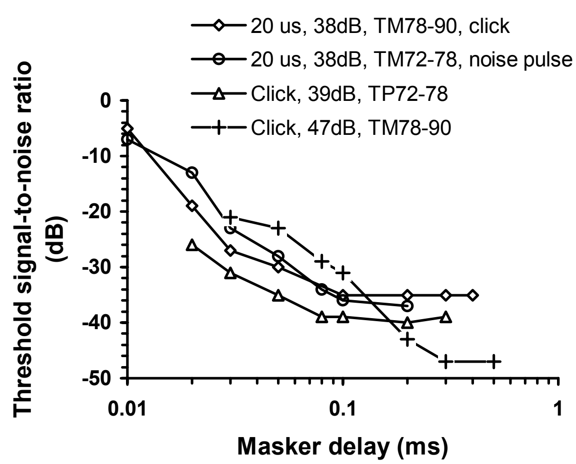

Fig. 8. Threshold signal-to-masker ratios as a function of the backward masker delay.

The backward masking functions in Fig. 8 presented as the dependence of a threshold signal-to-masker ratio on the masker delay. The lowest signal-to-masker ratios of -38 and -47 dB correspond to the absolute threshold for a click. For threshold ratios of -10, -26 and -36 dB threshold delays were around 0.01, 0.03 and 0.08 ms, respectively.

As the masker delay was decreased from 0.1 ms to 0.01 ms the threshold signal-to-noise ratio increased by as much as 30 dB. For the ideal integrator with an integration time of 0.256 ms [9, 10] the energy of the pair click-masker would be the same as long as the masker delay was shorter than 0.256 ms. For the dolphin just several microseconds difference in the masker delay noticeably change the click masked threshold. It is clear, that there was no chance for the dolphins to distinguish the energies of the click and pair click-masker for the signal-to-noise ratios as small as -20 to -30 dB. Integration of the signal and the masker would lead to a complete lost of the signal in the noise.

By definition, the time resolution is interval between two signals of equal amplitude. The time resolution defined at 0 dB signal-to-noise ratio is better than 0.02 ms for all tested masker levels. If the dolphin's auditory time resolution is limited by its integration time, we should conclude that the temporal masking results revealed the dolphin's integration time as short as around 0.02 ms.

The temporal masking function (Fig. 7) presents a temporal window within which the click and masker interfere with each other. At the 3-dB level the size of the window is between 0.02 and 0.03 ms. Even at the –20 dB level, the window width is smaller than 0.1 ms.

None of our dolphins has shown backward masking function similar to that found for dolphin 2 (Fig. 1). Clearly, with the noise masker it would be difficult for the dolphin, if at all, to discriminate the masker from a pair click-masker in frequency domain at least for the masker delay longer than 0.04-0.06 ms where the signal-to-noise ratios dropped below -20 dB (Fig. 7). The dolphin would have failed to discriminate the stimuli had it implemented a short-time frequency analysis with 0.3-ms chi-square window [10, 11] especially in case of the backward masking. Because a small click would enter the analysis window before a delayed strong noise masker, the window would make very shallow regular rippling in the spectrum practically disappear in random spectrum fluctuation.

B. Double clicks with different energy spectra

The largest interclick interval for which the dolphins were able to discriminate the double clicks with equal interclick intervals (Fig. 4) was found to be 0.1-0.11 ms (Fig. 9). For a 0.1-ms interval, the ripples in the energy spectrum of the double click are separated by 10 kHz, which can be considered as the estimate of frequency resolution of the dolphin sonar for a double click. Both dolphins failed to discriminate the double clicks with the ripple separation less than around 10 kHz. Therefore, the dolphin's frequency resolution for the double clicks proved to be much poor than around 2 kHz frequency resolution found for continuous rippled noise [27].

The threshold amplitude difference between the first and second clicks was found to be in inverse proportion to the interclick interval (Fig. 10). For a 0.11-ms interval, the dolphin discriminated between double clicks only when the first and second clicks were of the same amplitude.

