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Introduction

The need to minimize bycatch of toothed whales (odontocetes) in gillnets has long been recognized, because they are often top predators and thus essential to ecosystem resilience (IWC, 2018; Lewison et al., 2014; Reeves et al., 2013). It is likely that a key to achieving this goal is the improvement of gillnet acoustic visibility, because these species use underwater sonar for orientation. Previous work on increasing gillnet detectability for echolocating animals by making the nets more recognizable has been based on trial and error, without understanding the fundamental acoustic properties of the tested modifications. Consequently, these studies have produced mixed and sometimes contradictory result (Bordino et al., 2013; Larsen et al., 2007; Perrin et al., 1994; Trippel et al., 2009). We systematically identified small, passive reflective objects that can improve the visibility of gillnets at a broad range of frequencies, i.e., for many odontocetes (SC/68B/HIM/02, Kratzer et al., 2020). In this report, we re-iterate and summarize the past work and update it with angle-dependent broadband echosounder measurements as well as results from the first pilot trials using the modified gillnets in a commercial fishery in the Black Sea.

Material and methods

We simulated the acoustic reflectivity as target strength (MacLennan et al., 2002; Mooney et al., 2004) of a wide range of materials in different shapes, sizes, and environmental conditions (**Fehler! Verweisquelle konnte nicht gefunden werden.**) using the software COMSOL Multiphysics (*COMSOL Multiphysics*®, 2018). We verified the simulation results experimentally in an acoustic tank and took sonar images using a standard SIMRAD EK60 echosounder for a qualitative comparison (SC/68B/HIM02).

Table 1: Overview of parameters and their ranges used for parameter study using COMSOL

parameter	range	unit
Frequency	1–200	kHz
Diameter (d)	0.25–60	mm
Wall thickness	1–2.8	mm
Young’s modulus (E)	0.1–10	GPa
Object density (ρ)	1000–8000	kg/m³

Salinity (Sal)	0–31	psu
Temperature (T)	0–18	°C

The angle-dependent acoustic reflectivity was measured with an EK80 echosounder in a harbour berth. Echograms of gillnets with several different numbers of spheres per m^2 (Table 2) were ensonified across a broad range of frequencies (38 kHz – 170 kHz) from three different angles (0°, 20°, 45°). Acoustic reflectivity of these gillnets was measured in area backscattering strength S_a (MacLennan et al., 2002) as well as target strength TS.

Table 2: Properties of ensonified gillnets

Name	Material	Sphere-sphere interval [cm]	Stretched mesh size [mm]	Height of net [m]	Approx. number n of spheres/m^2 [m^{-2}]	Hanging ratio
Cod Ref	Nylon	N/A	110	3.6	0	0.5
Cod 60cm	Nylon	60	110	3.6	4	0.5
Cod 40cm	Nylon	40	110	3.6	9	0.5
Cod 20cm	Nylon	20	110	3.6	25	0.5
Turbot Ref	Natural fiber	N/A	400	2	0	0.33
Turbot 35cm	Natural fiber	vertical: 37 horizontal: 35	400	2	9	0.33

A first pilot trial using acoustically reflective nets took place in the turbot fishery in the Black Sea that is characterized by seasonally high bycatches of harbour porpoises (Bilgin et al., 2018; Bilgin and Köse, 2018). A total of 10 paired hauls, each with 2000 m of standard and 2000 m of modified gillnet took place off the coast of Sinop (Figure 1) between Sept – Dec 2019. The modified gillnets were equipped with 8 mm acrylic glass spheres at a vertical distance of 37 cm and horizontal distance of 35 cm from each other, as this is considered to be the “personal space” of a harbor porpoise (Nakamura et al., 1998). The size of the acrylic glass sphere was based on the simulation results (Kratzer et al., 2020) and matches the echolocation frequency of harbor porpoises. Aside from the addition of acrylic glass spheres, the nets were identical (mesh size: 400 mm, hanging ratio 0.33, height 5.5 meshes, orange/yellow natural filament).

