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Behavioral reactions of free-ranging harbor porpoises *Phocoena phocoena* encountering standard nylon and $BaSO_4$ mesh gillnets and warning sound

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ABSTRACT: Field tests suggest that high-density nets can reduce harbor porpoise *Phocoena phocoena* by-catch in demersal gillnet fisheries. However, it is not clear whether acoustic reflectivity or twine stiffness are responsible for this. We conducted sonar tests in a tank in the frequency range of 110 to 190 kHz and found that the target strength of the high-density $BaSO_4$ net was 7.2 dB higher at 150 kHz than that of the standard nylon net. In a fjord on Vancouver Island, Canada, we investigated porpoise surfacing and echolocation behavior as they encountered 2 surface gillnets (45 × 9 m, 165 mm mesh size) made of (1) standard 100% nylon and (2) a mix of $BaSO_4$ and nylon. The distribution of click intervals shifted to longer intervals when the $BaSO_4$ net was used (median = 51 ms vs. 45.2 ms for the standard net; Kolmogorov-Smirnov test, $p < 0.001$), indicating a greater target distance. We estimated that porpoises are able to detect $BaSO_4$ nets 4.4 m in advance of standard nylon nets. However, an unexpected low percentage of echolocating porpoise groups within 50 m of the center of nets (standard 30.6%, $BaSO_4$ 19.3%) indicates that additional measures may be necessary to reduce by-catch. A subsequent experiment showed that transmission of 2.5 kHz tones as a warning sound increased biosonar use by a factor of 4 compared to controls (16.7% for controls vs. 71.4% for groups during ensonification; chi^2-test, $p < 0.001$). The combination of reflective nets and warning sounds may be a promising mitigative tool.

KEY WORDS: Harbor porpoise · *Phocoena phocoena* · Barium sulfate · Reflective gillnet · By-catch mitigation

INTRODUCTION

Small cetaceans are susceptible to incidental entanglement and mortality in various forms of gillnet fisheries throughout their distribution range. Because of this by-catch, the harbor porpoise *Phocoena phocoena*, although still abundant as a species, has experienced major population declines in parts of its range, most notably in the central and eastern Baltic Sea (Koschinski 2002). Incidental takes 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).

Because of high by-catch rates, acoustic alarms ('pingers') became mandatory in the Danish cod fishery around ship wrecks (Larsen et al. 2002b) and other gillnet fisheries in the North Baltic and Celtic Seas (Council of the European Union 2004) as well as in the New England gillnet fishery in a spatial–temporal scheme (Waring et al. 2002). Although shown to be

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effective (e.g. Koschinski & Culik 1997, Kraus et al. 1997, Trippel et al. 1999, Culik et al. 2001), pinger deployment has a number of disadvantages. Harbor porpoises may habituate to the sound (cf. Cox et al. 2001) or the sound may be so aversive that they are excluded from parts of their habitat (cf. Culik et al. 2001). Also, users may fail to replace batteries in time, resulting in 'black holes' in the nets (cf. Berggren et al. 2002). Such non-ensonified spaces may suggest a safe escape to the porpoises and result in even more by-catch. Further, non-compliance with pinger deployment has been observed in restricted areas in the Gulf of Maine in recent years (D. Palka, pers. comm.).

Another possible way in which to mitigate by-catch is to improve the acoustic reflectivity of nets to increase detectability by the porpoises' biosonar. During 2 yr of a field trial in the Bay of Fundy (Canada), no porpoises were caught in 231 strings (300 × 4 m) of high-density $BaSO_4$ nets, while 12 individuals became entangled in nets comprised of 467 strings of standard nylon (Trippel et al. 2003). Larsen et al. (2002a) achieved a similar by-catch reduction using nets with iron-oxide-enriched twine in the Danish cod fishery: 8 porpoises were caught in standard nylon nets (effort: 61 km d^{-1}) and none in iron-oxide nets (68 km d^{-1}).

Standard nylon and $BaSO_4$ nets differ in several respects; i.e. composition of net material, stiffness, transparency, color and acoustic reflectivity. To which degree each of these factors is responsible for the reduction in by-catch shown by Larsen et al. (2002a) and Trippel et al. (2003) is unclear. To address this, we (1) investigated the target strength of a $BaSO_4$ net in a test tank, (2) conducted a field study to visually and acoustically observe the behavior of free-ranging harbor porpoises close to a standard nylon and a $BaSO_4$ gillnet and (3) examined if echolocation activity — a critical factor in detecting nets — can be increased by transmitting a pure 2.5 kHz tone (cf. Kastelein et al. 1995b).