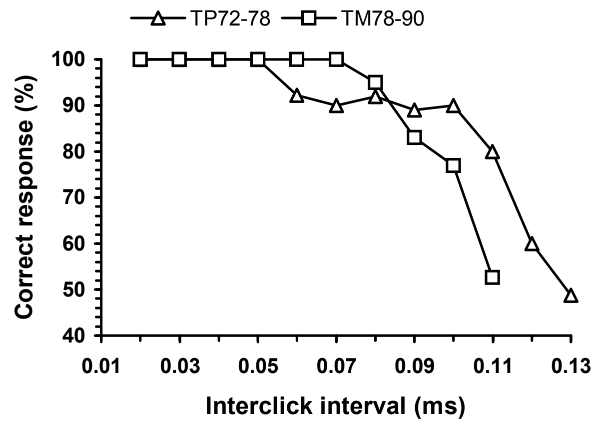

Fig. 9. Dolphin discrimination between the double clicks as a function of the interclick interval. The first and the second clicks have the same amplitude.

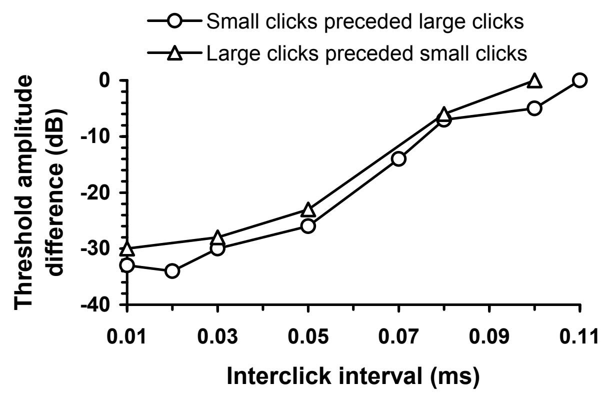

Fig. 10. Threshold amplitude difference between the first and second clicks of the double clicks as a function of the interclick interval.

The threshold amplitude difference sharply increased when the interval was decreased from 0.1 to 0.04 ms which could be expected for the double click discrimination in the frequency domain. The differences in frequency spectra only occur if the first and the second click interfere with each other in the auditory system. The shorter interclick interval, the stronger clicks interfere with each other producing bigger differences in the frequency spectra. As an interclick interval was further decrease to 0.01 ms, the threshold amplitude difference changed insignificantly. For interclick intervals between 0.01 and 0.04 ms, the threshold differences in the click amplitudes were as big as around 30 dB.

The 0.1-ms threshold interval is obviously smaller than the 0.3-ms chi-square analysis window suggested for a short-time spectral analysis of the double clicks [10, 11]. Despite clear differences in the short-time energy spectra generated with the 0.3-ms chi-square window (Fig. 11), the dolphin failed to discriminate the double clicks with 0.1-ms intervals if the amplitude difference between the clicks was more than 3-5 dB

(Fig. 10). The dolphin apparently used much shorter integration window, for which interference between the clicks was not strong enough to produce tangible for the dolphin differences in the short-time spectra.

The dependence of the click amplitude difference on the interclick interval (Fig. 10) for the double clicks with first clicks larger than second clicks was practically the same as that for the double clicks with the reversed click order (Fig. 3). This suggests a symmetric analysis window, rather than asymmetric chi-square window [10, 11].

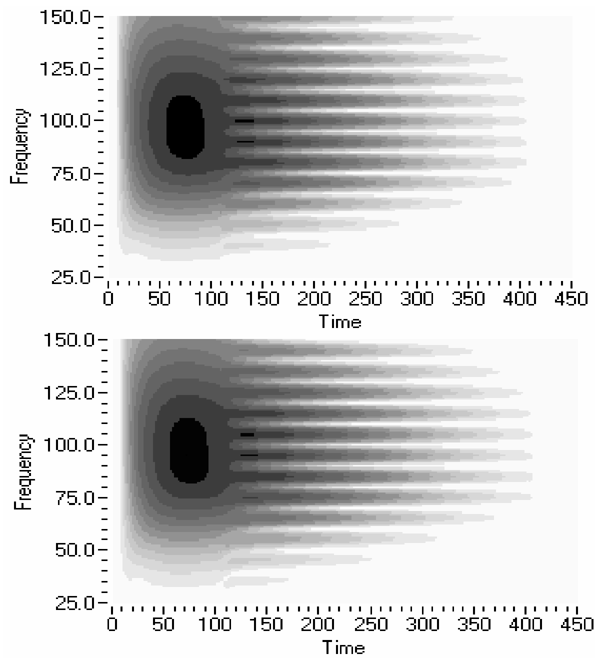

Fig. 11. STFT spectrograms generated for the double clicks with first clicks 10-dB larger than second clicks using a 0.3-ms chi-square window (analysis at the acoustical side of transducers). Interclick intervals were 0.1 ms. Time scale is in microseconds.