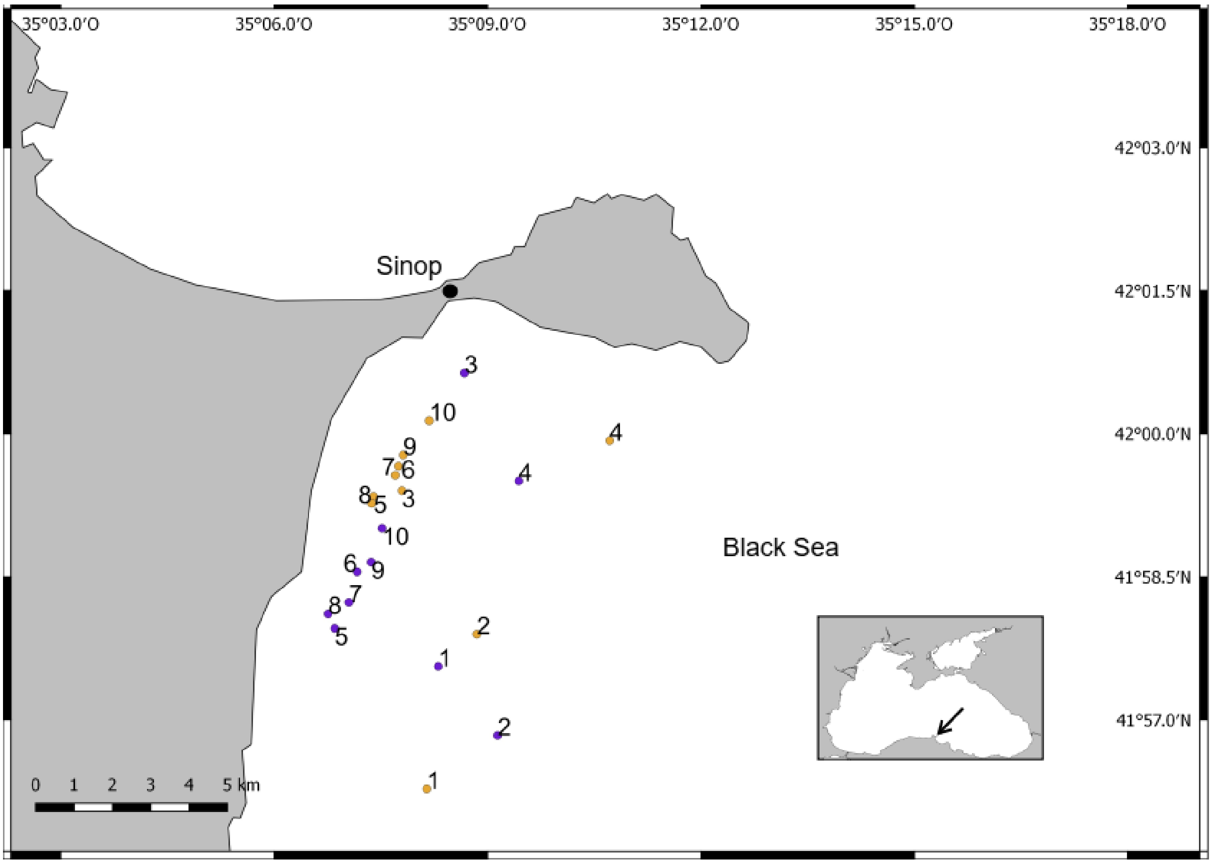

Figure 1: Study area of the 10 hauls off the coast of Sinop, Turkey. The dots mark the middle of the gillnets (purple=standard, yellow = modified).

Results

Simulation of target strength, identification of ideal passive reflector

In a first step, we simulated TS of spheres in a large range of parameters (diameter, density, elasticity) in order to narrow the parameters down to the relevant properties and combinations of size and material characteristics (SC/HIM68B/02) for different odontocetes frequencies. From these simulations, it became evident that the ideal material that could be used for reflectors smaller than 20 mm in diameter, is acrylic glass. It has a similar density as seawater, thus will likely not influence the net behavior, is transparent and thus inconspicuous to fish and, most importantly, spheres made from acrylic glass resonate when the so-called eigenfrequency of a sphere matches the ensonification frequency. The eigenfrequency is an object-specific characteristic which results from geometric properties (diameter) and mechanical properties (density, elasticity). This means, that the echolocation frequency of different odontocetes species matches a certain diameter of acrylic glass sphere, resulting in a design guide for many odontocetes (Figure 2). The results were confirmed by measuring the target strength of two acrylic glass spheres (6.4 mm, 9.6 mm diameter) as well as reference objects (table tennis ball, steel ball). At 130 kHz, the acrylic glass spheres had similar TS values as the reference objects, despite being substantially smaller (Figure 3).