In the field, we visually and acoustically recorded a number of behavioral parameters in order to assess differences in porpoise behavior close to each net type. We hypothesized that harbor porpoises swimming towards the experimental nets would react to the $BaSO_4$ net from a greater distance than to the standard net, if the former net type were better detectable. This would be expressed in a larger minimum distance and longer click intervals (reflecting a higher target range). We also hypothesized that porpoises might show differences in the intensity with which they explored both net types when gathering information on (e.g.) position, size or movement. During such exploratory behavior we would expect variability between nets in the duration of interactions as well as in the number of clicks logged.

MATERIALS AND METHODS

Target-strength measurements of net materials in tank. Standard and $BaSO_4$ net material samples were investigated at the German Federal Armed Forces Underwater Acoustics and Geophysics Research Institute, Kiel. Net material (1 × 1 m) was stretched out in a tank (5 × 5 m, depth 3 m) with mesh sizes slightly elongated downwards. The net material was ensonified with continuous wave pulses at frequencies from 110 to 190 kHz and 0.2 ms width. When very short pulses are chosen in order to minimize boundary effects, tank measurements are comparable with free field measurements. The sound pulses were transmitted by a transducer (B&K 8105) placed at 1.5 m depth at a distance of 0.8 m orthogonal to the net panel. The signals were generated by a synthesizer (HP 8904) connected to a gate (B&K 4440) and a power amplifier (B&K 2713). The echoes from the net were received by a measuring hydrophone (Reson TC 4014) located 0.2 m from the transducer and 0.8 m from the net. A laboratory amplifier (Reson VP 2000) and a bandpass filter with a band width of 80 to 300 kHz (Precision Filters 6611) were used for signal conditioning. AD-conversion and data recording were performed using a high-speed digital oscilloscope (Le Croy, LT344).

Study area and period of field experiment. From 7 to 21 August 2003, we conducted behavioral observations of free-ranging harbor porpoises in Fortune Channel (49° 11′ N, 125° 46.5′ W), Vancouver Island, Canada. The fjord-like area is regularly frequented by harbor porpoises and offers calm protected conditions (Beaufort scale 0) for 3 to 7 h per day. These are perfect conditions for tracking positions of the porpoises (Koschinski & Culik 1997, Culik et al. 2001, Koschinski et al. 2003). Boat traffic is rare, with a maximum of 10 small outboard-powered boats per day. Since we wanted to reduce net visibility as much as possible, we chose these nutrient-rich coastal waters. The inshore areas of the temperate rainforest zone on the Canadian west coast favor low underwater visibility caused by plankton blooms.

Experimental nets. We tested 2 different net types during the field experiments. For each deployment, 1 of the experimental nets (chosen randomly) was positioned at the surface in up to 30 m deep water and at a maximum distance of 260 m (distant end) from a rocky island (from which we observed the porpoises). A small outboard-powered inflatable boat moored to the shore enabled observers to rescue porpoises within 2 min of a possible entanglement.

One experimental net was a standard nylon gillnet typically used in the groundfish fishery off the eastern coast of the USA and Canada, consisting of a semi-transparent, bluish nylon filament with a diameter of

0.62 mm. The other net was composed of nylon twine of the same diameter to which a $BaSO_4$ filler had been added (3% by volume, 10% by weight). Since $BaSO_4$ is bright white, the strands had been dyed green to mask the net in seawater. Each net was 45 m long and 9 m deep with a stretched-mesh size of 16.5 cm. Each head rope was carried by a float line with ellipsoid foam floats (8 × 12 cm) spaced every 1.35 m, and the lead line attached to the nets weighed 55 g m^{-1}.

Since the nets differed in color, it was important to assess the distance at which each could be observed under water. Net material of each type 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 a black as well as a white background to reproduce visibility against the bright water surface and dark depths, respectively. Visibility of the $BaSO_4$ net varied between 4.8 and 1.6 m during the course of the study, and that of the standard net was between 2.2 and 0.7 m.

To make the experimental nets safer in case of accidental entanglement, they were cut into vertical strips 2.3 m wide and 7 m long, enabling entangled porpoises to surface and breathe until rescued by the observers. The strips were connected at 1 m intervals with breakaway ties of self-adhesive electric tape. The upper 2 m of the net panels were intact.

Production of warning sound. The behavior of porpoises in the vicinity of a float line (without net) was compared to that with the same float line plus a 2.5 kHz sound stimulus.

Tones with a frequency of 2.5 kHz (source level = 127 dB re 1 µPa, 1 m, repetition frequency = 67 min^{-1}, pulse duration = 0.3 s) were generated with a music software program (Cool Edit pro) and recorded on an audio CD. These sinus-sounds were replayed using a car CD player (Blaupunkt 'Kiel') in a waterproof bin (Ø 46 cm, height 56 cm) and an underwater transducer (ITC 4005b) deployed at a depth of 4.5 m from 2 cylindrical foam floats (Ø 16 cm, length 14 cm; see Fig. 1). At the same depth we placed a click detector (see 'Logging of harbor porpoise echolocation activity' subsection) at a distance of approximately 1 m from the transducer to record echolocation activity of the porpoises.

