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Warning sounds at reflective nets: triggering and improving echolocation in harbour porpoises *Phocoena phocoena*

Submitted by: **ASCOBANS Secretariat**

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Warning sounds at reflective nets: triggering and improving echolocation in harbour porpoises *Phocoena phocoena*

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Abstract

To date, technical methods available to reduce harbour porpoise by-catch in gillnet fisheries remain unsatisfactory: Traditional acoustic alarms, also called “pingers” use aversive sounds to keep harbour porpoises away but may exclude them from critical habitat. And while new gillnets made of acoustically enhanced material increase the chance of detection for porpoise biosonar, the animals often do not echolocate and by-catch reduction remains below expectations.

We tested a new approach by combining a barium sulphate net in conjunction with warning sounds. Low-intensity (115 dB re 1µPa, 1m) 2.5 kHz pure sounds without harmonics were supposed to alert, not chase away harbour porpoises. Whereas the original Lien-pinger (2.7 kHz with strong harmonics, 115 dB re 1µPa, 1m) keeps harbour porpoises initially at 170 m from the sound source (Koschinski and Culik 1997), pure 2.5 kHz tones used here increase the median closest surfacing distance from 21.3 m (n = 23, barium sulphate net without sound) to 34.7 m (n = 21, barium sulphate net with sound), a difference of 13.7 m. Closest approach to the ensonified standard net was 38.7 m (n = 23).

Below the surface, shortest click-intervals (measured via POD), an indirect measure of target distance, were highest in the ensonified barium sulphate net (median = 64.7 ms, n = 9) as opposed to the same net without sound (42.8 ms, n = 25; KS-Test, $p < 0.05$). The difference translates to an increased minimum target distance of 16 m, corresponding to an increase in reaction time of 8.4 – 13.3 s, depending on swimming speed. Minimum click intervals near the ensonified standard net were 51.6 ms (n = 23).

The use of warning sounds also led to a reduction of time spent within 80 m of the centre of the net: from 104 s (Median, n = 20) when using barium sulphate nets without sound to 32 s (n = 14) when warning sounds were played back (KS-Test, $p < 0.05$). Near the ensonified standard net animals spent 24s (n=12). The number of clicks per minute recorded within 80 m of the net increased from 54 (barium sulphate net without sound, n = 10) to 64 (standard net with sound, n = 8) to 86 (barium sulphate net with sound, n = 5).

We are confident therefore that warning sounds can trigger harbour porpoises to increase their vigilance near acoustically-enhanced gillnets. Experiments in gillnet fisheries will have to show whether this can effectively reduce by-catch.

Key words: harbour porpoise, by-catch, enticing sound, pingers, warning, reflective nets, barium sulphate, fishery.

Introduction

According to estimates of the International Whaling Commission (IWC) approximately 300.000 small cetaceans die each year in the various forms of fisheries (WWF 2003). Incidental takes of harbour porpoises in the Gulf of Maine, Bay of Fundy, and the North, Celtic and Baltic Seas may exceed sustainable levels and potentially threaten these local stocks (e. g., Trippel et al. 1999; Vinther 1999, Koschinski 2002). Gillnets present the highest risks for small cetaceans (Perrin et al. 1994; Culik 2004) and harbour porpoises (*Phocoena phocoena*) most often become entangled in bottom set gillnets (Vinther 1999, SGFEN 2002b, Koschinski 2002). The reason for this lies presumably in the poor perceptibility of nylon nets in turbid coastal waters, at night or at great water depths (e. g., Jefferson et al. 1992).

Besides using vision, small cetaceans explore their surroundings acoustically by using clicks (Au 1993). However, echolocating harbour porpoises can only detect standard nylon nets from a maximum distance of 3 to 6 m (Kastelein et al. 2000), which is often too short to avoid collision. Since ASCOBANS, the Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas was ratified in 1994, measures for by-catch reduction are discussed (e. g., ASCOBANS 2002, SGFEN 2002a,b). These include active and passive acoustic fishing gear modifications.

Active acoustic devices include so called „pingers“, which emit sound which is aversive to small cetaceans. At first it was supposed that these sounds would warn marine mammals and increase their alertness. Recent investigations, however (Culik et al. 2001, IWC 2000), show that pingers deter harbour porpoises and induce them to avoid ensonified areas. The consequence is a significant exclusion from their natural habitat.

Another possibility to mitigate by-catch is to improve the acoustic reflectivity of nets for the porpoises' biosonar. Field trials in the Bay of Fundy (Canada; Trippel et al. 2003) and in the Danish cod fishery (Larsen et al., 2003a) using barium sulphate and iron oxide nets, respectively, showed significant by-catch reductions. Catch rates of target species were not affected. According to the manufacturer (Atlantic Gillnet Supply, Gloucester, Maine, USA) and Mooney et al. (2004), the acoustic reflectivity of barium sulphate nets for porpoise sonar clicks is enhanced. Acoustic target strength measurements in Koschinski et al. (submitted) and Culik & Koschinski (2004) confirm that the reflectivity of a barium sulphate net is 7.2 dB higher than that of a standard net of same twine diameter and mesh size. From a behavioural study they conclude that harbour porpoises should be able to detect barium sulphate nets from a greater distance. For example, porpoises increased their minimum click interval duration in the vicinity of barium sulphate nets as opposed to a standard net which indicates a longer target range. However, the authors also found that only a small percentage of all observed porpoise groups used their biosonar near the nets. This may explain, why by-catch reduction with acoustically enhanced gillnets was unsatisfactory in some experiments (Trippel and Shepherd 2004; Northridge et al. 2003).