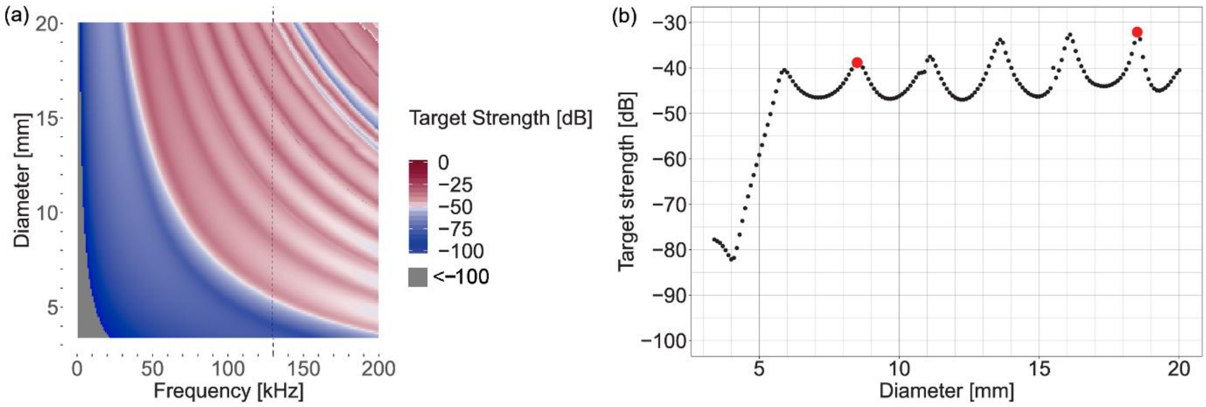

Figure 2: Target strength of acrylic glass spheres across frequency range (x-axis) and different sizes (y-axis); the white areas are values of -50 dB, the target strength of a gillnet (Kastelein et al., 2000) (a). Target strength of acrylic glass spheres exemplarily at 130 kHz, the echolocation frequency of harbor porpoises (b). The dashed line in (a) shows the cross-section displayed in (b). Red dots mark the maximum target strength values of spheres below 10 mm and 20 mm, respectively.

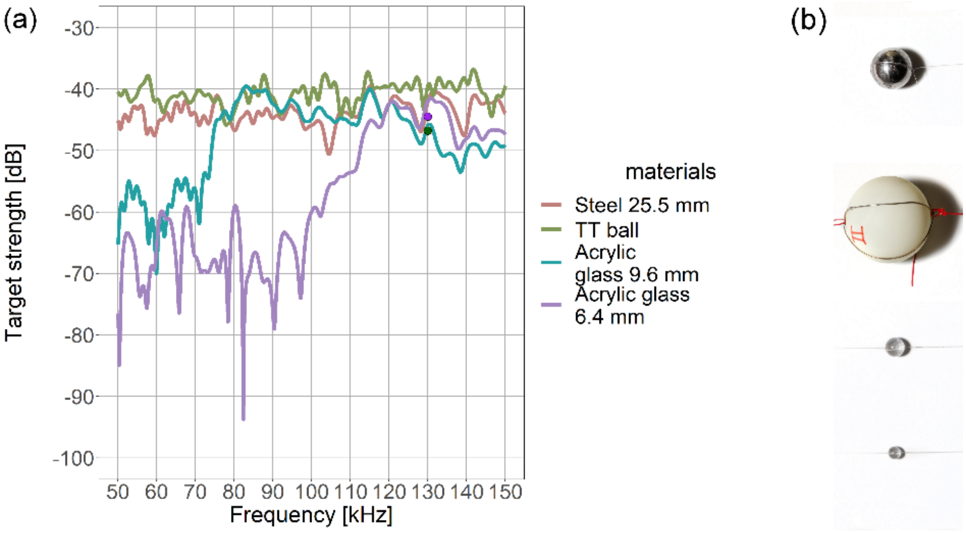

Figure 3: Target strength values (a) of various measured objects (b) of different materials. Dots in (a) indicate the corresponding simulated values at 130 kHz.