Theodolite tracking of harbor porpoises. An electronic theodolite (GDM 610, Trimble Navigation) was positioned on a rocky island overlooking an area of approximately 500 × 1000 m on both sides of the float line or experimental net. Instrument height above sea level varied from 4.75 to 7.62 m, depending on the tide. We focused our attention on a 50 m radius around the net in order to determine the minimum distance of surfacing porpoises approaching the net and to perceive collisions, so that a swift rescue could be undertaken if needed.

One observer constantly scanned the area with and without binoculars (Zeiss Victory 10 × 40, Hensoldt), while the other focused on the sighted porpoises, using the short-range finder of the theodolite, and logged their positions.

The theodolite was used to record horizontal and vertical angles as well as the time (to the nearest second) of each surfacing of porpoise associations ('groups') or single individuals. In groups of 2 or more, the foremost porpoise was tracked. Theodolite elevation above sea level was obtained approximately every 30 min 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 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 (0°) for measurements of the horizontal angle of sightings. The accurate position of surfacing individuals could readily be calculated from data of theodolite elevation above sea level as well as horizontal and vertical angles of surfacings using trigonometric equations.

Because of tidal currents, the position of the float line or net and click detector were not constant. These were recorded at fixed intervals and interpolated. From surfacing-position data we obtained minimum distances to the net panel and the click detector for porpoise groups. Only data from individuals that came closer than 50 m to the center of the net was used for data analysis. This distance was used to define a 'close interaction'. Further, the closest observed approach to the net panel was plotted and measured for each porpoise group or individual.

In a second experiment using a sound stimulus, the distance to the sound source (in the center of the float line) was also measured. For both experiments we determined the time during which porpoises were observed within the 50 m radius.

Logging of harbor porpoise echolocation activity. In order to detect and analyze acoustic activity of harbor porpoises, a click detector (T-POD v1, No. 68, Chelonia) was suspended from a float in the middle of the net panel at 4.5 m depth. In the sound experiment the position was next to the transducer (Fig. 1). The 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 www.chelonia.demon.co.uk/). Settings of the T-POD were adjusted to: Frequency Filter A = 130 kHz and B = 90 kHz; log all clicks >30 µs duration; ratio = 4; filter sharpness A = 10 and B = 18; intensity threshold = 0; no limit (maximum number of clicks logged during 10 s period).

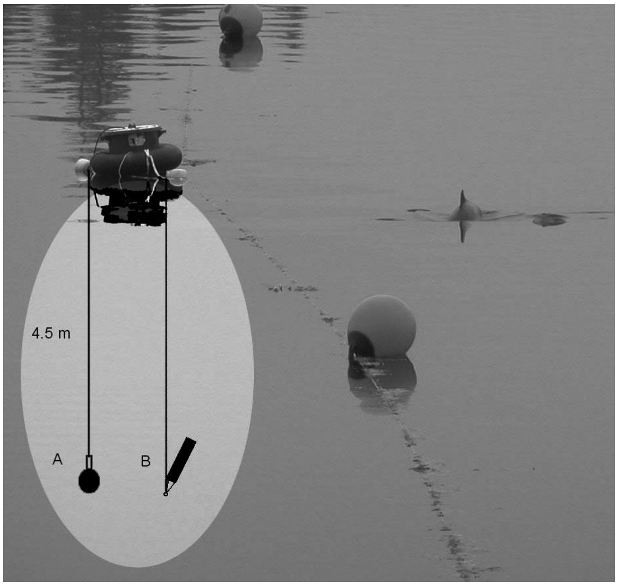

Fig. 1. Experimental field set-up for production of tonal 2.5 kHz warning sound at float line, showing floating bin containing CD-player and battery. A: transducer; B: click detector. In the background 2 surfacing porpoises can be seen

For click-train detection we used the software tpod.exe v. 5.42. The 4 categories CetHi, CetAll, +? and +?? were chosen. This implies that not only click trains identified with a high probability, but also doubtful click trains were included: Thomsen et al. (2005) found that valuable information on click trains is lost, when only high-probability click trains are used for analysis. Therefore all click trains detected by the software were checked manually for false positives (e.g. clicks from random or non train-producing noise sources or trains with regular sequences such as 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. Boat sonars were not logged.

Data analysis. We obtained data from 6 deployments with the standard net (14 h spread over 4 d) and from 9 with the $BaSO_4$ net (26.5 h spread over 8 d); 1 deployment (2.8 h) was conducted without a net, using only the float line, and 3 (total of 12.5 h) were conducted with an ensonified float line.