By generating short 2.5 kHz pure tone pulses in the field, Culik and Koschinski (2004) and Koschinski et al. (submitted) increased the percentage of echolocating porpoise groups during visually observed interactions by a factor of 4. The number of clicks emitted per encounter also increased. The distance of surfacing harbour porpoises to the net, however, remained unchanged, indicating that the tested sounds did not elicit the same response as pingers (cf. Koschinski and Culik 1997; Culik et al. 2001). These results were promising enough to combine warning sounds and reflective nets and test both methods in conjunction.

The aim of the field study presented here was therefore to test the reaction of harbour porpoises to (1) a standard net with warning sound, (2) a barium sulphate net with sound and (3) a barium sulphate net without sound. Warning sounds consisted of 2.5 kHz pure tones at low intensity (115 dB re 1µPa, 1m).

Material and methods

Study area and study period

From 8 to 20 August 2004, behavioural observations on free-ranging harbour porpoises were conducted in Fortune Channel (49^{o} 11' N, 125^{o} 46.5' W), Vancouver Island, Canada (*c.f. photographs in appendix 1*). The fjord-like area offers calm protected conditions at Beaufort 0 for 3 - 7 hours per day and is regularly frequented by harbour porpoises. These are perfect conditions for tracking the positions of the animals (Koschinski and Culik 1997, Culik *et al*. 2001, Koschinski *et al*. 2003). Boat traffic in the area is rare with a maximum of 10 small out-board powered boats per day. Since we wanted to reduce net visibility as much as possible, these nutrient rich coastal waters were well suited for the experiment: the inshore areas of the temperate rainforest zone at the Canadian west coast favour low underwater visibility caused by plankton blooms as a result of nutrients washed from rivers into the fjords.

Experimental nets

Two different net types were tested during field experiments. In each session one of the experimental nets was positioned at a maximum distance of 130 m (distant end) from a rocky island from which animals were observed at a water depth between 18 and 36 m. A small outboard powered Zodiac moored to the shore enabled the observers to rescue animals within 2 min of a possible entanglement.

The first experimental net was a standard nylon gillnet which is typically used in the fishery for groundfish such as cod (*Gadus morhua*), pollock (*Pollachius virens*), haddock (*Melanogrammus aeglefinus*) and spiny dogfish (*Squalus acanthias*) off the East Coast of the USA and Canada. It consisted of a semi-transparent bluish nylon filament with a diameter of 0.62 mm. The second net was composed of a nylon twine of the same diameter with a barium sulphate filler added (3 % by volume, 10 % by weight). Since barium sulphate is bright white, the strands had been dyed with green colouring to mask the net in sea water. Both nets were 45 m long and 9 m deep. Stretched mesh size was 16.5 cm. The head line was carried by a float line with ellipsoid foam floats (8 x 12 cm) spaced every 1.35 m. The leadline attached to the nets had a weight of 55 g / m.

Since both net types had a different colour it was important to assess underwater visibility. Net material of both types was attached to a Secchi-disk (diameter 25 cm, half white, half black). We measured visibility of the disk itself and both net materials against black as well as white background. This was supposed to simulate visibility from a porpoises perspective against the bright water surface and the dark sea floor. Figure 1 shows visibility data before and after each experimental session. Mean visibility of the barium sulphate net against white background was 1.93 m (SD = 0.35, maximum = 2.9 m), the standard net was visible at a mean of 1.37 m (SD = 0.27, maximum = 1.9 m).

In order to make the experimental nets safer for the animals in case of accidental entanglement, nets were cut into vertical strips 2.3 m wide and 7 m long enabling entangled animals to surface and breathe until being rescued by the observers. The upper 2 m of the net panels remained intact. Strips were reconnected at 1 m intervals with breakaway ties consisting of electric self-adhesive tape.

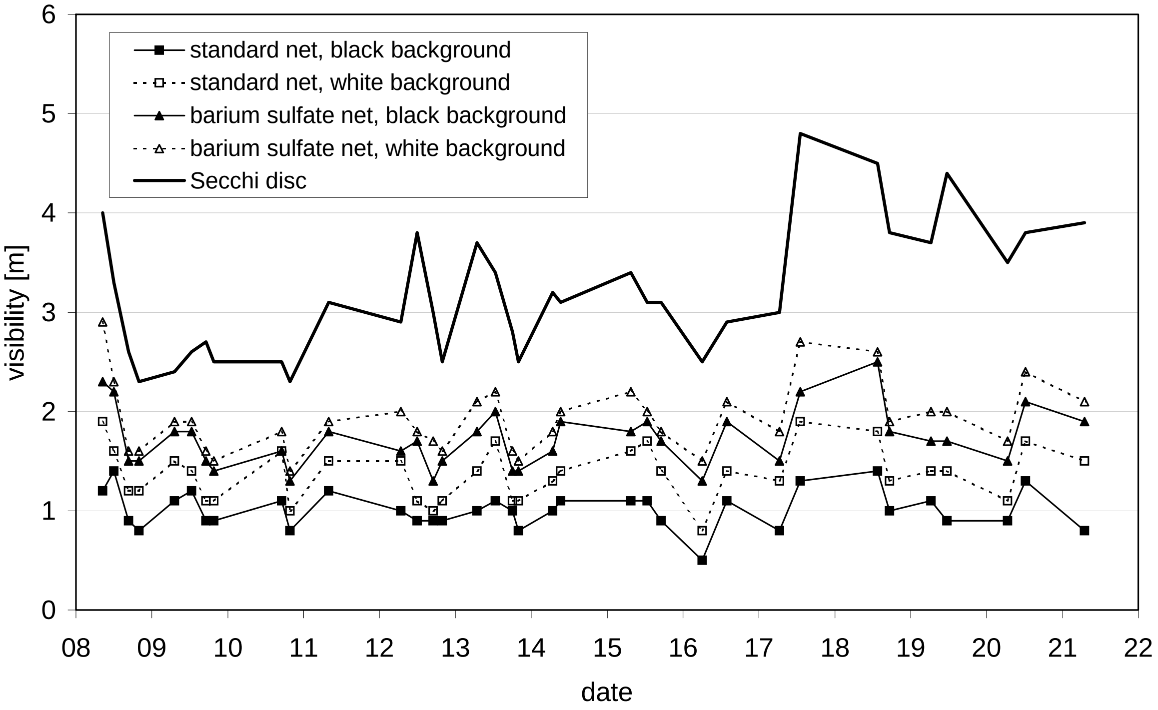

Fig. 1. Under-water visibility [m] during the course of the experiment in August 2004.