The simulation of thin filaments as a proxy for gillnets showed that increasing the density of filaments is not going to substantially change the TS (SC/68B/HIM02). The only potential increase in TS is given for very elastic filaments, however, these often do not have a high tensile strength, making them unsuitable as gillnet material.

Angle-dependent acoustic reflectivity of modified gillnets

Following the determination of the optimal acoustic reflector (acrylic glass sphere), the acoustic reflectivity of gillnets with different numbers of spheres per m² from different angles was determined. The acoustic reflectivity was determined qualitatively in terms of the spatial distribution of echoes in the acoustic beam (echograms, Figure 4 exemplarily for the 120 kHz transducer) as well as quantitatively by determining area backscattering strength (Figure 5 a, b) and target strength (Figure 5 c, d) from the echograms. The area backscattering strength and TS were determined for each single frequency as well as the frequency range 120 – 140 kHz, which corresponds to the echolocation frequency range of harbor porpoises (Møhl and Andersen, 1973; Villadsgaard et al., 2007), the odotontocete that this gillnet modification is designed for. Gillenets equipped with acrylic glass spheres have a substantial increase in acoustic reflectivity, both in terms of area backscattering strength and target strength. Additionally, the acoustic pattern in the echolocation beam is changed and appears as a barrier in the acoustic beam.

