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Gillnet modifications to reduce bycatch of harbor porpoises

Ph.D. thesis by Isabella Maria Friederike Kratzer

January 2018 – January 2021

National Institute of Aquatic Resources (DTU Aqua), Technical University of Denmark

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„Also wollmer mal so sagen, vor 40 Jahren, da hätt sich keiner um den Beifang gekümmert. (…) Die ganze Welt ist im Umbruch und das is natürlich wichtig, dass man das schützt alles. Und es ist auch wichtig, dass man sich da Gedanken macht. Kein Mensch will ein Schweinswal fang', Kein Mensch will ne Kegelrobbe fang', Kein Mensch- oder kein Fischer will irgendwas fangen."

„But, let's say, like 40 years ago, nobody would have cared about bycatch. (…) The whole world is changing and it's of course important that you protect all that. And it's also important to think about it. No one wants to catch a harbor porpoise, No one wants to catch a grey seal, no one- or no fisher wants to catch anything."

Barz (2019) - Interview with fisher „Pinie"

PREFACE

The present thesis was submitted in partial fulfilment of the requirements for obtaining a Doctor of Philosophy (Ph.D.) degree. The thesis consists of a synopsis and three supporting papers. When submitted, one paper was published and two were under review.

The work took place at the National Institute of Aquatic Resources (DTU Aqua) in the Section for Ecosystem Based Marine Management in Lyngby (Denmark) of the Technical University of Denmark, as well as at the Thünen Institute of Baltic Sea Fisheries (Thünen-OF) in the Working Group Fisheries and Survey Technology in Rostock (Germany), from January 2018 to January 2021. During my thesis, I had the opportunity to participate and present at two meetings of the ICES Working Group on Fishing Technology and Fish Behaviour (WGFTFB) in Hirtshals (2018) and Shanghai (2019). Together with Lotte Kindt-Larsen (DTU) and Peter Ljungberg (SLU), I co-chaired a Topic Group on "Passive Gears" at WGFTFB in 2019. I was furthermore granted the opportunity to present parts of my thesis at the ICES Annual Science Conference (Hamburg, 2018) and the World Marine Mammal Conference (Barcelona, 2019).

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I would like to thank my colleagues at WTD71, Ingo Schäfer and Arne Stoltenberg, for their help, time and hard work in conducting the simulations and acoustic measurements. Thank you to Micha Dähne, all volunteers and Master students who stood hours and hours on a cliff – rain or shine – to look for harbor porpoises in Fyns Hoved. Many thanks to the fishers, as well as my friends and colleagues in Turkey, Sabri Bilgin and Süleyman Özdemir, and their families for their hard work and amazing hospitality – *teşekkür ederim*!

A thousand times thank you to my family: *mille grazie* to my mum for the love of the sea and *tausend Dank* to my dad for the love of fish, and both of them for always believing in me. I cannot thank enough Serena, Tom, Maria and Elisa for their encouragement. This thesis would not have been possible without the help of many friends: many thanks go to the *Dänische Delikatessen* Steffi and Fanny for endless support through all ups and downs, my *Urlaubsteam* Mone, Maggie and Susi for sticking through it with me for more than 15 years, Helen and Vincent for always providing a place to get away, Heie, Mathias, Henning and Hannes for the laughs and the worst jokes in the world, the *lady*fest Rostock gäng* for making sure there's more to life than science, Maria for our beer-brewing adventures, my flatmates (including four-legged and furry) for making our house our home and Steffan for the listening skills. And lastly, infinite thanks to Silvi: thank you for all the adventures, the fun, your encouragement, your patience, and most of all for putting things into perspective.

TABLE OF CONTENTS

SUMMARY (ENGLISH)

Gillnets are passive fishing gears that belong to the oldest and most frequently used gears worldwide, providing income and food for millions of people. They are most used in small-scale and artisanal coastal fisheries and operated from small boats often less than 12 m in length. Gillnet fisheries provide approximately 20% of the global catch of consumption fish. Gillnets are easy to handle, very fuel efficient due to their passive nature, have almost no impact on the sea bottom and are very size selective. The operating principle is very simple: a net is set vertically in the water column like a curtain, marked with buoys on the water surface and left to soak for a given time. Fish do not see the very thin filaments of the netting and get entangled. To obtain the catch, the net is hauled in and fish are removed. Often, the net is directly set again afterwards. The main drawback of gillnets is the incidental bycatch of marine megafauna, including small toothed whales (odontocetes) like harbor porpoises (*Phocoena phocoena*). Several populations of odontocetes are classified as "endangered" with bycatch playing a major role among other reasons. Odontocetes echolocate at high frequencies, but seem to be unable to sufficiently classify gillnet netting as impenetrable barriers, i.e. they entangle and drown. Increasing the acoustic detectability of gillnets for odontocetes by making the netting highly acoustically visible could reduce the bycatch of harbor porpoises and other odontocetes, given that the animals actively echolocate in the direction of the net. Within this thesis, an optimal acoustic reflector was systematically identified (**Paper I**), the acoustic properties of gillnets were determined for various gillnet modifications using this optimal reflector (**Paper II**) and a first commercial trial to assess the effect of the reflectors on bycatch of harbor porpoises was carried out (**Paper III**).

In **Paper I**, optimal acoustic reflectors that substantially increase the acoustic reflectivity of gillnets were identified across a large frequency range, and thus for many odontocetes species, through a systematic simulation study. Best results were achieved for small acrylic glass spheres. The simulation results were experimentally verified for selected objects in an acoustic tank. A single acrylic glass sphere of approximately 8 mm in diameter has almost the same acoustic reflectivity as an air-filled table tennis ball which is five times larger in diameter and gives a very strong echo. A single sphere also has a higher or equal acoustic reflectivity as the area of a gillnet at 130 kHz, the echolocation frequency of harbor porpoises. The spheres have

almost the same density as seawater, should thus be almost neutrally buoyant and hence not significantly influence the hydrodynamic properties and catch efficiency of the modified gillnet.

Paper II describes the angle-dependent acoustic properties across a large frequency range of a nylon gillnet and a gillnet made from natural fiber, and modifications of these gillnets. The nets were modified with different numbers of acrylic glass spheres per m^2 of netting. Acoustic reflectivity was quantified in terms of area backscattering strength (S_a) and target strength (TS). Acoustic spatial patterns were visualized in echograms. Gillnets modified with acrylic glass spheres have a higher acoustic reflectivity than the standard nets, even when equipped relatively sparsely with acrylic glass spheres. The standard nets become less acoustically visible when ensonified from an angle, while the gillnets equipped with spheres largely stay equally visible or become even more visible with increasing inclination. Furthermore, the spheres create a clear spatial pattern that could aid harbor porpoises to perceive the gillnets as impenetrable barriers.