Theodolite tracking of harbour porpoises

An electronic theodolite (GDM 610, Trimble Navigation Ltd., Sunnyvale, USA) was positioned on a rocky island overlooking an area of approximately 500 x 1000 m on both sides of the experimental nets. Instrument height above sea-level varied from 4.45 m to 7.29 m depending on the tide.

One observer constantly scanned the area with bare eyes or binoculars (Zeiss Victory 10x40, Hensoldt AG, Wetzlar). The other observer focussed on the sighted animals using the short-range finder of the instrument and logged the positions.

The theodolite was used to record horizontal and vertical angles as well as the time (to the nearest second) of each surfacing of harbour porpoise groups or single animals. Whenever possible the leading animals were tracked. Theodolite elevation above sea level was obtained approximately every 30 minutes by measuring the angle of the water surface at a plumb line attached above sea level on the opposite shore. The distance to a mirror on the top of the plumb line was measured using the built-in laser distance-meter of the theodolite. Theodolite elevation above sea-level was linearly interpolated between recording intervals. The plumb line also served as reference point (angle 0 degrees) for measurements of horizontal sighting angles. The accurate position of surfacing animals could readily be calculated from data of theodolite elevation above sea level as well as horizontal and vertical angles of surfacings using trigonometric equations.

Due to tidal currents, the position of the net and click detectors were not constant. These were recorded every 30 min and interpolated. From surfacing position data of individual porpoise groups we obtained minimum distances to the net panel and the click detector (and sound source) in the centre of the net. Only animals which surfaced within a 80 m radius of this click detector were incorporated in data analysis. This distance was used to define a 'close interaction'. Further, we determined the time during which animals were seen within the 80 m radius.

Production of warning sound

The behaviour of porpoises in the vicinity of a barium sulphate net (without sound) was compared to the situation at a barium sulphate and a standard net when a tonal 2.5 kHz sound stimulus (Source level = 115 dB re 1µPa, 1m, repetition frequency = 67 min^{-1}, pulse duration 0.3 s) was played (Fig. 2). The standard net was not used without sound because we feared a high collision risk (cf. Culik and Koschinski 2004, Koschinski et al. submitted).

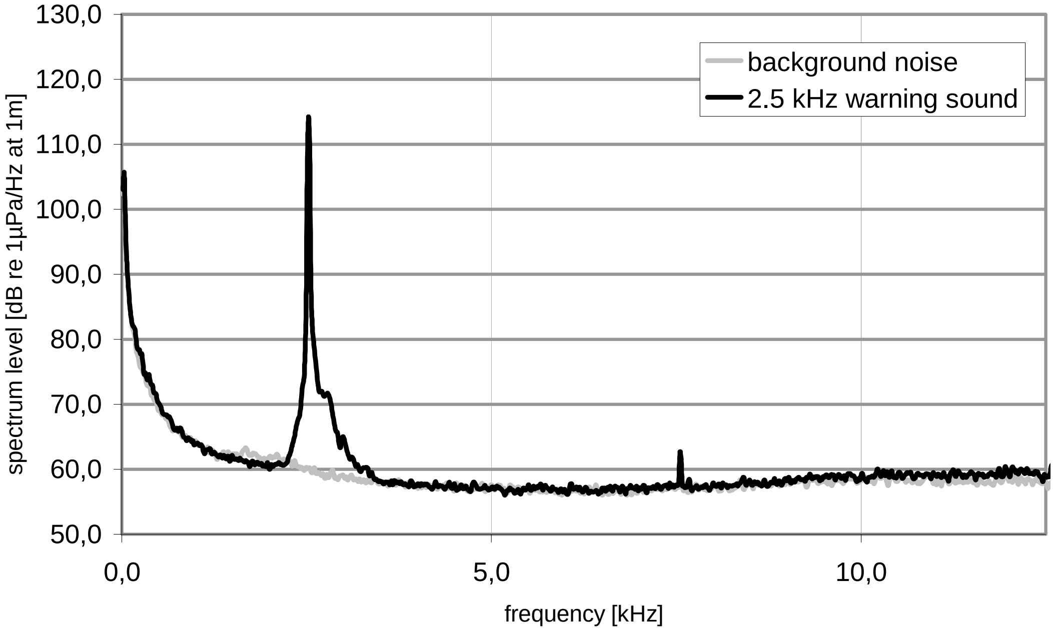

Fig. 2: Frequency spectrum of 2,5 kHz pure tone generated to warn harbour porpoises

Tones were generated with a music software program (Cool Edit pro) and recorded on an audio CD. These sounds were replayed using a car CD player (Blaupunkt 'San Remo CD

34) in a waterproof bin (∅ 46 cm, height 56 cm) and an underwater transducer (ITC 4005b) deployed at 4.5 m depth from two cylindrical foam floats (Ø 16 cm, l 14 cm). At the same depth we placed a click detector at a distance of approximately 1 m from the transducer to record harbour porpoise echolocation activity.