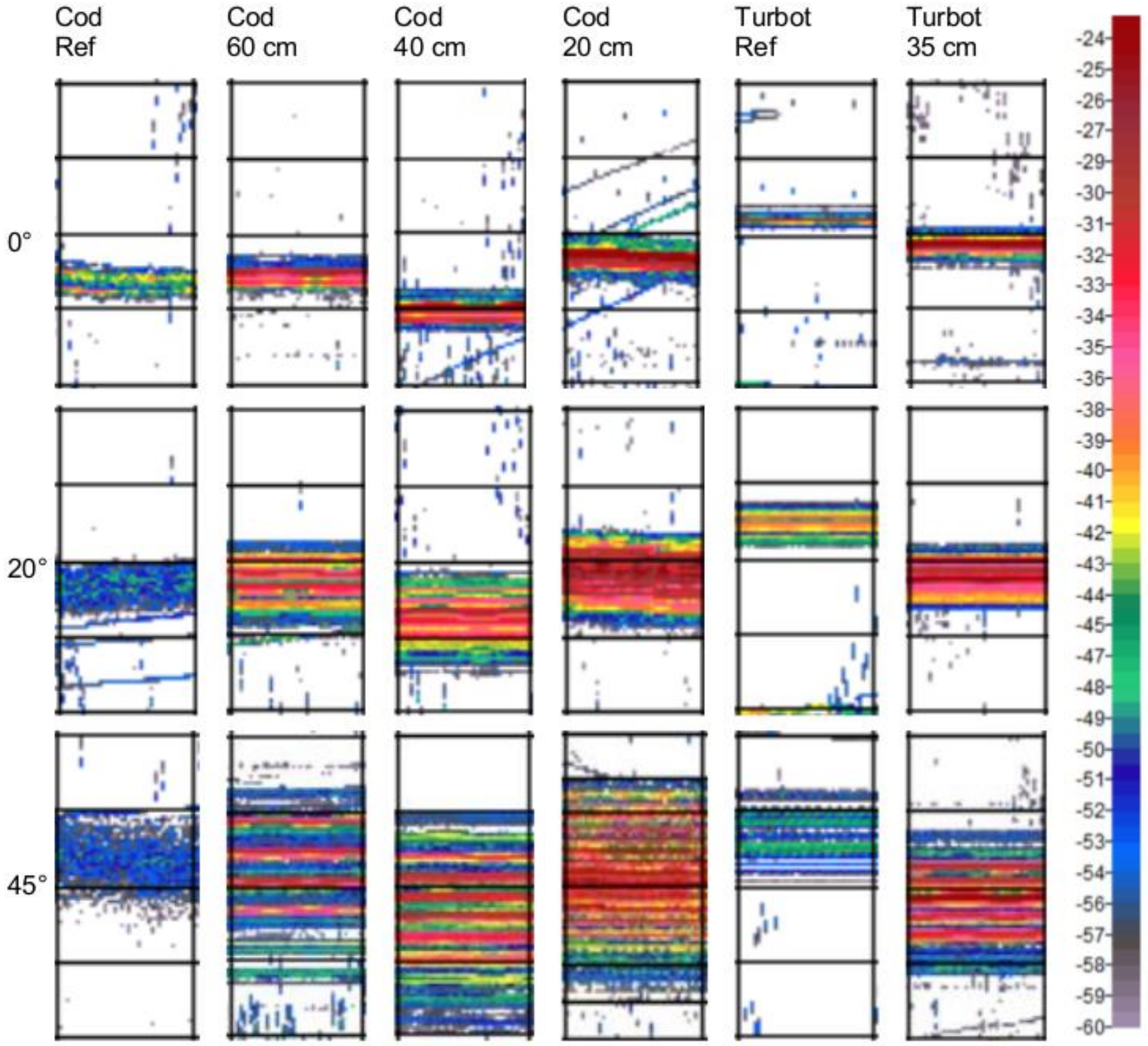

Figure 4: Echograms of standard („Ref“) gillnets and gillnets modified with different sphere-sphere intervals from three different ensonification angles (0°, 20°, 45°) using the 120 kHz transducer. Echo strength is depicted in S_v [dB] (grey: low echo, red: strong echo, see color scale). The spheres become clearly visible as red rows, especially at 45° inclination. Small echoes around the gillnet are noise or small fish – these data points were excluded from the analysis.