In **Paper III** the first pilot fishery trial using a gillnet equipped with acrylic glass spheres was carried out in the Turkish Black Sea turbot fishery to quantify the efficacy of bycatch reduction of the modified gillnet. Ten pairwise hauls were carried out, each with a modified and a standard gillnet. The gillnet with acrylic glass spheres caught less harbor porpoises than the standard gear (2 vs. 5 animals) and there was no difference in catch of demersal species such as thornback ray (*Raja clavata*) or turbot (*Scophthalmus maeoticus*). As only ten hauls were carried out, there was low statistical power and the difference in bycatch of harbor porpoises was not statistically significant. Nevertheless, the results are a promising step forward and form the basis for further improvement and upcoming large-scale fishery trials.

RESUMÉ (DANSK)

Garn er passive fiskeredskaber, der hører til blandt de ældste og mest brugte redskaber i Verden og som giver indtjening og mad til millioner af mennesker. De bliver mest brugt i småskala, kystnært fiskeri og anvendes typisk fra småbåde, der oftest er under 12 m. Garnfiskeri står globalt for omkring 20% af konsumfiskeriet. Garn er nemme at håndtere, meget brændstoføkonomiske grundet deres passive natur, har næsten ingen påvirkninger af havbunden og er meget størrelsesselektive. Garnfiskeri er meget enkelt at udføre: garnene sættes lodret i vandet som et gardin, markeret med bøjer på havoverfladen, og fisker i en bestemt periode. Fisk kan ikke se de meget tynde tråde på garnene og bliver viklet ind i maskerne. Garnene hales ind og fiskene kan fjernes. Ofte bliver garnene sat igen med det samme på samme sted. Den væsentligste ulempe ved garnfiskeri er den utilsigtede bifangst af marin megafuna omfattende bl.a. små tandhvaler som marsvin (*Phocoena phocoena*). Flere populationer af tandhvaler er truede bl.a. på grund af bifangst. Tandhvaler ekkolokaliserer med høje frekvenser, men synes at være ude af stand til at klassificere garn som uigennemtrængelige forhindringer, hvilket medfører at de bliver viklet ind i garnene og drukner. Øgning af garnenes akustiske synlighed ved at gøre netmaskerne akustisk meget synlige kunne reducere bifangsten af marsvin og andre tandhvaler, forudsat at de aktivt ekkolokaliserer mod garnene. I denne afhandling identificeres systematisk en optimal akustisk reflektor (**Paper I**), garns akustiske egenskaber ved forskellige modifikationer med den optimale reflektor bestemmes (**Paper II**), og en første afprøvning i et kommercielt fiskeri blev gennemført for at vurdere effekten af reflektorerne på bifangsten af marsvin (**Paper III**).

I **Paper I** identificeredes gennem systematisk simulering over et stort frekvensområde, og dermed for mange arter af tandhvaler, en optimal akustisk reflektor, der meget væsentligt øger garns akustiske reflektivitet. Bedste resultater opnåedes med små kugler af akrylglas. Resultaterne af simuleringerne blev eksperimentelt efterprøvet for udvalgte objekter i en akustisk tank. En enkelt akrylglaskugle med en diameter på c. 8 mm har nærved samme akustiske reflektivitet som en luftfyldt bordtennisbold med en fem gange større diameter, og giver et meget stærkt ekko. En enkelt kugle har samme eller højere akustiske reflektivitet som et garn ved 130 kHz, som er den frekvens marsvin ekkolokaliserer ved. Akrylglaskuglerne har næsten samme vægtfylde som havvand, har derved næsten neutral opdrift og burde

derfor ikke i væsentlig grad påvirke de modificerede garns hydrodynamiske egenskaber eller deres fangsteffektivitet.

Paper II beskriver hvordan de akustiske egenskaber for nylongarn, garn fremstillet af naturlige fibre og modifikationer af disse to typer garn ændrer sig afhængigt af indfaldsvinkel over et stort frekvensområde. Garnene var modificerede med forskelligt antal akrylglaskugler pr. m² garn. Akustisk reflektivitet blev kvantificeret som 'area backscattering strength' (S_a) og 'target strength' (TS). Rumlige akustiske mønstre blev visualiseret med ekkogrammer. Garn modificeret med akrylglaskugler havde en højere akustisk reflektivitet end standard garn, selv når der var relativt få akrylglaskugler pr. m² garn. Standardgarnene bliver mindre synlige når de akustiske signaler ikke er vinkelrette på garnene, mens garn med akrylglaskugler forbliver lige synlige eller endda bliver mere synlige med indfaldsvinkler under 90 grader. Desuden danner akrylglaskuglerne et klart rumligt mønster, som kan hjælpe marsvin til at opfatte garnene som en ugennemtrængelig barriere.

I **Paper III** beskrives det første pilotforsøg i et kommercielt fiskeri med garn modificeret med akrylglaskuglerne, udført i fiskeri efter pighvar i Sortehavet, for at kvantificere effekten af de modificerede garn på bifangsten af marsvin. Ti parvise garnrøgtninger blev gennemført, hver med et modificeret og et standardgarn. Garnene med akrylglaskugler fangede færre marsvin end standardgarnene (2 mod 5 dyr), og der var ingen forskel i fangsten af demersale arter som sømrokke (*Raja clavata*) og pighvar (*Scophthalmus maeoticus*). Fordi der kun blev gennemført ti parvise røgtninger, var der lav statistisk styrke i analyserne og forskellen i bifangst af marsvin var ikke statistisk signifikant. Ikke desto mindre er resultaterne lovende, og kan danne grundlag for yderligere forbedringer og et kommende stor-skala forsøg i det kommercielle fiskeri.