Several visually and acoustically recorded behavioral parameters were used to assess differences in porpoise reactions to both net types: (1) minimum distances to the net panel; (2) duration of 'close interactions' (i.e. time between first and last surfacing within 50 m radius of center of the net); (3) percentage of close interactions with echolocation click trains logged; (4) number of clicks per close interaction; (5) click intervals (i.e. time elapsed between clicks within click trains).

From click-detector data (time and duration of all clicks) we calculated click intervals within each click train. The click interval is an indirect measure of the momentary target 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). Thus the 2-way travel time plus a lag time for processing the information determines the target distance. This measure may be a key factor in determining whether a porpoise avoids or collides with a net. If the $BaSO_4$ net is acoustically enhanced we would expect more longer and less shorter click intervals compared to the standard net. The momentary target range can be calculated as:

$$\mathrm{D}_{\mathrm{target}} = (I - T_{\mathrm{l}})\, v / 2 \qquad (1)$$

where $\mathrm{D}_{\mathrm{target}}$ = target range (m), I = click interval (s), and T_{l} = lag time (s), and v = underwater sound velocity, approx. 1500 m s^{-1} (Richardson et al. 1995).

In order to omit click trains which were not produced in the vicinity of the net, only those that could be matched with porpoise groups or individuals surfacing within 2 min of the recording and a 50 m radius of the click detector were used for analysis. This radius was chosen conservatively because of the short distance from which a porpoise can theoretically detect a net (Hatakeyama & Soeda 1990, Au & Jones 1991, Au 1994, Mooney 2003, Mooney et al. 2004) and corresponds to half the certain detection range of the click detector used in this study.

Furthermore, we examined the correlation between the minimum click interval and the maximum click duration within each analyzed click train. The duration of a click as recorded by the click detector is a measure of 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 the distance only. This means that when an echolocating porpoise is targeting primarily on the click detector and not the net, a strong negative correlation between minimum click intervals and maximum click duration within click trains should be found (Carlström 2003). Such a correlation was not observed during the net experiment (standard net: $n = 77$, $r = 0.023$, $p > 0.05$; $BaSO_4$ net: $n = 73$, $r = 0.159$, $p > 0.05$), indicating random orientation of porpoises towards the click detector.

RESULTS

Target-strength measurements

For a frequency of 150 kHz, which is closest to the echolocation frequency of a harbor porpoise (Au 1993), the target strength (TS) of the $BaSO_4$ net was 7.2 dB higher than that of the standard nylon net (Fig. 2). This was the maximum value in the investigated frequency range of 110 to 190 kHz. At 190 kHz the TS difference between the 2 nets was only 4.1 dB.

Visual observation of porpoise behavior close to $BaSO_4$ and standard nylon nets

Minimum distance to net panel

Distance data was not normally distributed. The median closest approach distance to the net panel was 18 m for the standard net (n = 48) and 17.5 m for the $BaSO_4$ net (n = 88). This difference was not significant (Kolmogorov-Smirnov test, KST: $p > 0.05$, $D = 0.16$).

Duration of 'close interactions'

With the standard net, close interactions lasted for a median of 24 s (n = 37) compared to 20 s (n = 66) when the $BaSO_4$ net was used. There was no significant difference between the 2 experimental set-ups (KST: $p > 0.05$, $D = 0.104$).

Percentage of close interactions with logged echolocation clicks

When the standard nylon net was in use, 30.6 % of all porpoise groups (11 out of 36) used their biosonar. With the $BaSO_4$ net, only 19.3 % (17 out of 88) of the groups echolocated. However, this difference was not significant (chi^2-test: $p > 0.05$, $chi^2 = 1.84$, df = 1).

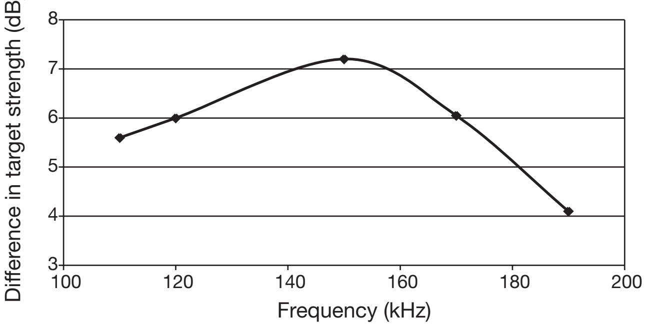

Fig. 2. *Phocoena phocoena.* Measured target-strength difference between standard nylon net and $BaSO_4$ net for normal (90°) sound incidence in frequency range 110 to 190 kHz

Number of clicks per close interaction

During close interactions the median click number was 0 for each net type (standard net: n = 36; $BaSO_4$ net: n = 88) since in most groups (96 out of 124) no echolocation activity was recorded. However, a comparison of the distribution of click number per interaction revealed a highly significant difference between the 2 nets (KST: $p < 0.001$, $D = 0.35$). When comparing only echolocating porpoises, we found a highly significant difference in the distribution (median number of clicks = 56 with the standard net, n = 10 and 23 with the $BaSO_4$ net, n = 13; KST: $p = 0.021$, $D = 0.438$).