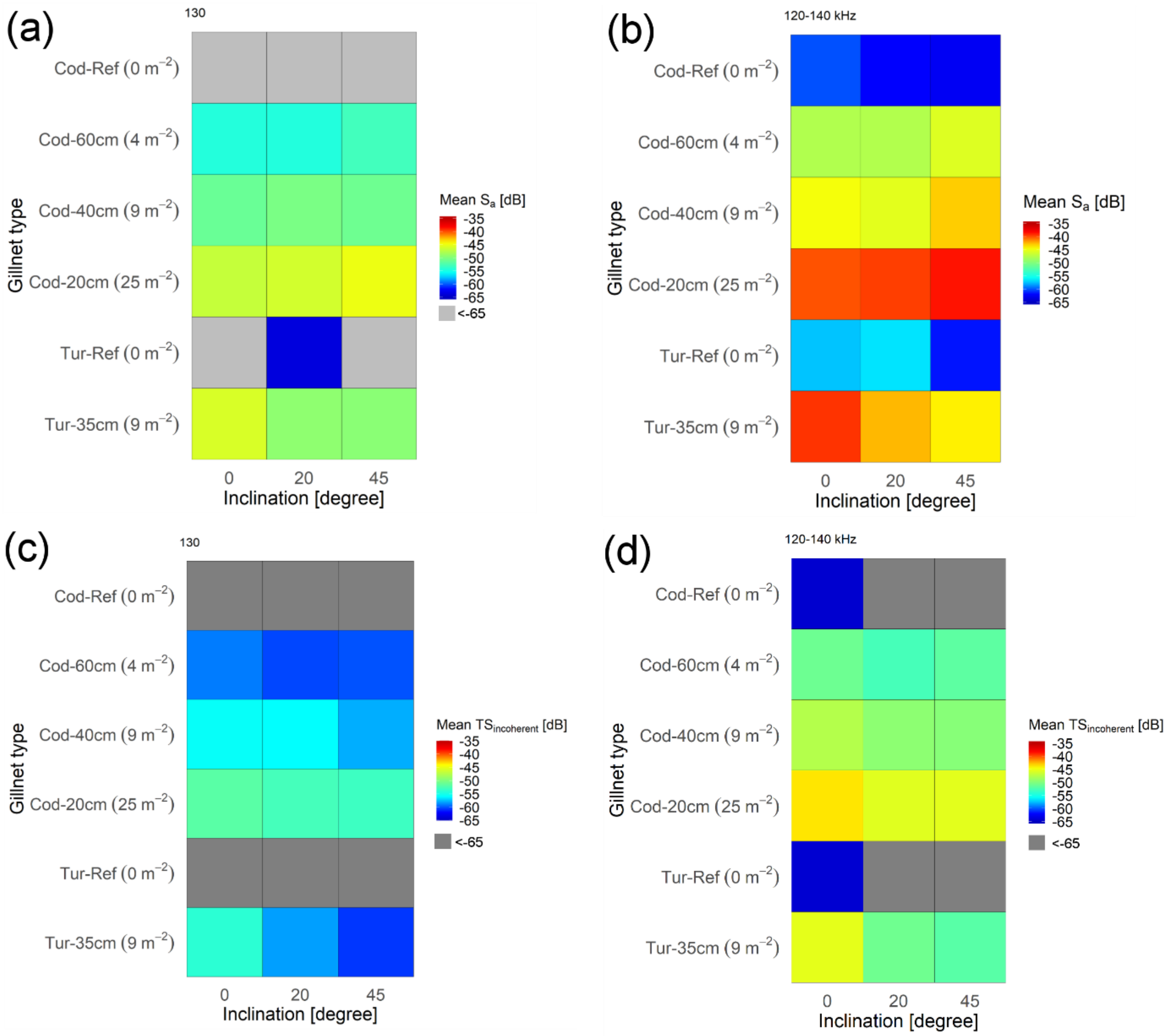

Figure 5: S_a values (a, b) and incoherent TS values (c, d) of all measured gillnets (number of spheres per m² in brackets) at 130 kHz (a, c) and in the frequency range 120 – 140 kHz (b, d).

First pilot trials of an acoustically visible gillnet in a commercial fishery

To test the effect of an acoustically visible gillnet on the bycatch of harbor porpoises as a model species as well as to investigate the practical handling of a new fishing gear, 10 paired hauls were carried out in the commercial turbot fishery in Sinop, Turkey.

The most commonly caught fish was thornback ray (*Raja clavata*, 193 individuals) with no significant difference between standard and modified gear. Only 4 specimens of the target species Black Sea turbot (*Scophthalmus maeoticus*) were caught. The catch efficiency for bottom-dwelling species did not seem to be compromised by the attachment of acrylic glass spheres.

In total, seven harbour porpoises were caught, five in the standard net and two in the modified gillnet (Figure 6). Possibly due to the low number of hauls, no statistical difference could be determined, as a power analysis showed that with the given bycatch rate, 130 hauls would be needed to determine a difference with 80% power.

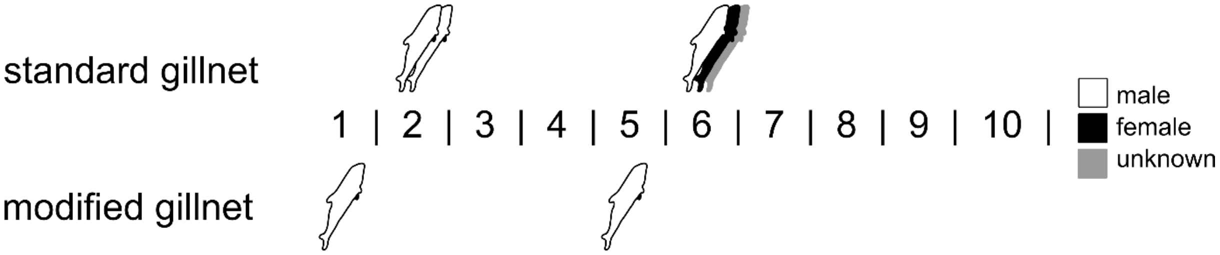

Figure 6: Overview of the bycaught harbor porpoises during the ten hauls (numbers) in the Black Sea. Animals are shown by gear and sex.

The handling of the gear revealed some areas of improvement. Most importantly, the initial preparation of the gillnets was done by hand, i.e. the spheres were individually glued to the gillnet. For larger trials to confirm the promising results regarding the bycatch reduction potential, there is the need to develop an automated process to equip gillnets with acrylic glass spheres. The fishers faced some issues with both the standard net and the modified net, e.g. the nets become entangled and wrapped around the headline as they pass the pulleys of the hauler. Changing the headrope from a twisted rope to a braided rope could mitigate this issue. Furthermore, the clearing of the nets is done by hand after each haul, which can take up to five days, depending on the amount of litter and seaweed. An automated net stacker, as often used on, e.g., Danish and German vessels, could greatly facilitate this process.