LIST OF PAPERS

Paper I: Kratzer, I.M.F., Schäfer, I., Stoltenberg, A., Chladek, J.C., Kindt-Larsen, L., Larsen, F., Stepputtis, D., 2020. Determination of Optimal Acoustic Passive Reflectors to Reduce Bycatch of Odontocetes in Gillnets. Frontiers in Marine Science 7. DOI:10.3389/fmars.2020.00539

Paper II: Kratzer, I.M.F, Stepputtis D., Santos, J., Lütkefedder F., Stoltenberg, A., Hartkens, L., Schaber, M., Kindt-Larsen, L., Larsen, F. Angle-dependent acoustic reflectivity of gillnets and their modifications to reduce bycatch of odontocetes using sonar imaging. Under Review at Fisheries Research

Paper III: Kratzer, I.M.F., Brooks, M.E., Bilgin, S., Özdemir, S., Kindt-Larsen, L., Larsen, F., Stepputtis, D. Using acoustically visible gillnets to reduce bycatch of a small cetacean: first pilot trials in a commercial fishery. Under Review at Endangered Species Research

ABBREVIATIONS

ASCOBANS	Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas
ACCOBAMS	Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area
ALDFG	Abandoned, lost or otherwise discarded fishing gear
$BaSO_4$	Barium sulfate
CMS	Convention on the Conservation of Migratory Species
dB	Decibel
EEZ	Exclusive Economic Zone
EU	European Union
EC	European Council
GPa	Gigapascal
ICES	International Council for the Exploration of the Sea
IO	Iron-oxide
IWC	International Whaling Commission
kHz	Kilohertz
MMPA	Marine Mammal Protection Act
MPA	Marine Protected Area
NBHF	Narrow Band High Frequency
NOAA	National Oceanic and Atmospheric Administration
Pa	Pascal
PBR	Potential Biological Removal
PML	Perfectly matched layer
PMMA	Polymethylmethacrylat (acrylic glass)
REM	Remote Electronic Monitoring
S_a	Area backscattering strength
s_a	Area backscattering coefficient
S_v	Volume backscattering strength
s_v	Volume backscattering coefficient
TS	Target strength
TRP	Take Reduction Plan
WGBYC	ICES Working Group on Bycatch of Protected Species

1 General Introduction

People have been fascinated with whales, dolphins and porpoises, all belonging to the order of Cetacea, for centuries. Interactions between humans and cetaceans have, for most nations, gone from active hunting to welfare and conservation (Harrop, 2003). Humans benefit from cetaceans directly through tourism (Cisneros-Montemayor et al., 2010) and indirectly through their role in keeping ecosystems, and thus ecosystems services (Millennium Ecosystem Assessment, 2005), stable. Some species of large whales have an important function in the primary production of marine ecosystems through the so-called "whale pump" (Roman and McCarthy, 2010). As top predators, the impact of cetaceans is also vital to keep ecosystems resilient (Estes et al., 2011). Despite the fact that the deliberate killing of cetaceans is now largely frowned upon, they are still under threat from many, largely anthropogenic, impacts, such as pollution, ship strikes, climate change, habitat degradation and increased underwater noise (Reeves et al., 2003; IWC, 2019). One of the biggest threats for cetaceans, particularly small toothed whales (Odontoceti), is the incidental bycatch in fisheries, especially gillnet fisheries (Reeves et al., 2013; IWC, 2018). The bycatch of small cetaceans in gillnets has been recognized as an emerging problem by the International Whaling Commission (IWC) already in the 1970s (IWC, 1972). Species that inhabit the coastal waters like, e.g., the harbor porpoise (*Phocoena phocoena*), are especially prone to bycatch when their habitat overlaps in space and time with the fishing grounds of small-scale gillnet fisheries (Jefferson et al., 2008; Kindt-Larsen et al., 2016). Harbor porpoises are a protected species covered by the U.S .Marine Mammal Protection Act (MMPA, 1972), the Appendix II of the Bern Convention (Bern Convention, 1979), the Appendix II of the Convention on Conservation of Migratory Species (CMS, 1979) and the Annex II and IV of the Habitats Directive (EC, 1992, 43), making deliberate killing of these animals illegal and giving them a status of special protection. There are several national and international agreements to preserve this species, especially from anthropogenic impacts, with repeated calls to tackle the issue of bycatch (ASCOBANS, 1992; NMFS and NOAA, 1998; ACCOBAMS, 2001). There is urgent need for mitigating the conflict between nature conservation and gillnet fisheries, to be able to preserve odontocetes species, but also to provide fish as a protein source and income for millions of people around the world (Waugh et al., 2011; Suuronen et al., 2017; Thomas et al., 2020).

2 GILLNET FISHERIES

Gillnet fishing is one of the oldest fishing methods worldwide. Fishing with nets dates back to at least 6000 B.C. on the Peruvian coast and remains of net sinkers on nets found in Mesopotamia have been dated back to 5000 B.C. (Sahrhage and Lundbeck, 1992). Gillnets are a stationary operated gear and were made from natural fibers like cotton and hemp until the introduction of nylon that led to the industrialization of gillnet fisheries in the 1950s and 1960s. Gillnet fishing became highly efficient due to the low cost of nylon nets, the prolonged durability of the new material, the increase in catch efficiency caused by the material characteristics of nylon, and the increasing availability of mechanized haulers (Pycha, 1962; Potter and Pawson, 1991). The low maintenance costs and ease of handling led to a wide application of gillnets and they now belong to the most commonly used passive fishing gears worldwide (He, 2006).

2.1 Distribution and operation

Despite being a widespread gear, the use of gillnets is characteristic for small-scale fisheries that often operate from small boats, fishing close to the coast (Chuenpagdee et al., 2006; Shester and Micheli, 2011). These boats make up a large part of the fleet in many countries. Globally, approximately 20% of the landed catch caught in the EEZ (Exclusive Economic Zone) is caught in gillnets with great variability between countries (Waugh et al., 2011). In Germany, almost 80% of the vessels are less than 12 m in length and mainly operate static nets in the Baltic Sea (Anon, 2018). Approximately 30% of the professional vessels in Denmark are listed as “gillnetters” (Landbrugs- og Fiskeristyrelsen, 2017) and landed more than 5000 t of flatfish and roundfish in 2015 (Savina, 2017). Almost all of these vessels are less than 12 m in length. According to the European fleet register, approximately half of all registered vessel in the European Union (EU) list gillnets as their primary gear; 90% of these vessels are less than 12 m in length (EC, 2020).

2.2 Description of fishing gear and fishing process

Gillnets are panels of netting that make up a wall-like structure. They are commonly made from very thin twine attached to a lightweight line at the top (often termed “floatline” or “corkline”) and a heavyweight line at the bottom (often termed “leadline”). The leadline is often longer than the floatline to facilitate the entanglement of fish. Gillnets can be set as bottom-set gillnets, driftnets, trammel nets, fixed nets and encircling nets (He and Pol, 2010). Bottom-set gillnets are usually set standing on the bottom and raise vertically in the water column like a curtain (Figure 1) and are almost invisible to fish due to the properties of the twine.