Logging of harbour porpoise echolocation activity

In order to detect and analyse acoustic activity of harbour porpoises, three click detectors (T-POD v1, ser. nr. 58 and 68, T-POD v4, ser. nr. 444, Chelonia, Penzanze, England) were suspended from floats: one in the middle of the net panel next to the transducer (nr. 58) and two at the distant end (nr. 68 and 444) at 4.5 m depth. The POD-detector is configured to detect 130 kHz narrow-band echolocation clicks in trains from porpoises (*cf*. Cox *et al*. 2001). It is self-contained and automatically logs the start and finish of each porpoise click to 10 µs resolution (for details see http://www.chelonia.demon.co.uk/).

Settings of the T-PODs were adjusted as follows: frequency filter A = 130 kHz and B = 90 kHz, log all clicks >10 µs duration, ratio = 4, AQ = 10 (ratio = 5 , AQ = 5 for the v4 POD), BQ = 18, intensity threshold: 0, limit (maximum number of clicks logged during 10 s period): none.

For click train detection we used the software *tpod.exe v. 5.42*. The four categories “CetHi”, “CetAll”, “+?” and “+??” were chosen. This implies that click trains identified with a high probability and doubtful click trains were included. All click trains detected using this procedure were checked manually for false positives (*e. g*., clicks from fish finders or other kinds of sonars). Important factors for accepting logged click trains are variability of click intervals (time elapsed between clicks) and duration of clicks. As a result all detected click trains were related to porpoises. Ships’ sonar pulses (with constant click intervals) were never recorded.

Data analysis of click intervals

From click detector data (times and duration of all clicks) we calculated click intervals within each click train. The click interval is an indirect measure for the momentary maximum range of the porpoise’s sonar. It is proposed that during orientation a porpoise’s sonar operates in “pulse mode”, *i. e*. sending out a click and receiving the target echo before sending out another click after a specific lag time (*cf*. Au 1993). Therefore the two-way travel time plus a lag time for processing the information determines the maximum target distance. This measure may be a key factor in determining whether a porpoise avoids or collides with a net. In an earlier experiment we determined longer minimum click intervals in the vicinity of the barium sulphate net (Culik & Koschinski 2004, Koschinski et al., submitted).

The momentary maximum acoustic detection range can be calculated as follows:

(1) $$D_{max} = (I - T_l)\, v / 2$$

with

D_{max} = maximum detection range (m)

I = click interval (s)

T_l = lag time (s)

v = under water sound velocity, approximately 1,500 $m{*}s^{-1}$ (Richardson *et al*. 1995).

In order to omit click trains which were not produced in the vicinity of the net, only trains which could be matched with porpoise groups surfacing within an 80 m radius of the click detector in the centre of the net were used for the analysis. This radius was chosen conservatively due to the short distance from which a porpoise can theoretically detect a net (Hatakeyama and Soeda 1990, Au and Jones 1991, Au 1994, Mooney 2003, Mooney *et al*. 2004) and corresponds to the distance in which 90 % of all logged porpoise groups were seen during a former experiment using the same detector settings (cf. Culik and Koschinski 2004, Koschinski et al. submitted).

Results

We obtained data from 3 sessions with the barium sulphate net without warning sound (7.1 h spread over 2 days), from 10 sessions with the ensonified barium sulphate net (34.5 h spread over 6 days) and from 8 sessions with the ensonified standard net (30.3 h spread over 5 days). During the course of this experiment one harbour porpoise collided with the barium sulphate net when the warning sound was inactive.

Several visually and acoustically acquired behavioural parameters were compared in order to identify differences in porpoise reactions to both net types:

(1) minimum distances to the net panel and to the centre of the net,

(2) duration of ‘close interactions’,

(3) duration of click intervals (*i. e*., time elapsed between clicks within click trains).

(4) percentage of interactions with echolocation clicks logged,

(5) number of clicks per minute.

Finally, the orientation of echolocating harbour porpoises with respect to the click detector and sound source was assessed from the correlation between click duration and inter click interval duration.

Minimum distance to the net panel and to the centre of the net

Theodolite data enabled us to compare minimum distances of surfacing porpoise groups to the net panel as well as to the click detector in the centre of the net. In both cases data distribution was not normal. The median observed closest approach distance to the net panel was 21.3 m in the barium sulphate net without sound (n = 23). When warning sound was replayed at the same net this distance increased to 34.7 m (n = 21) and to 38.7 m at the ensonified standard net. The difference between ensonified nets and the silent barium sulphate net was significant (p < 0.01, Kolmogorov-Smirnov test, KST). A similar result was obtained when comparing the minimum distances of porpoise groups to the click detector in the centre of nets (Fig. 3): Median values were 32.3 m to for the barium sulphate net without sound, 53.5 m for the ensonified barium sulphate net and 55.6 m for the ensonified standard net.

Thus, in our experiment warning sound increased closest approach distances to the nets irrespective of the net material.