Click intervals

The closest approach distance of porpoises to the nets may be the most important factor in characterizing net detectability. Since visual observations revealed only closest approaches in surfacing individuals, we tried to infer closest approach distance in diving porpoises from click intervals. Since we do not know exactly what the porpoises did underwater when their clicks were recorded, a distribution of all click intervals can give an indication on target ranges used more often than others. Fig. 3 shows that click intervals between 55 and 85 ms were observed more often near the $BaSO_4$ net than the standard nylon net, while 40 to 50 ms intervals were less common than for the standard net. The median click interval in the vicinity of the standard nylon net was 45.2 ms (n = 939; 11 groups) while in the vicinity of the $BaSO_4$ net, it was 51 ms (n = 673; 17 groups). The difference is highly significant between both distributions (KST: $p < 0.001$, $D = 0.11$). Because subsequent intervals within click trains cannot be considered statistically independent, we repeated this comparison concentrating on median inter-

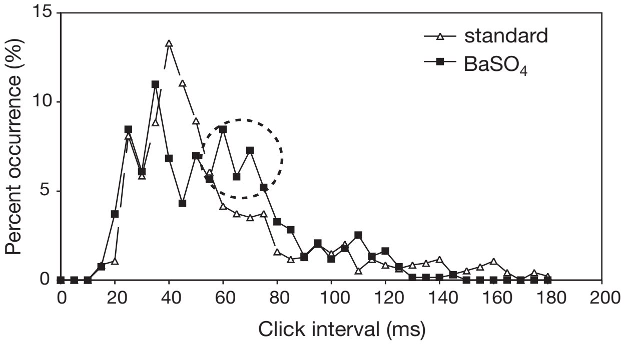

Fig. 3. *Phocoena phocoena.* Distribution of click intervals of harbor porpoises echolocating within 50 m radius of click detector. Circle marks range of intervals in which echolocation activity was significantly higher at the $BaSO_4$ than at the standard nylon net (Kolmogorov-Smirnov test; $p < 0.001$)

vals per click train. Further, we restricted these to values between 35 and 101.7 ms. The low cutoff of 35 ms corresponds to harbor popoise lag time in a complex spatial situation (Verfuß et al. 2005) and falls within the range reported by Au et al. (1999). The high cutoff of 101.7 ms delineates the 50 m target range radius, assuming a lag of 35 ms. Performing this procedure, we also found a significant difference between both distributions (KST: $p = 0.016$, $D = 0.308$, standard: $n = 51$, $BaSO_4$: $n = 46$.

Influence of 2.5 kHz tone on porpoise behavior

Since only a few porpoise groups used their biosonar in the vicinity of the experimental nets, we investigated whether it is possible to increase echolocation activity by transmitting 2.5 kHz tones as a warning sound. Whereas the closest approach distances and duration of interactions did not vary significantly, the other parameters we investigated did. During sound periods, the median closest approach distance of porpoises to the click detector and transducer was 24.8 m ($n = 22$) compared to 27.9 m for the control ($n = 24$). This difference was not significant (KST: $p > 0.05$, $D = 0.262$). Porpoises stayed within 50 m of the transducer and click detector for a median of 32 s ($n = 22$) when tones were replayed compared to 17 s ($n = 17$) during the silent period. But again, this difference was not significant, due to highly variable data (KST: $p > 0.05$, $D = 0.294$).

When transmitting the 2.5 kHz tones we found that echolocation activity was exhibited by 71.4 % of all porpoise groups (15 of 21 groups), whereas in the control only 16.7 % of all interactions (4 of 24 groups) were accompanied by click activity. This 4-fold increase in echolocating groups was highly significant (chi^2-test: $p < 0.001$, $chi^2 = 13.77$, $df = 1$). Individuals displaying acoustic activity in the 50 m range of the click detector also increased the number of clicks (median = 111, $n = 18$) during the ensonified periods compared to the control period (median = 36, $n = 4$; KST: $p < 0.01$, $D = 0.833$). During periods with sound, median click intervals lasted 47.3 ms ($n = 2637$). During the control period, the median click intervals were 42.1 ms ($n = 124$). This interesting result has yet to be confirmed.