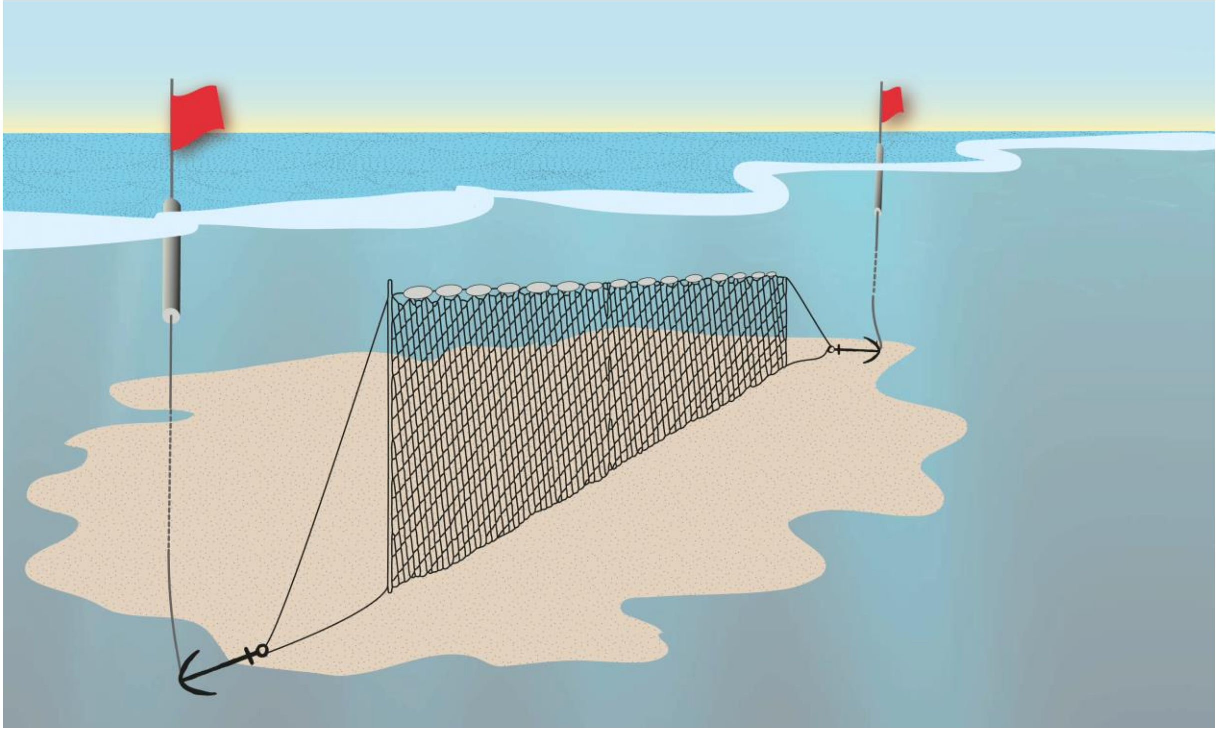

Figure 1: Schematic drawing of a gillnet (floatline with individual floats on top, leadline on the sea bottom) including marker buoys (flags) and anchors

Several net panels strung together form a gillnet fleet. The order in which a fleet is set out, is typically as follows: buoy – anchor – net(s) – anchor – buoy. A buoy marks the start and end of the fleet, the anchors keep the net in place. The fleet is set from the back or the side of a vessel (Figure 2 a). Additional anchors and buoys may be set along the nets if the fleet is very long. After setting, the fleet stays in place for a certain soak time and is then hauled again either by hand or using a hydraulic hauler (b). Fish are picked from the net and the net is often set again right after being cleared.

(a) (b)

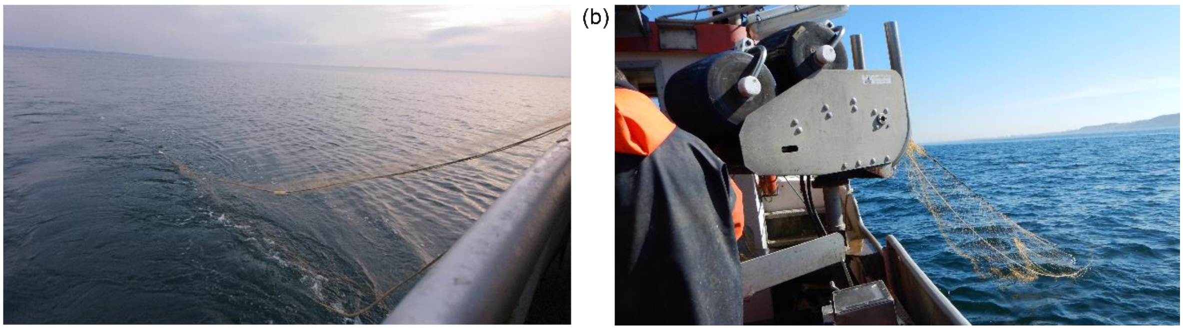

Figure 2: Setting from the back of the vessel (a) and hauling of a gillnet with a hydraulic gillnet hauler (b)

Depending on the target species and the environmental conditions, such as water temperature or time of day, the soak time can vary between a few hours (Tregenza et al., 1997) and several days (Kennedy et al., 2019; **Paper III**). Soak time and movement patterns of available fish determine the fishing area of a gillnet, i.e. the area in the vicinity of the gillnet in which fish are available for capture during the soak time (He, 2003). One of the most influential parameters is water temperature, as it influences the movement of fish making them thereby more or less vulnerable to gillnets (He and Pol, 2010).

Fish encountering the netting can be caught in four ways: gilling, wedging, snagging and entangling (He and Pol, 2010). When gilled, the fish is caught with the net behind the gill cover. Wedging means that the fish is caught by the largest part of the body. Snagging means the fish is caught by the teeth or mouth. A fish is said to be entangled when it is wrapped in the meshes usually after struggling to escape, and often after being captured in one of the above mentioned ways (He and Pol, 2010).

The filament type and diameter will determine how flexible and elastic the netting is and thus influence the likelihood of a fish getting caught. The filament diameter and number of filaments in the twine of the netting depends on the target species. It can be as low as 0.15 mm when, e.g., pikeperch is targeted (Turunen, 1996) and more than 1 mm when shark is targeted (Walker et al., 2005; Lucchetti et al., 2020). While there is a negative relationship between catch efficiency and the ratio between twine thickness and mesh size for some species (Hovgård, 1996), likely reaching a minimum, thinner twine can cause the netting to be more easily damaged and lead to more bycatch of, e.g., unwanted crustaceans (He and Pol, 2010), potentially resulting in decreased fishing time due to more effort in clearing the netting and increased costs. Both monofilament and multifilament twines are used, as well as a mixture between the two called multimono filament. Multimono-filament carries the advantages of monofilament and multifilament without their respective weaknesses, as they are very flexible while having a high tensile strength (Dahm, 1986).