Clearly, the dolphins could discriminate the double clicks as long as interference between the first and the second clicks in the auditory system was sufficient to produce detectable by the dolphin differences in the frequency spectra. At interclick intervals longer than around 0.1 ms, the double click disintegrated for the dolphin into two separate acoustic events. In this respect, the 0.1 ms threshold interval can also be considered as the estimate of the time resolution of the dolphin's auditory bandpass filters. This estimate is worse than that derived previously from the temporal masking experiments. The 0.02-0.03 ms time resolution estimated in the temporal masking experiment obviously required reception with auditory filters as broadband as at least 30-50 kHz. It appears that dolphins are capable of adjusting the bandwidth of the auditory filters to significant extent. It fact, this could be already suggested from two different backward masking functions measured for dolphin 1 and dolphin 2 (Fig. 1).

The differences between the energy spectra in Fig. 4 are always bigger, for corresponding interclick intervals, than between spectra of the double clicks with different intervals [8]. Therefore, the threshold 0.1-ms interval is also a maximum interval for frequency discrimination of the double clicks with different interclick interval as well as target echoes with different intervals between highlights.

The threshold amplitude difference between the first and second clicks changed with the interclick interval change (Fig.10) in the same proportion as the threshold difference between the click and masker changed with the masker delay change (Fig. 1, dolphin 2) [5, 6]. This suggests that for the masker delays shorter than 0.1 ms dolphin 2 discriminated the masker from the pair click-masker in the frequency domain.

It should be noticed that as long as the first and second clicks interfere in the auditory filters producing different energy spectra, the waveforms of a single filter reaction to the comparison double clicks are also different. Some experimental results do suggest that dolphins are capable of discriminating the auditory filter reactions in the time domain [23, 25].

C. Temporal summation

The masked thresholds for a click proved to be independent of the noise masker duration for both dolphins (Fig. 12).

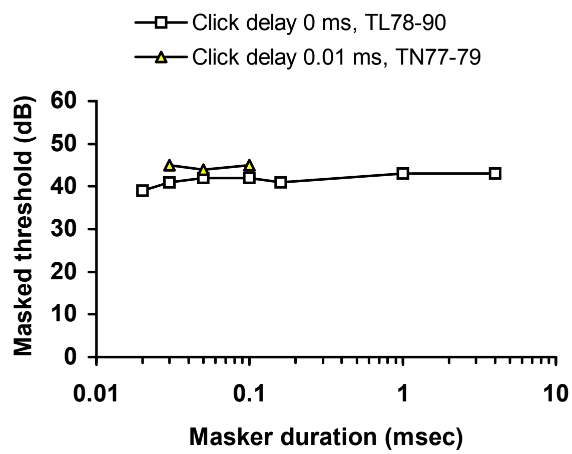

Fig. 12. Masked thresholds for a click as a function of the noise pulse duration. 0 dB corresponds to the click absolute threshold.

The threshold energy differences between the noise masker alone and the click plus the noise pulse changed from 6-8 dB for a 0.03-ms masker, to 1-3 dB for a 0.3-ms masker. The dolphin's intensity difference threshold is as small as around 1 dB [5, 7]. If the dolphin have discriminated the stimuli by difference in their energies, it would have shown much better than 6-10 dB energy thresholds for short noise maskers. The independence of the click masked threshold from the noise pulse duration (Fig. 12) indicates the absence of the auditory signal integration beyond 0.02 ms.

It would also be difficult to find any persistent differences in the short-time spectra of the stimuli generated with a 0.3-ms chi-square window (Fig. 13). Only if the analysis window is shorter than 0.03-0.05 ms, the click could be identified by a big energy peak above the noise level regularly appearing at the same location.