DISCUSSION

Comparison of standard nylon and $BaSO_4$ nets

Larsen et al. (2002a) and Trippel et al. (2003) found a significant harbor porpoise by-catch reduction in gillnets containing iron-oxide or $BaSO_4$ particles compared to nets comprised of 100 % nylon. However, it was not clear whether acoustic parameters, stiffness, or other factors were responsible for this. Enhanced acoustic detectability would have an effect on small cetaceans before net contact, whereas net stiffness (cf. Larsen et al. 2002a, Mooney 2003) or reduced breaking strength (cf. Northridge et al. 2003) would only have an effect after collision.

Another possible factor is greater visibility of high-density net material. In a commercial fishery using bottom set gillnets, this factor may only be of importance during setting and retrieval. For example, in the Bay of Fundy and Gulf of Maine, nets are frequently set as deep as 100 m (Trippel et al. 1999). At these depths, light levels are below 0.6 mmol m^{-2} s^{-1} (F. Page unpubl. data). In our experiment, surface light levels were obviously higher, but visibility (Secchi-depth) was low compared to surfacing distance and target range of harbor porpoises derived from click intervals — while maximum visibility of the net meshes was 2.2 m for the standard net and 4.8 m for the $BaSO_4$ net, median surfacing distances from the nets were approximately 4 to 8 times higher (standard net: 18 m, $BaSO_4$ net: 17.5 m). The same was true for the median target distance calculated from click intervals. Using a lag time of 35 ms, target range was 7.6 m for the standard net and 12 m for the $BaSO_4$ net (Table 1).

Acoustic observations

Target-strength measurements. At an approach angle of 90° and a frequency of 150 kHz, our measurements in a tank resulted in a 7.2 dB higher target strength of the $BaSO_4$ compared to the standard net. This is higher than measurements by Mooney et al. (2004), who used a simulated dolphin click and similar mesh size and twine diameter as ours and measured a TS difference of 3.5 dB at an approach angle of 70°. However, at higher and lower approach angles their TS differences were even lower and reached zero at 90°.

At 190 kHz, our measurement of the TS difference between the 2 nets (4.1 dB) was comparable to that reported by Trippel et al. (2003), who recorded 4.2 to

Table 1. *Phocoena phocoena*. Estimated theoretical target distances of both net types using median click-interval values of 42.2 ms for the standard net and 51 ms for the $BaSO_4$ net and 3 different lag times

Lag time (ms)	Target distance (m) Standard net	$BaSO_4$ net
11.7	25.1	29.5
20	18.9	23.3
35	7.6	12

5.2 dB using a 200 kHz multibeam sonar. Assuming a spherical (20 logR) spreading of reflected sound energy, our TS difference of 7.2 dB translates into a range difference of 2.3 m. However, depending on the exact location of the net mesh in the measuring tank, sound energy received from the $BaSO_4$ net varied considerably. This means that, in principle, a porpoise can detect high-density nets better than their standard counterparts, but detection is determined by approach angle, hanging ratio, ambient noise and other factors. Absolute detection distances also depend on the source level used by echolocating porpoises. This parameter could not be measured in our study.

Click intervals. Maximum detection distance is reflected by the click intervals in porpoise click trains. For orientation, porpoises typically use click intervals around 50 ms (Verboom & Kastelein 2003). In this detection mode, target distance can be derived from the 2-way travel time and a lag time (cf. Au 1993). During prey capture, the distance of the prey cannot be calculated in this way because intervals are rapidly decreasing from 10 to 1.5 ms and hence are too short for processing each single click (cf. Busnel & Dziedzic 1967, Au 1993, Kastelein et al. 1995a).

During experiments in Fortune Channel, we recorded no click intervals shorter than 11.7 ms. Therefore, we suspect that in our experiments all click trains correspond to the pulse mode used during orientation. Significant differences were found in the distribution of click intervals of echolocating harbor porpoises during close interactions. For both net types, porpoises most frequently used intervals of 35 to 40 ms (Fig. 3). This corresponds to the results of Kastelein et al. (1995a) who found that harbor porpoises navigating around ropes mainly use click trains with intervals of 40 ms or longer.

In the vicinity of the $BaSO_4$ net, however, we recorded more click intervals between 55 and 85 ms compared to the standard nylon net, while intervals of 40 to 50 ms were less common than in the nylon net. This shift to longer intervals indicates that the porpoises' biosonar aimed further ahead when encountering the $BaSO_4$ net.

Unfortunately, there is inconsistent information with respect to the lag time required by harbor porpoises during orientation. In our experiment the shortest recorded click interval (11.7 ms) may correspond to the lag time. Au et al. (1999) measured lag times of 20 to 35 ms in harbor porpoises during a detection task of an object at a distance of 7 to 9 m. During navigation tasks, Verfuß et al. (2005) found nearly constant lag times at distances from 26 to 12 m, ranging from 14 to 19 ms in an enclosure without additional equipment, and from 26 to 36 ms when hydrophones, cameras and cables were in the water. The authors conclude that lag times used during navigation are considerably longer in a more complex spatial situation.