Another important feature of a gillnet is the hanging ratio, defined as the ratio between the horizontal set length of the net and the horizontal stretched length of the net (Hovgård and Lassen, 2000). The hanging ratio determines the shape of the mesh during the fishing process, influences the flow properties through the netting and hence affects the behavior of the net underwater. The floatline and the leadline (Figure 3) determine the amount of hydrostatic uplift and downforce, respectively, and further influence the behavior of the net underwater. Both, hanging ratio and the type of floatline and leadline, are associated with the catch efficiency (Angelsen et al., 1979; Machiels et al., 1994). The netting color is often a matter of personal choice of the fisher, but there is evidence that it affects the catch rates of some species (Hamley, 1975; Hovgård and Lassen, 2000; Balık and Çubuk, 2001; Orsay and Dartay, 2011).

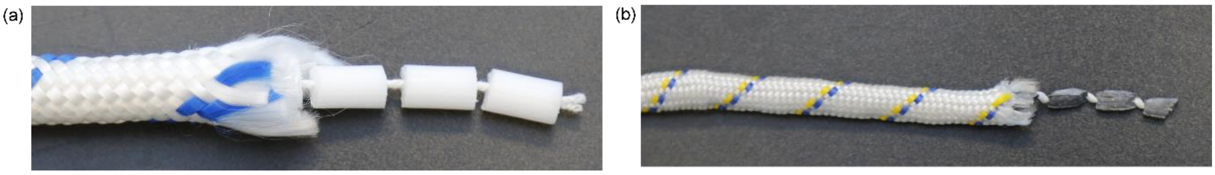

Figure 3: Floatline with foam elements for uplift (a) and leadline with weights for downforce (b) as often used in European fisheries

All of the above mentioned characteristics (twine type and twine diameter, hanging ratio, type of floatline and leadline, netting color, mesh size) influence the catch efficiency and selectivity of gillnets (Hamley, 1975). Every fishing gear selects a certain part of the available fish populations and selectivity is the term for the quantification of this selection process (Wileman et al., 1996). Usually, selectivity curves refer to size selectivity, i.e. the probability that a fish of a given size is retained in a gear. Where selectivity of gillnets is concerned, the mesh size is the most influential factor, as gillnet selectivity largely follows the Baranov's principle of geometric similarity (Baranov, 1948), albeit that this principle does not capture the entire selection process, as it does not account for other effects, such as fish behavior or net saturation effects (Hamley, 1975). Gillnet selection curves are usually bell-shaped with one or two modes (Figure 4), i.e. one or two maxima in the probability of capture of a fish of a given size, depending on the catch process (Hamley and Regier, 1973). Smaller fish can escape through the meshes and larger fish cannot penetrate the mesh far enough to be caught, as their girth in the head region is much larger than the perimeter of the mesh (Hovgård and Lassen, 2000). The shape of the curve is influenced by the body shape of the fish, i.e. deep-bodied fish will have a narrower selection curve than slender fish where the selection curve will be less sharp (Hamley, 1975). Selectivity curves that are skewed to the right represent a larger portion of tangled fish compared to narrow selection curves, where most fish are gilled (Hamley, 1975). The narrower the curve, the smaller the size range of fish captured. The mesh size of gillnets for commercial purposes varies with target species and ranges from 32 mm stretched mesh size in the Baltic

Sea herring fishery (MLU MV, 2006) to 400 mm stretched mesh size in the turbot fishery in Turkey (**Paper III**).

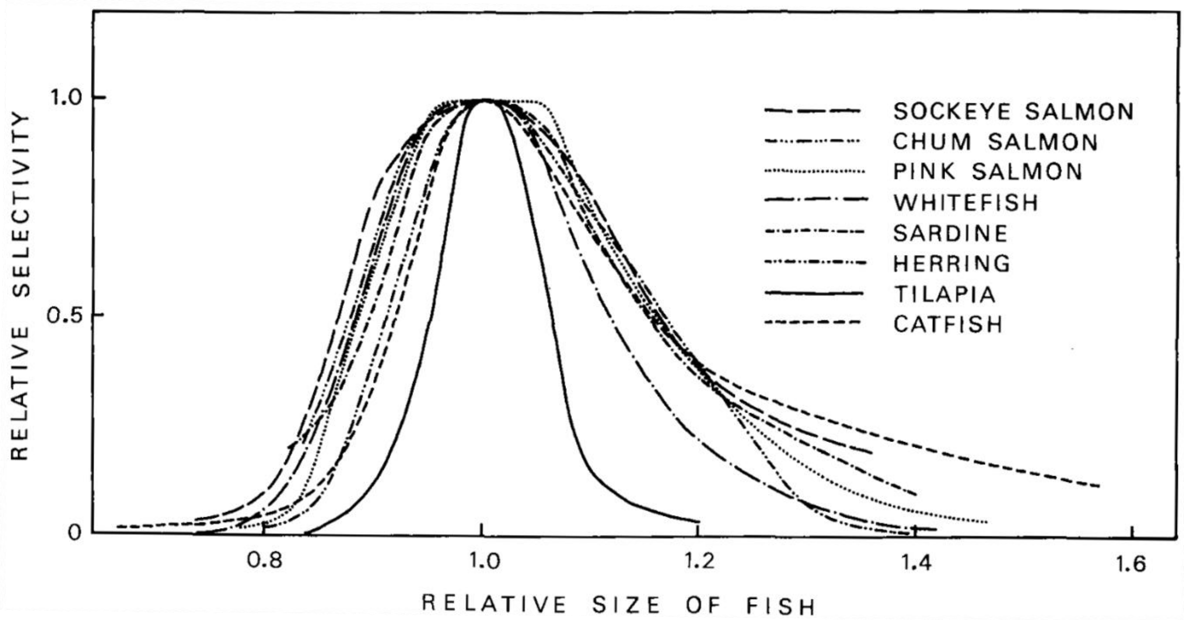

Figure 4: Indirectly estimated selectivity curves of several different fish species. All curves are standardized to the same modes and heights. Note that catfish (*Clarias mossambicus*) is skewed to the right due to the slender shape of the fish. From Hamley (1975)

2.3 Sustainability considerations

Gillnet fisheries are considered to have low carbon emissions and low sea bottom impact compared to fisheries using active gears owing to their stationary mode of operation (MacDonald et al., 1996; Suuronen et al., 2012; Savina et al., 2018).