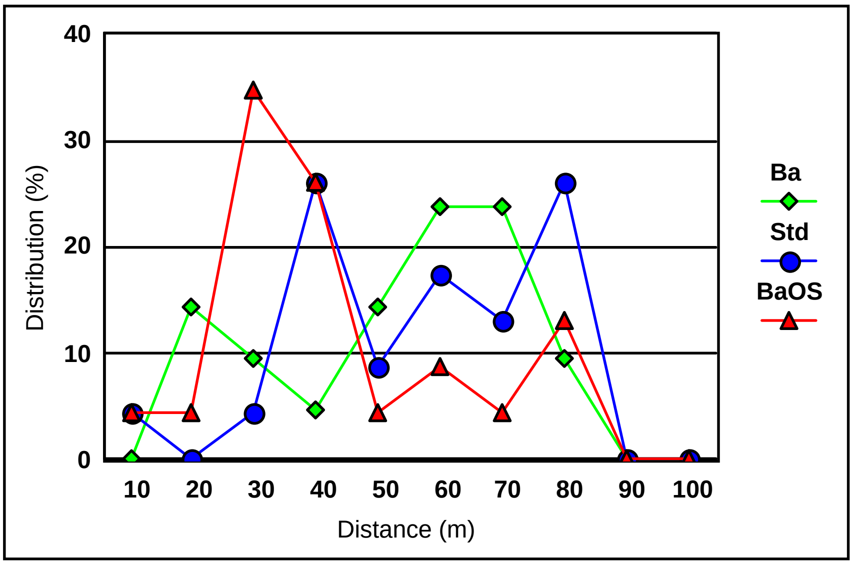

Fig 3: Distribution of surfacing distances of harbour porpoises with respect to net type. Ba: barium sulphate net with warning sound. Std: Standard net with warning sound. BaOS: Barium sulphate net without sound.

Duration of ‘close interactions’

We compared the time between the first and the last surfacing within an 80 m radius of the click detector attached in the centre of the net. Since not all porpoise groups met the criterion of surfacing at least twice in this radius, this reduced the amount of data available for analysis (Fig. 4). When we presented the barium sulphate net without sound porpoise groups stayed in the vicinity of the net for a median of 104 s (n = 20). This interval decreased to 32 s when the same net was ensonified with warning sound (n = 14). During ensonification of the standard net, animals left the 80 m radius after a median of only 24 s (n=12). Again, the difference between ensonified nets and the barium sulphate net without sound was significant (p = 0.02, KST). This indicates that warning sounds decrease the time spent near nets.

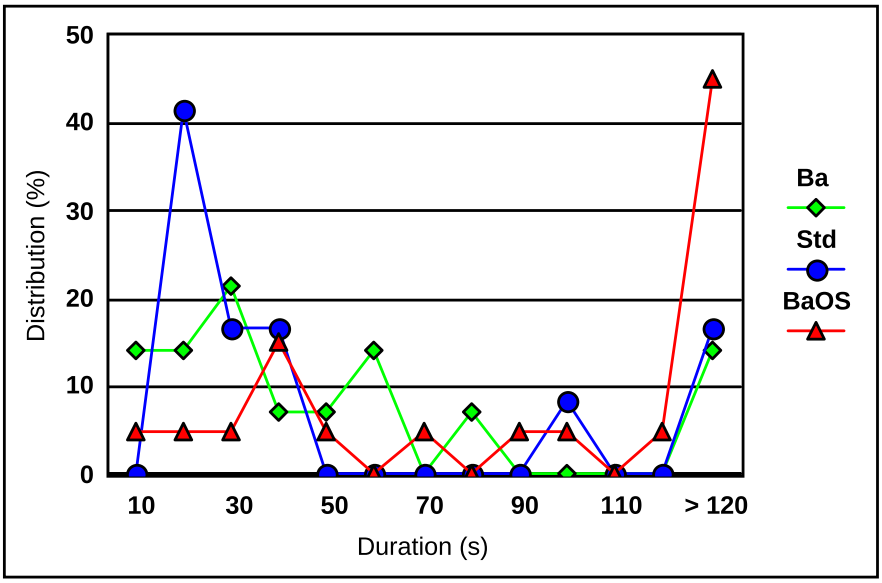

Fig 4: Distribution of time spent within an 80 m radius around the centre of the net. Ba: barium sulphate net with warning sound. Std: Standard net with warning sound. BaOS: Barium sulphate net without sound.

Duration of click intervals

The closest approach distance of the porpoises to the nets may be the most important factor to characterize their detection ability. Since visual observations reveal only closest approaches in surfacing animals (see above), we had to infer closest approach distance in diving and echolocating animals from the duration of shortest click intervals used in click trains. When the barium sulphate net was presented without sound we logged 25 click trains of 8 porpoise groups. At the barium sulphate net with sound, 9 click trains of 5 groups were received and at the ensonified standard net 8 porpoise groups left 23 click trains on the POD in the centre of the net.

The shortest click intervals (Fig. 5) were recorded in the vicinity of the barium sulphate net without sound (median = 42.8 ms). Intervals increased significantly to a median of 64.7 ms when warning sound was played at this net ($p < 0.05$, KST). When we presented the ensonified standard net to the porpoises, we measured a median value of 51.6 ms. The difference to both other treatments was not significant.

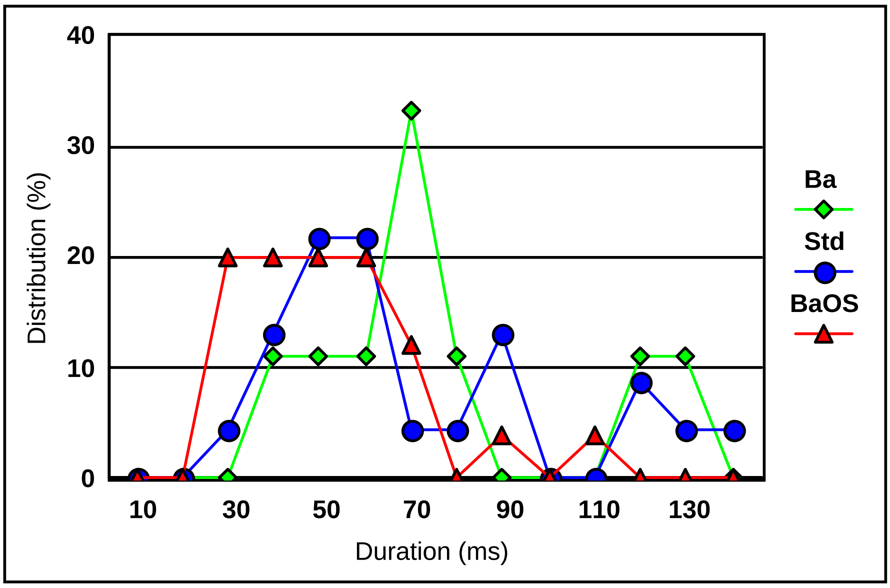

Fig 5: Distribution of click interval durations in harbour porpoises surfacing within an 80 m radius around the centre of the net. Ba: barium sulphate net with warning sound. Std: Standard net with warning sound. BaOS: Barium sulphate net without sound.