Since existing information on lag time is inconsistent, we calculated (Table 1) target distances for different possible lag times using Eq. (1). Using the median values for click intervals, this resulted in target distances ranging from 7.6 to 25.1 m for the standard net (median click interval 45.2 ms) and between 12 and 29.5 m for the $BaSO_4$ net (median click interval 51 ms). These calculations show that for short ranges, Eq. (1) is very sensitive to changes in lag time. However, assuming harbor porpoise lag time to be constant regardless of net type, the difference in detectability between standard and $BaSO_4$ nets remains also constant at 4.4 m.

From source level and target strength data, Kastelein et al. (2000) predicted that porpoises can detect standard net material from a distance of 3 to 6 m. Mooney et al. (2004) calculated for a net panel with a similar mesh size (14.7 cm) but a thinner twine diameter (0.51 mm), a 90% detection distance between 2.8 and 3.6 m for the standard net and 3.4 and 4.5 m for the $BaSO_4$ net (approach angles between 10 and 30° from normal). The higher target range values we calculated from harbor porpoise click intervals may be explained by the detection of the net in addition to more reflective parts such as the float and lead line. Au & Jones (1991) and Au (1994) were able to show that 0.635 cm twisted polypropylene line attached to the net material increases reflectivity, and hence detection distances. A float line within the water column can be detected from 16 m (Kastelein et al. 2000), but our float line was not fully submerged. A detection distance of 9 m for a lead line of unknown thickness was estimated by Hatakeyama & Soeda (1990), whereas 12 m was calculated by Kastelein et al. (2000) for a lead line similar to the line used in this study (50 g m^{-1}). These values compare well with the target distance we derived from median click intervals using a lag time of 35 ms (7.6 to 12 m). This lag time corresponds to the lag time found by Verfuß et al. (2005) in a complex spatial situation. It can be assumed that a net in the water consisting of mesh, mooring, lead and head ropes (and sometimes fishes) represents a complex acoustical situation with multiple echoes.

Our data showed a greater target distance of the $BaSO_4$ compared to the standard net. The difference in the median click intervals indicates a 4.4 m longer target range in the former. At an average swimming speed of 1.5 ms^{-1} (Teilmann 2000) this difference would increase the reaction time of a porpoise by 2.9 s. At maximum speed (6.3 ms^{-1}) a porpoise would have 0.7 s more time to avoid the relevant net. If the peaks in the distribution curve are taken for calculations (standard = 40 ms; $BaSO_4$= 60 ms), the range difference would increase to 15 m, translating into an increase in reaction time by 10 s at an average speed or 2.4 s at maximum speed, respectively.

Use of echolocation by porpoise groups. If only a minor fraction of all harbor porpoises use echolocation in the vicinity of nets, an increase in target strength would be of limited value. In our experiment, echolocation could be recorded in only 19.3 to 30.6% of porpoise groups within a 50 m radius of the net center and in 16.7% of groups when only a float line was presented. In field trials with a salmon driftnet and an anglerfish net in a Norwegian fjord, Graner (2003) reported that echolocation activity substantially decreased when porpoises circumnavigated these. Within a 50 m radius around the net, the author recorded only a few clicks, while in the 50 to 100 m radius region considerable echolocation activity took place; no explanation for this phenomenon was given. However, it suggests that other attributes of a net are used as navigational cues. The low proportion of echolocating porpoise groups in our experiment may have been a reaction to a perceived probable danger. Especially in the North Pacific, where killer whales *Orcinus orca* prey frequently on marine mammals, it may be advantageous to remain silent or to only sporadically use echolocation when an unfamiliar and hence potentially dangerous cue is perceived.

Further, under commercial fishery conditions, when nets are often set at 100 m and mainly overnight (Trippel et al. 1999) porpoises may echolocate more frequently than during our experiment, which was conducted close to the surface during daylight. Using click detectors set in a fjord in Scotland at 40 m, Carlström (2003) found more echolocation encounters at night than during the day and reported a shift to shorter click intervals at night. The latter is probably related to prey capture (cf. Busnel & Dziedzic 1967).

Another factor which may increase echolocation activity in the vicinity of actively fishing nets is the presence of prey fishes or entangled fishes. This could have 2 consequences for the porpoises: (1) higher echolocation activity might increase the possibility of detecting a net, but porpoises might be distracted from nets while pursuing mobile prey; (2) net echoes might also be masked by the echoes from prey fishes (Pence 1986, Au & Jones 1991).