Nevertheless, as with all fishing methods, there are environmental, social and economic impacts associated with the use of gillnets. One reason for negative impacts is the substantial food loss during gillnet fishery (Suuronen et al., 2017), which is problematic as fish are a large source of protein for millions of people as well as the basis for their income (FAO, 2020). Food loss in gillnets occurs pre-harvest and post-harvest, e.g. through depredation by marine mammals (Königson et al., 2007; Lauriano et al., 2009) and discarding (Gray et al., 2005), respectively. Poor fish quality due to catch damage potentially results in lower prices and less income (Savina et al., 2016). These issues can be addressed in several ways. Depredation by dolphins and seals is currently counteracted by using deterrent devices (Waples et al., 2013) or switching to alternative gears (Hemmingsson et al., 2008).

Gillnet fisheries

A major concern is food loss occurring in abandoned, lost or otherwise discarded fishing gear (ALDFG or ghost nets), as it can have severe impacts on both the ecological and the economic sustainability of gillnet fisheries (Suuronen et al., 2017). In the Baltic Sea, ghost nets originally used in the cod gillnet fisheries, keep a relative catch efficiency of 20% of their original level during the first three months before declining to around 6% within 27 months (Tschernij and Larsson, 2003). Fish caught in ghost nets are neither used for direct consumption, nor available for the population, thus they are uncontrolled catches and account for an additional removal of individuals from their population, e.g. up to 0.5% to 30% of the landed catch in some European and North American fisheries (Suuronen et al., 2017). Retrieval of ghost nets requires prior knowledge of the overlap between fisheries and ghost net hotspots (such as wrecks and reefs) or information from fishers where the gears were lost in order to be carried out efficiently (Egekvist et al., 2017). Detecting lost gillnets using standard echosounders is difficult due to their faint echo (**Paper II**), but the use of a high-frequency tool such as a side-scan sonar may offer an opportunity, if operated by an experienced acoustic technician (Kappenman and Parker, 2007; Link et al., 2019).

The main point of critique of gillnets is their poor species selectivity (He, 2006) and the incidental bycatch of marine megafauna, such as marine mammals, turtles and seabirds, both in gillnets classified as ALDFG (Stelfox et al., 2016) as well as in operating gillnets (Lewison et al., 2004, 2014).

Globally, almost 400,000 seabirds die in gillnets every year (Žydelis et al., 2013) posing a threat to several populations (Žydelis et al., 2009; Marchowski et al., 2020). Mitigation efforts include the modification of gillnets through the use of lights (Mangel et al., 2018; Cantlay et al., 2020), high-contrast panels or conspicuous colors of the netting (Melvin et al., 1999; Field et al., 2019), acoustic alarms (Melvin et al., 1999; Glemarec, 2020) as well as operational modifications like time-area closures (Regular et al., 2013). However, these mitigation methods have only proven to work for some species in selected fisheries. Furthermore, turtles are regularly bycaught in gillnets (Peckham et al., 2007; Alfaro-Shigueto et al., 2011). Mitigation methods with respect to turtle bycatch are reviewed in Gilman et al. (2010) and have shown promising results, especially when using green LEDs or UV-light (Wang et al., 2010, 2013). Sharks and rays are also bycaught in gillnets (Oliver et al., 2015) and mitigation methods include changes in the tension of the gillnet, i.e. increased uplift and downforce (Thorpe and Frierson, 2009), potentially the use of strobe lights (Ryan et al., 2017) and operational changes like decrease in soak time (Broadhurst and Cullis, 2020).

A major global bycatch issue in gillnet fisheries is the incidental capture of small toothed whales (Read et al., 2006; IWC, 2019). Thousands of small toothed whales across different species are killed annually in gillnets worldwide (Bordino et al., 2002; Dawson and Slooten, 2005; Perez and Wahrlich, 2005; Díaz López, 2006; Bjørge et al., 2013; Reeves et al., 2013), threatening several species to the point that they have been driven to the verge of extinction (Brownell Jr et al., 2019). One species, the baiji (*Lipotes vexillifer*), has already been eradicated mainly due to bycatch (Turvey et al., 2007) and the vaquita (*Phocoena sinus*) is likely to follow (D'agrosa et al., 2000; Taylor et al., 2017). Technical mitigation methods are reviewed in Werner et al. (2006) and Hamilton and Baker (2019) and discussed particularly for harbor porpoises in Chapter 3.4.

3 HARBOR PORPOISE

Harbor porpoises are marine mammals belonging to the order of Cetacea and suborder of Odontoceti (toothed whales). Along with the delphinidae family, they are often classified as small toothed whales as opposed to, e.g., sperm whales. Harbor porpoises have a relatively stocky body and measure around 1.6 m in length (Reeves et al., 2002) with a very dark grey back, light grey flanks and a white belly (Figure 5).

Figure 5: Harbor porpoise. Photo by Ecomare/Salko de Wolf Den Hoorn Texel/ CC BY-SA 4.0

They are elusive and shy animals that normally do not jump or even move their head out of the water (Jefferson et al., 2008). Their triangular shaped dorsal fin and typical "rolling" surfacing behavior make them identifiable in the field, if spotted during their very brief surfacing time (Figure 6).

(a)  (b) 

Figure 6: Harbor porpoises surfacing. A mother-calf pair (a) and a single harbor porpoise (b)

The life history of harbor porpoises has been described as “living life in the fast lane” with shorter life spans, earlier sexual maturity and higher reproduction rates than other cetaceans (Read and Hohn, 1995). Harbor porpoises have a high metabolic demand to maintain their body temperature in cold waters and have been documented to feed almost continuously, making them susceptible to disturbance, as their feeding can be disrupted by noise (Wisniewska et al., 2016).

3.1 Worldwide distribution and abundance

Harbor porpoises inhabit the cold and temperate coastal waters of the Northern hemisphere (Bjørge and Tolley, 2009), including the Baltic Sea (Bjørge and Donovan, 1996), Black Sea (Notarbartolo di Sciara, 2002) and Mediterranean Sea (Cucknell et al., 2016). The geographic distinction has led to a classification of three subspecies: *P. p. phocoena* in the North Atlantic, *P. p. vomerina* in the Eastern North Pacific, *P. p. relicta* in the Black Sea and an unnamed subspecies in the western North Pacific (Jefferson et al., 2008). Depending on the geographic region, harbor porpoises are abundant or part of locally endangered populations.