Thus, warning sound at the barium sulphate net increased the target distance of harbour porpoise biosonar. This finding confirms the result that the closest approach distance to the net is increased in surfacing animals during the use of warning sound.

Percentage of interactions with echolocation clicks logged

When no sound was played at the barium sulphate net, echolocation clicks were logged by the 3 PODs during 75 % of interactions (n = 24). This rate is reduced to 48 % in both ensonified net types (barium sulphate: n = 21, standard net: n = 21). This difference is not significant ($p > 0.05$, $Chi^2 = 5.5$, Chi^2-test) due to the limited amount of data.

Number of clicks per minute

We assumed that when porpoises detect an object in their course they explore it in detail to gain information on its position, size, or movement and that the number of clicks or other acoustic parameters vary accordingly.

The number of clicks logged during an interaction varied considerably (barium sulphate without sound: median = 36, n = 8, barium sulphate with warning sound: median = 8, n = 5, standard with warning sound: median = 27, n = 8). Furthermore, the duration of interaction was dependent on treatment (see above). Therefore we related the number of clicks logged during an interaction to its duration. As a result, the number of clicks per minute (from combined click data of all 3 PODs) could be compared between the three treatments: at the barium sulphate net without sound we logged a median of 54 clicks*min^{-1} (n = 10). When the net was ensonified this value increased to 86 clicks*min^{-1} (n = 5). At the ensonified standard net we measured 64 clicks*min^{-1} (n = 8). Due to the limited amount of data this can only be interpreted as a trend.

Provided that echolocation rate represents a measure for the intensity of net inspection this result points to a more intensive investigation of nets during the use of warning sound.

Orientation of porpoises with respect to sound source and POD

In addition to the parameters shown above, we examined the correlation between the minimum click interval and the maximum click duration within each analysed click train. The duration of a click as recorded by the click detector is a measure for the distance and orientation of porpoises in relation to the detector. *I. e*. clicks with a high received level (such as clicks directed at the click detector or clicks from a short distance) are logged as long clicks. Distant and indirect clicks are logged only partly and are shown as shorter clicks. Click intervals are a measure of distance only.

This means that when an echolocating porpoise is targeting primarily the click detector and not the net, a strong correlation between minimum click intervals and maximum click duration within click trains should be found (Carlström 2003).

Such a correlation was not observed during sessions with the barium sulphate net without sound as well as with sound ($p > 0.05$). Data from the standard net with warning sound, however showed a correlation ($r^2 = 0.26$, $p < 0.01$). Finally, if data of both ensonified nets were pooled the regression was significant ($r^2 = 0.22$, $p < 0.01$).

Discussion

Properties of barium-sulphate nets

Trippel et al. (2003) and Larsen et al. (2003) report that acoustically enhanced nets catch significantly less harbour porpoises in fisheries experiments than comparable nylon nets. Since then, specialists discuss whether the acoustic properties of the enhanced twine were responsible for these results or other factors such as better visibility, increased stiffness or tensile strength (Larsen et al. 2003, Northridge et al. 2003).

Culik and Koschinski (2004) and Koschinski et al. (submitted) found that simulated harbour porpoise clicks at 150 kHz yield a significantly stronger target strength (+ 7.2 dB) in a barium-sulphate net as opposed to a comparable standard net. Furthermore, Culik and Koschinski (2004) and Koschinski et al. (submitted) tested a standard and a barium sulphate net in the field and found significant differences in the acoustic behaviour of harbour porpoises. Using a click detector they determined that the minimum click intervals used in click trains were 5.8 ms longer (derived from median values) when harbour porpoises were confronted with the barium sulphate net as opposed to the standard net. Assuming a sound velocity of 1,500 m/s (Richardson et al. 1995) and two way travel time (porpoise – target – porpoise), this converts to a difference in target distance of 4.4 m. At mean swim speeds of 1.9 m/s (Schulze 1996) or 1.2 m/s (Teilmann 2000) this increase in perceptibility expands reaction time by 2.3 – 3.2 s (Culik and Koschinski 2004, Koschinski et al. submitted).

This is more than reported by Mooney (2003) on the basis of target strength measurements. In a barium-sulphate net with lower mesh size and twine diameter (extended mesh size 147 mm, twine diameter 0,51 mm) he calculated an increase in perceptibility of only 0,6 - 1,1 m as opposed to a comparable nylon net. For a coarser barium-sulphate net made of thicker twine (extended mesh size 305 mm, twine diameter 0,9 mm) he calculated a difference of 2,6 m.

Low echolocation frequency in swimming harbour porpoises

Although barium sulphate nets could be detected at greater range via porpoise biosonar than standard nylon gillnets, this advantage remains often unused: Culik and Koschinki (2004) and Koschinski et al. (submitted) only recorded sonar clicks in 19.3% of all visually confirmed harbour porpoise approaches to a barium sulphate net and in only 30% of all approaches to a standard net. This is confirmed by Graner (2003) who determined a very low sonar activity in harbour porpoises approaching a standard nylon net by more than 50 m, whereas biosonar activity within 50 – 100 m of the net was intense. Finally Kastelein (1995a) often observed only sporadic echolocation activity in harbour porpoises maintained in a dolphinarium.