Number of clicks. Cox & Read (2004) did not find any difference in harbor porpoise echolocation near standard or $BaSO_4$ nets set by commercial fishermen in the Bay of Fundy at 100 to 130 m depth. However, the resolution of their parameters (number of clicks h^{-1} and number of click-positive 10 s intervals h^{-1}) may have been too low to evaluate and compare individual echolocation behavior. Further, their method did not distinguish between individuals close to the net and those at a distance and not interacting with it.

In our study, in which we visually observed harbor porpoises near the nets while simultaneously recording their acoustic behavior, we were able to record the click number for each close interaction. Click distribution differed significantly between the 2 net types. The median number of clicks used by echolocating groups was higher at the standard net, with more than twice as many clicks recorded than at the $BaSO_4$ net (56 vs. 23 clicks). This indicates that porpoises investigated the $BaSO_4$ net less intensively than the standard nylon net, perhaps because they recognized it as a barrier from a greater distance.

Stiffness of net material

Measurements by Larsen et al. (2002a) and Mooney (2003) revealed that high-density nets in general are stiffer than standard nets with the same twine diameter. Mooney (2003) also showed that stiffness decreases with increasing soak-time of nets. Larsen et al. (2002a) assumed that the by-catch reduction demonstrated in 2 fisheries experiments (Larsen et al. 2002a, Trippel et al. 2003) was due to the increased stiffness of high-density gillnets and that harbor porpoises virtually ‘bounce off’ the net. During our study, 2 accidental observations showed that this can occur for high-density and for standard net materials (a third collision resulted in an entanglement in the standard net). Because of limited collision data during our study, it was impossible to determine if this happens more often in the $BaSO_4$ net. We are also unsure of the extent of this type of escape behavior from bottom-set nets.

In the third year of the Canadian fishery study by Trippel & Shepherd (2004), a less distinct by-catch reduction was found. In another study, Northridge et al. (2003) reported an even higher by-catch in $BaSO_4$ nets than in standard nets, with 8 harbor porpoises and 10 seals in the former as opposed to only 3 porpoises and 5 seals in the latter (171 vs. 173 hauls of 2700 m-long nets for the $BaSO_4$ and standard nets, respectively). However, in their experiment, $BaSO_4$ and standard nets differed with respect to twine diameter and mesh size.

The above-mentioned studies indicate that net soak time, porpoise or prey density and behavior, low echolocation activity or any combination of these factors may have been responsible for the variation in by-catch recorded in the various field trials. Further research is necessary to obtain a better understanding of the mechanisms responsible.

2.5 kHz tone as warning

As harbor porpoises do not use their biosonar continuously, how can echolocation activity in the vicinity of nets be increased in order to enhance their detectability?

In earlier laboratory experiments, Kastelein et al. (1995b) found that 2 porpoises investigated a pinger with a clear 2.5 kHz tone, whereas a pinger with the same fundamental frequency but strong harmonics induced avoidance behavior. Echolocation activity was recorded, but not quantified in their report. In a field study by Koschinski et al. (2003), the simulated sound of an offshore wind generator (30 to 800 Hz, source level = 128 dB re 1 µPa, 1 m) induced a 2-fold increase in echolocation activity of free-ranging harbor porpoises. On the other hand, Kastelein et al. (2005) found that several types of acoustic emissions (with most energy emitted at around 12 kHz) potentially useful in acoustic data transmission could be turned into a deterrent by increasing the sound amplitude from 130 to 170 dB (re 1 µPa, 1 m). From these reports and the data presented herein we infer that harbor porpoises could be induced to use their sonar by low-intensity, pure sounds.

In our preliminary experiment we demonstrated that it is possible to increase the proportion of echolocating harbor porpoise groups by a factor of 4 by transmitting 2.5 kHz tones (source level = 127 dB re 1 µPa, 1 m). The sound also significantly increased the number of clicks per interaction, indicating intensified investigation, perhaps a sign of curiosity. This shows that sound does not necessarily have the negative impacts associated with large-scale pinger deployment, such as habitat exclusion. Culik et al. (2001) found that a PICE/ Aqua-Mark pinger (in an experiment similar to the one presented here and at the same study site) displaced porpoises by 530 m, whereas in the present study harbor porpoises maintained a median closest-approach distance of 24.8 m to the warning sound, a distance not different from that maintained by controls.

In this study, we were able to clearly show differences in target strength of standard and barium-sulfate nets and in the acoustic behavior of porpoises in the vicinity of these 2 net types. However, the low echolocation rate recorded in the vicinity of nets can represent a problem for the detection by porpoises of even acoustically enhanced nets. Pure tones were shown to increase echolocation activity. Further research to examine the possibility of using warning sound with reflective nets is recommended.

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