While abundant and stable in the North Sea and Skagerrak/Kattegat/Belt Seas (Hammond et al., 2013, 2017), the population in the Baltic Proper (Huggenberger et al., 2002; Wiemann et al., 2010; Galatius et al., 2012; Gallus et al., 2012) is under high anthropogenic pressure and has declined in the past centuries (Benke et al., 2014), leading to a classification of the harbor porpoise as critically endangered in the Baltic Sea (Hammond et al., 2008). The most recent abundance estimate suggests that there may only be 497 (95% CI 80-1,091) animals left in the Baltic Proper population (Amundin, 2016).

Both the stocks in the Eastern Atlantic (Gulf of St. Lawrence, Gulf of Main/Bay of Fundy) seem stable and are not considered “strategic” by NOAA (Dufour et al., 2010; NOAA, 2019a). Other populations in the Pacific area, specifically in U.S. and Canadian waters (Salish Sea, British Columbia), are also stable, while some Alaskan stocks are declining (COSEWIC, 2016; Elliser and Veirs, 2019; NOAA, 2019b).

The harbor porpoise subspecies in the Black Sea is listed as endangered on the IUCN Red List (Birkun and Frantzis, 2008), as the current population remains at around 10% of its original size (Fontaine et al., 2012).

3.2 Echolocation of harbor porpoises

Harbor porpoises rely on several senses to perceive their environment. Their vision is fairly well adapted to both, air and water (Kastelein et al., 1990), and chemoreception also seems to play a role (Frady et al., 1994; Wartzok and Ketten, 1999). However, hearing is their main sense of perception as light is quickly absorbed under water and hearing can still be used under murky and dark conditions. Harbor porpoises have extremely well developed hearing capabilities and orientate themselves through echolocation or biosonar, i.e. they emit acoustic signals and perceive their environment through the received echoes, as well as other sounds (Verfuß et al., 2005; Wahlberg et al., 2015). The difference in time from emission to reception lets them determine the distance to the target. All odontocetes echolocate, but the frequency of their sounds depends on the species. Harbor porpoises belong to the species of odontocetes emitting the highest frequencies (Morisaka and Connor, 2007). The advantage of high frequency clicks is the high resolution of the received echoes, thus they are able to locate small targets. On the other hand, the range of the signals is rather short, as shorter wavelengths, resulting from higher frequencies, are absorbed more quickly in water (Au, 2000).

The intense ultrasonic signals produced by harbor porpoises are narrow-band high-frequency (NBHF) short-pulsed clicks (Møhl and Andersen, 1973). The frequency of the clicks is centered around 130 kHz with a 6 – 26 kHz 3-dB bandwidth (Teilmann et al., 2002; Villadsgaard et al., 2007). Measurements of source levels differ between captive and wild harbor porpoises and range between 157 – 172 dB re 1 µPa pp @ 1 m and 178 – 205 dB re 1 µPa pp @ 1 m, respectively (Au et al., 1999; Villadsgaard et al., 2007). The duration of a click is very short, only around 44 – 113 µs (Villadsgaard et al., 2007; Clausen et al., 2011), but repeated very fast. When searching for prey, harbor porpoises click around 15 – 100 times per second, but the inter-click-interval (ICI) is reduced greatly when approaching a prey target, ending in a terminal buzz right in front of the fish where the ICI is 1.5 ms (Verfuß et al., 2009). The ICI is modulated to avoid an overlap from the echoes of the clicks, and harbor porpoises are able to adjust the amplitude when approaching a target (Atém et al., 2009). When communicating, harbor porpoises use the click repetition rate to convey behavior. Communication calls and aggressive behaviors have a significant difference in click repetition rates per second, i.e. communication calls display an upsweep in click rate, while aggressive calls are characterized by a high repetition rate only (Clausen et al., 2011).

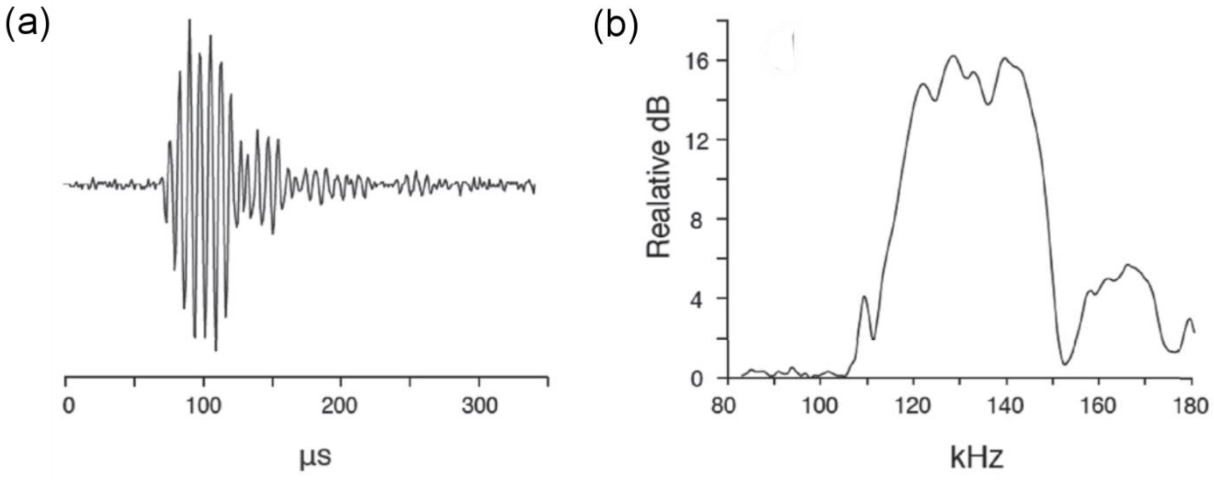

Figure 7: Harbor porpoise click shape and duration (a) and power spectrum of the click (b). Modified from Miller (2010)

The clicks are produced by forcing air through their "phonic lips" and emitted in a narrow 11 – 13° beam (Koblitz et al., 2012) through a fatty tissue in the front of the head, the melon (Figure 8). The echoes are received through the mandible and the signals are conducted through fatty tissues to the middle ear and, subsequently, to the inner ear (Miller, 2010).