Discussion

Creating sustainable ways to reduce species loss while maintaining provisional ecosystem services can be a challenge. Previous work to reduce the bycatch of toothed whales (odontocetes) includes time and area closures (Gormley et al., 2012; Murray et al., 2000), the use of acoustic deterrent devices (pingers), and experiments with supposedly acoustically enhanced nets (Bordino et al., 2013; Dawson et al., 2013; Kraus et al., 1997; Larsen et al., 2007; Larsen and Eigaard, 2014; Mangel et al., 2013).

Here, in order to expand the portfolio of technical measures to reduce bycatch of toothed whales, we systematically explored the acoustic properties of a wide range of gillnet filaments, as well as a range of objects that could be added to gillnets to enhance their acoustic detectability. We identified species-specific resonators that might increase the TS of gillnets and thus potentially increase the detection distance for odontocetes. The modifications might not only let odontocetes detect gillnets earlier, but also make the gillnets appear as objects they cannot swim through, if mounted properly.

Based on the requirements omnidirectionality, small size, neutral buoyancy and strong echo we identified acrylic glass spheres as the optimal reflector, which also has further advantages like transparency, availability and a low water absorption coefficient (SC/68B/HIM02).

Other polymer materials could also be used as acoustic targets, but are not considered further in this work. Therefore, the acoustic properties of targets made of these materials need further investigation.

We also showed that changing the filament itself is not going to increase the acoustic reflectivity of the gillnet, as there is a size threshold that limits the interception of acoustic energy. If objects are too small in diameter, the acoustic wave bends around the object rather than being reflected (Medwin and Clay, 1998).

Following the simulations, the acoustic reflectivity of gillnets with different sphere patterns was tested in a harbor berth. The echograms revealed distinct patterns when gillnets are equipped with acrylic glass spheres, even at relatively large (60 cm) distances. As the gillnets were inclined relative to the transducer, the acoustic reflectivity of some gillnets with spheres increased, while the acoustic reflectivity of the standard nets decreased, similar as in other experiments (Au and Jones, 1991; Kastelein et al., 2000; Mooney et al., 2004). The increase in reflectivity of gillnets with spheres is likely a result from more simultaneously ensonified targets, resulting in the addition of the reflectivity of the single spheres. The increase in absolute reflectivity as well as the improvement in acoustic pattern shows that the barrier effect of gillnets with acrylic glass sphere could be achieved from any angle of approach.

The first pilot trial of the gillnets with acrylic glass spheres in the commercial fishery revealed promising, but not ultimately conclusive results. While a bycatch reduction was achieved when using the gillnets with acrylic glass spheres, the low number of hauls hampers drawing a statistically robust conclusion. Further trials on a larger scale are needed to confirm the bycatch reduction potential.

The trials also show that also using acoustically visible nets cannot eliminate bycatch entirely. One reason why harbor porpoises still entangle in acoustically visible nets could be that their narrow echolocation beam (Koblitz et al., 2012) is not directed towards the net due to distraction (Kastelein et al., 1995) or bottom-grubbing (Lockyer et al., 2001), or they are swimming in silence (Linnenschmidt et al., 2013; Wright et al., 2017). Early research has suggested to combine a “wake-up call” with acoustically visible nets to most effectively reduce bycatch in gillnets (Goodson, 1997). For harbor porpoises such a device could be a PAL (PorpoiseALert), a device that has shown to reduce bycatch of harbor porpoises in the Western Baltic Sea (Chladek et al., 2020) and increases the echolocation rate of harbor porpoises (Culik et al., 2015). Combining PAL and gillnets with acrylic glass spheres has a promising potential to be a technical mitigation effort to effectively reduce bycatch of harbor porpoises.

The next steps would be:

a) a behavioral experiment observing odontocetes around gillnets with and without acrylic spheres with and without a wake-up call (scheduled summer 2021)
b) a larger-scale fishing trial using acoustically visible gillnets to confirm the bycatch reduction potential
c) the development of an automated process to produce gillnets with acrylic glass spheres

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