Culik and Koschinski (2004) and Koschinski et al. (submitted) also found that the number of clicks recorded per interaction near a barium-sulphate net (median 33 clicks) was 67% lower than near a standard net (55 clicks). Free-ranging harbour porpoises apparently investigated the enhanced net less intensively, which may have been related a) to a better visibility of the twine: visibility conditions were somewhat better during their field study than described here or b) to a more rapid perception, owed to the acoustic enhancement of the net. At greater depths, however, differences in visibility should not play a role. New results by Cox and Read (2004) show that harbour porpoises use their biosonar similarly in bottom set gillnets at 100-130 m depth, irrespective of twine composition. In their study the barium-sulphate net did not intensify biosonar use.

The low proportion of echolocating harbour porpoises near gillnets could also be responsible for the results of Trippel and Shepherd (2004) who report a higher by catch as opposed to their previous study (Trippel et al. 2003). Large by-catches in barium sulphate nets were also reported by Northridge (2003) and were even higher than in the controls. According to Northridge et al. (2003) the reason for this lies in the higher tensile strength of the barium-sulphate twine: this reduces the chance of entangled marine mammals to break free. However, neither twine diameter nor mesh size of the net types they compared were identical, so that a variety of factors could be responsible for the observed by-catch difference. In any case, the results of these studies show that acoustically enhanced gillnets cannot solve the by-catch problem by themselves.

Acoustic deterrents

Initially, acoustic devices called pingers were proposed to keep harbour porpoises away from nets (Lien and Hood 1994, Lien et al. 1995). At first, it was assumed that the sound would warn marine mammals and increase their alertness. Today we know that these devices deter harbour porpoises. In a field experiment, Culik et al. (2001) showed that a pinger with ultrasonic sweeps (20 - 160 kHz, 145 dB re 1µPa, 1m; PICE / AquaMark 100) was widely avoided: the median closest approach distance was 530 m. Another pinger type, the Dukane NetMark 1000 (10 kHz; 130 dB re 1µPa, 1m) pinger was avoided by 208 m and the closest observed approach to the original pinger prototype, the Lien-Pinger (2,7 kHz, 115 dB re 1µPa, 1m; Lien and Hood 1994, Lien et al. 1995) initially was 170 m (Koschinski and Culik 1997).

The disadvantages of pingers are obvious: acoustic pollution of the marine environment and habitat exclusion of harbour porpoises. This presumably reduces feeding success and therefore fitness. Another drawback is habituation: minimum approach distances decrease over time, with increased risk of entanglement (e. g., Koschinski and Culik 1997, Cox et al. 2003).

Nevertheless, acoustic alarms became mandatory in the Danish cod fishery around ship wrecks (Larsen et al. 2003b). Furthermore, the EU-commission has specified pinger use in several fisheries and areas as of 2005. This applies to vessels above 12 m length, which have to employ pingers year-round in driftnet and gillnet fisheries. However, there are exceptions for gillnets up to 400 m length in the North Sea, Kattegatt and Skagerrak, which only have to be equipped with pingers between August and October (EU-Commission 2004).

Preliminary tests with warning sounds

Since harbour porpoises do not constantly echolocate, the question is how the animals can be triggered to increase their vigilance near nets. Reflective nets can only be effective if the animals biosonar is active. The chance of reducing porpoise by-catch and thereby increasing net selectivity would greatly benefit from such a *biosonar trigger*.

Kastelein et al. (1995b) showed that in a tank, harbour porpoises avoided 2.5 kHz sounds with harmonics whereas pure sounds of the same frequency elicited inquisitive behaviour. Koschinski et al. (2003) report that in the wild, low frequency sounds induce harbour porpoises to increase click rates near the transducer. From this we hypothesized that „warning sounds“ would elicit a different behaviour than pingers.

In a preliminary field experiment without nets Culik and Koschinski (2004) and Koschinski et al. (submitted) confirmed the findings of Kastelein et al. (1995b): pure 2.5 kHz sounds (SL = 127 dB re 1µPa, 1m) increased the number of echolocating harbour porpoise groups by a factor of 4 instead of deterring the animals. Furthermore, the sounds significantly increased the number of clicks recorded per interaction.

Combination of barium sulphate nets and warning sounds

Based on the promising results of the preliminary study as well as on published results we decided to combine barium sulphate nets and warning sounds. We hypothesized that warning sounds would trigger echolocation behaviour and thus enable harbour porpoises to avoid the barium sulphate net in time.

During the experiment, and in bright daylight, one porpoise became entangled in the barium sulphate net without sound. During play-back of warning sounds, we noticed no further collisions. Since visibility during the field experiments was low, and net samples attached to the black and white Secchi disk could never be seen at depths greater than 1-2 m (Fig. 1), we suppose that the different optical properties of the two nets were without relevance.

In the preliminary tests Culik and Koschinski (2004) and Koschinski et al. (submitted) showed that warning sounds were not interpreted like the deterring noise emitted by pingers. In the present study, surfacing positions determined via theodolite showed that the distance to the barium sulphate net increased from 21.3 to 34.7 m when warning sounds were played back, a difference of 13.4 m. Habitat exclusion as seen in the results of Culik et al. (2001) was never observed.

A similar increase in the minimum distance to the net was also recorded under water. The shortest click intervals stored on the click detector increased from 42.8 ms (barium sulphate net without sound) to 64.7 ms (barium sulphate net with warning sounds). This corresponds to a difference of 16 m in target distance or an increase in reaction time of 8.4 – 13.3 s, depending on swim speed (see above).