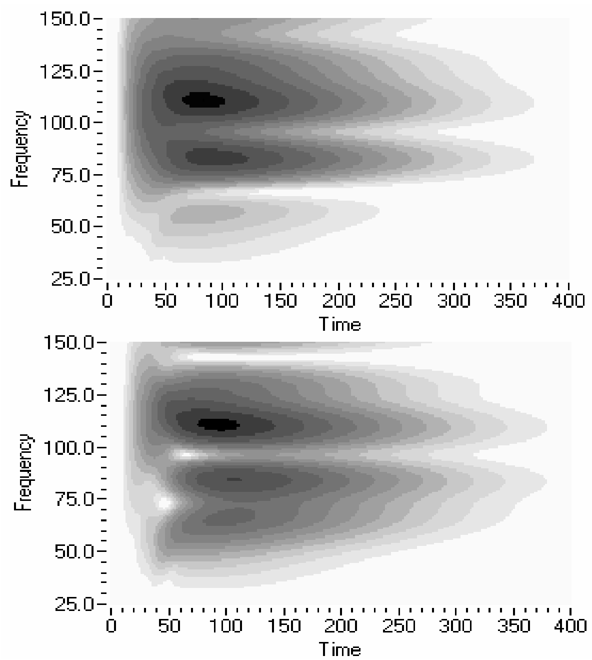

Fig. 13. STFT spectrograms generated for the click and 0.05-ms noise pulse (top spectrogram) and the noise pulse alone (bottom spectrogram) using 0.3-ms chi-square window. Signal-to-noise ratio was 6 dB above the threshold. The click was delayed by 0.01 ms relative to the noise onset.

The masked thresholds for a 100-kHz tone pulse in a 10-ms or 55-ms masking noise pulse were found to be independent of the tone pulse duration (Fig. 14).

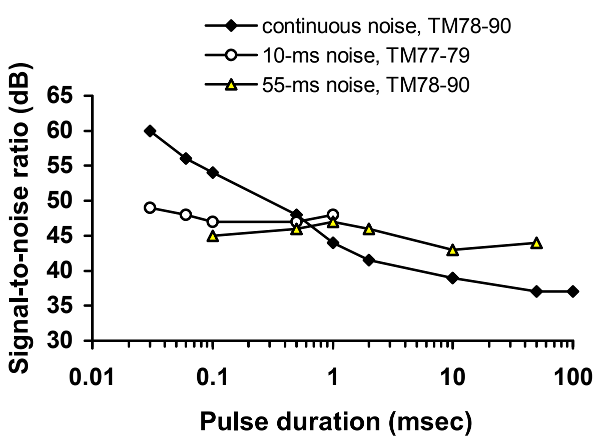

Fig. 14. Threshold ratio of the 100-kHz pulse intensity to the noise spectrum level versus duration of the pulse. The tone pulse was delayed by 0.01 ms relative to the onset of the masking 10-ms or 55-ms noise maskers.

The dolphin did not integrate the tone pulse despite that the integration would increase the signal-to-noise ratio with the pulse duration increase. At the same time, for the 100-kHz tone pulse in continuous noise, the threshold signal-to-noise ratio dropped by 3-4 dB per doubling of the tone pulse duration up to around 2 ms. As the tone pulse duration was increased to 100 ms the masked threshold reached around 36 dB which is close to the masked threshold for a pure 100-kHz tone [28, 29].

A 0.02-0.03-ms auditory integration time proved to be advantageous for detection in the noise pulse both a click (Fig. 12) and a short tone pulse. Excessive signal integration in continuous noise within approximately 2 ms pushed the threshold ratio for 0.03-ms tone pulse up to 61 dB (Fig. 14, continuous noise) compared to a 49-dB ratio for the tone pulse in the 10-ms noise pulse. The 2-ms signal integration produced better signal-to-noises ratio only for a tone pulse longer than 1 ms.

We have no reason to believe that the dolphin was not capable of integrating the tone pulse in the noise pulse. It simply chose not to integrate when it facilitated the tone pulse detection. The dolphin might know exact position of the tone pulse in the noise pulse. The onset of the noise masker was a reference point for the dolphin where to look for the tone pulse.

The dolphin's masked thresholds for a 100-kHz tone pulse in continuous noise (Fig. 14, continuous noise) dropped by around 3-4 dB per doubling of the tone pulse duration up to around 2 ms which can be considered as the dolphin's integration time for a tone pulse. The 2-ms integration time is much shorter than the integration time for a 100-kHz tone pulse of around 100 ms reported in [12].

The 0.02-0.03 ms auditory integration time is consistent with the auditory time resolution estimated in temporal masking experiments (Fig 6-8). With the auditory time resolution of 0.02-0.03 ms, dolphins are likely capable of the time domain discrimination of target echoes with multiple highlights. The frequency domain recognition of target echoes appears to be possible in the dolphin's auditory system only if an interval between highlights is shorter than 0.1 ms. However, there are some indications that the dolphin might use frequency filtration of the double clicks to generate differences in the time domain waveform of a filter reactions. In any case, there was no indication of the critical interval of 0.3 ms [5. 6] in our experiments. The dolphin's auditory analysis of click signals is certainly too complicated to be sufficiently described by a single auditory parameter either a time resolution or integration time constant.

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