When the standard net was ensonified, target distance did not increase by as much: click intervals were 51.6 ms, which corresponds to an increase in target distance of 6.6 m or 3.5 – 5.5 s more reaction time as opposed to the barium sulphate net without sound.

The moderate reaction of harbour porpoises to the warning sounds cannot be explained by low intensity or high transmission losses or by a high hearing threshold of the animals. Harbour porpoises can hear 2 kHz sounds above a threshold of 66 dB (Andersen 1970), or 72 dB re 1 µPa (Kastelein et al. 2002). Our measurements of received levels (unpublished data) show that this corresponds to a distance from the transducer of at least 120 m, or 140 m when using a conservative spherical spreading model for calculations (Richardson 1995).

Harbour porpoises did not spend more time within the ensonified observation radius (< 80 m) when warning sounds were played. This may be interpreted as a cautious reaction or by the fact that the animals could detect the sound source and the net in its vicinity faster than without warning sound. Porpoises reduced the time spent from 104 s (barium sulphate net, no sound) to 32 s (ensonified barium sulphate net). Whereas harbour porpoises ensonified the barium sulphate net in an unfocussed manner, this behaviour changed when the sound transducer was operated. The correlation between click duration and minimum click interval shows that the sound source was targeted during operation when sound was on. However, we suppose that the surroundings, e.g. the net, were also investigated, since the correlation coefficient remained low.

However, in the present study the proportion of echolocating as opposed to quiet harbour porpoises was not significantly affected by playing sound, as opposed to the 2004 Culik and Koschinski study. We attribute this to the low sample size.

Disadvantages of warning sounds

It could be objected that the use of warning sounds creates the same disadvantages as those described for pingers, i. e. acoustic pollution, high costs, cumbersome handling and habituation of the animals to the sound. However, the degree of acoustic pollution is greatly reduced due to the low source levels used in this study (115 dB re 1 µPa, 1 m). Low source levels translate into lower power requirements and longer battery life, which in turn should be reflected by lower device costs over time as opposed to pingers. And finally, the problem of habitat exclusion observed in pingers is not an issue here.

However, habituation of harbour porpoises to the 2.5 kHz warning sounds cannot be excluded and would have to be investigated. We hypothesize that by the time habituation occurs, the porpoises may have had a fair training in net avoidance near the sound transducer and will have learned to associate nets with the perceived sounds. This could be a negative association, if harbour porpoises learned to associate food with ensonified nets („dinner bell“ effect cf. Dawson 1991). However, there is wide agreement that harbour porpoises do not consider entangled fish as prey. This is supported by the fact that most by-catch occurs in wide mesh nets (e.g. Vinther 1999). The size spectrum of fish captured with these nets is way beyond the prey selection of harbour porpoises (e. g., Recchia and Read 1989).

Sounds emitted by pingers affect catch rates of target fish species (Culik et al. 2001). However, these effects are not necessarily negative: sounds emitted by a Lien-Pinger actually increase herring catch rates from 4.3 fish m^{-1} to 6.2 fish m^{-1} . This difference was significant, whereas the effects of Dukane- and PICE-Pingers on herring catch rates in the same fishery were not.

Evaluation of results

We summarize the current state of the art as follows:

1) barium sulphate nets increase minimum perception distance for harbour porpoises by 4.4 m as opposed to standard nylon nets and thus increase reaction time by at least 2.3 s (Koschinski and Culik 2004).
2) Harbour porpoises use their biosonar only sporadically, so that the advantages of reflective nets do not always manifest themselves (Koschinski and Culik 2004).
3) 2.5 kHz pure tone warning sounds do not elicit the same behaviour as pingers and do not deter harbour porpoises nor exclude them from their habitat (this study).

4) Warning sounds increase the biosonar's target distance at the barium sulphate net by 16 m which corresponds to an increased reaction time of 8.4 – 13.3 s. This reduces the risk of collision (this study).
5) When the standard net is ensonified, the target distance is only increased by 6.6 m which expands reaction time by only 3.5 – 5.5 s (as opposed to the barium sulphate net without sound; this study).
6) Warning sounds reduce the amount of time harbour porpoises spend in the vicinity of the net (< 80 m) from 104 to 32 s (median). This further reduces the risk of collision. The effect is also observed with the standard net (24 s; this study).
7) The acoustic activity, i. e. the proportion of echolocating porpoises as well as the number of clicks per interaction could be increased significantly in the preliminary investigations with somewhat stronger warning sounds (SL = 127 dB re 1µPa, 1m; Koschinski and Culik 2004).
8) When less intensive sounds were produced (SL = 115 dB) the number of clicks recorded per minute was somewhat increased (this study).

From these findings we infer that 2.5 kHz pure sounds in conjunction with barium sulphate nets offer a promising alternative to reduce by-catch in gillnet fisheries. In order to confirm these findings the following steps have now to be taken:

1) Autonomous devices need to be developed which are capable of emitting the described warning sounds. This has to be achieved by taking the requirements of fishermen into consideration (e. g. SEAFISH 2003).
2) The effects of sound intensity on porpoise behaviour need to be investigated in more detail in order to optimise the devices with respect to range and power consumption.
3) Field trials in a commercial gillnet fishery have to be conducted in order to test the combination of warning sounds in conjunction with barium sulphate and standard nets under realistic conditions (e.g. Trippel et al. 2003; Northridge et al. 2003). In a comparison of nets with and without sound the following has to be tested:
    a) whether the catch rates of the target species are affected,
    b) whether warning sounds actually reduce by-catch,
    c) whether the use of barium sulphate nets over standard nylon nets increases the effect of warning sounds or whether this is independent of net type.

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