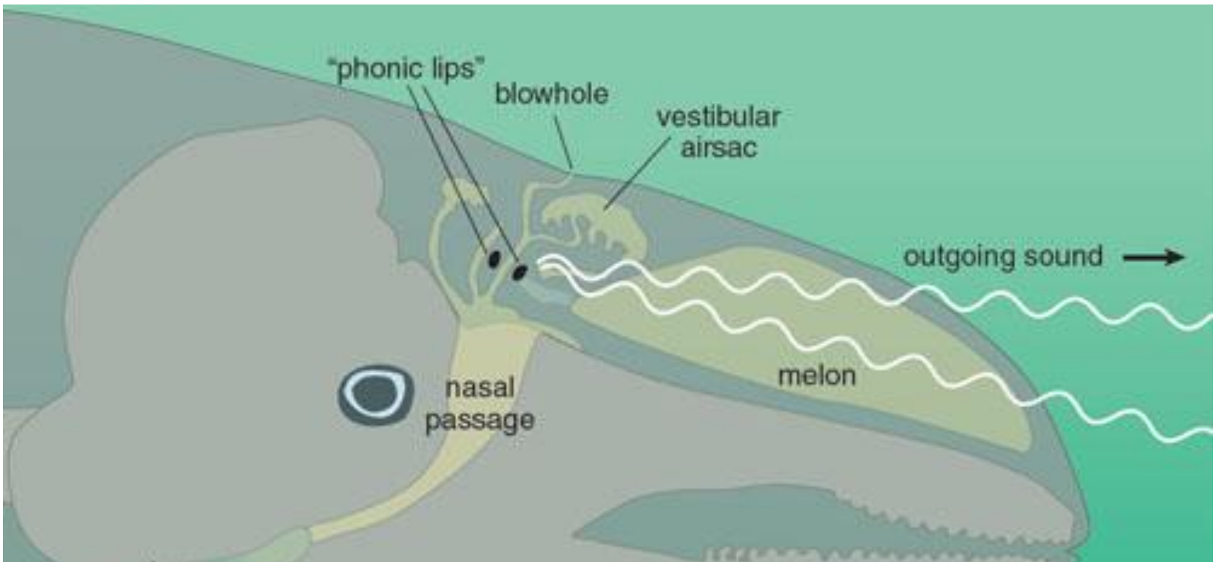

Figure 8: Sound production and sound reception in a harbor porpoise. From Wahlberg et al. (2015)

The hearing sensitivity of harbor porpoises is best between 80 – 140 kHz, but they are able to hear signals in a much larger range between 0.25 – 180 kHz (Kastelein et al., 2002). Harbor porpoises have several mechanisms to be able to distinguish signals from noise when listening for echoes. Their beam width and thus field of view can be adjusted (Wisniewska et al., 2015), they have directional hearing, i.e. their receiving beam has an opening of 22° (Kastelein et al., 2005), and there is a series of auditory filters in place to extract echoes from noise (Wahlberg et al., 2015). Harbor porpoises scan their environment by moving their head and thus the echolocation beam (Wisniewska et al., 2012). It is difficult to assess how harbor porpoises integrate the signals from the received echoes, i.e. the final image that harbor porpoises perceive of their surrounding is unknown. However, the nature of the repetitive pulses has been compared to stroboscopic lights, resulting in fast sequential snapshots of the environment (Wahlberg et al., 2015).

3.3 Bycatch of harbor porpoises in gillnet fisheries

Interactions between harbor porpoises and gillnets are almost always fatal (Figure 9), as harbor porpoises can only hold their breath for several minutes (Westgate et al., 1995; Reed et al., 2000) and gillnets are typically set for at least several hours (see Chapter 2.2).

(a) (b)

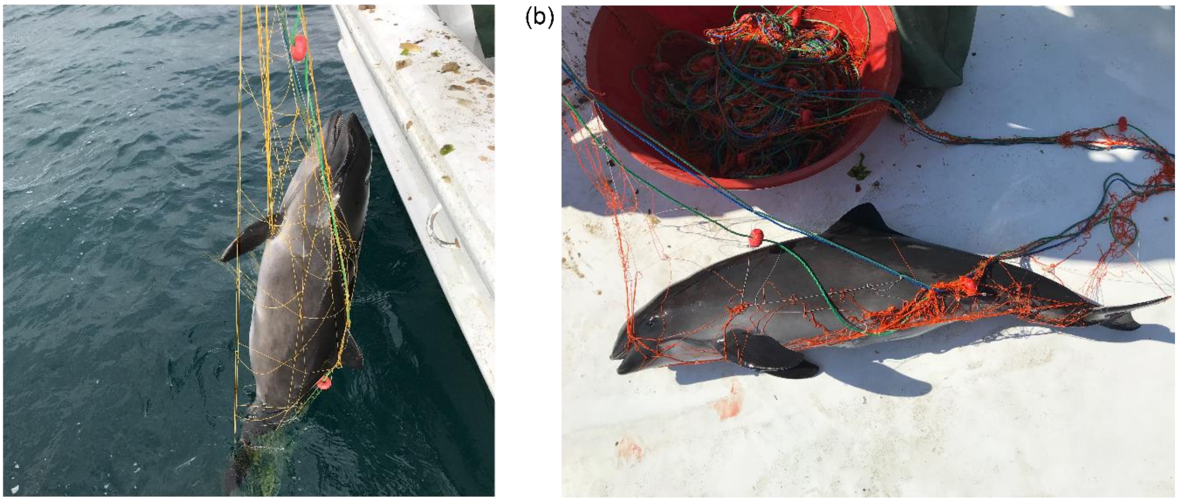

Figure 9: Harbor porpoises bycaught in a Turkish turbot gillnet. Photo in (a) by Sabri Bilgin, (b) by author

Bycatch of harbor porpoises in gillnets is an issue which has several aspects. The two most important aspects concern firstly, the lack of reliable bycatch numbers in many fisheries and secondly, a lack of understanding of the underlying causes of bycatch.

Harbor porpoise

According to Annex XIII in Regulation (EU) 2019/1241, bycatch monitoring of cetaceans shall be carried out only in certain areas in the EU and on vessels greater than 15 m using specific gear (EU, 2019). ICES WGBYC (International Council for the Exploration of the Sea Working Group for Bycatch of Protected Species), has repeatedly highlighted the lack of compliance of member states to the previous, more strict regulation (Council of the European Union, 2004), as well as the shortcomings of the regulation regarding the required observation effort on vessels larger than 15 m, since a large part of the bycatch of harbor porpoises is likely taken by vessels smaller than 15 m (ICES, 2019). Poor compliance to regulations regarding bycatch reduction and lack of enforcement has also been reported for U.S. fisheries (Orphanides and Palka, 2013). Many states rely on their fishery observer program to document harbor porpoise bycatch, which can lead to underestimation of bycatch rates, as only a part of the fleet can be covered by observers – especially vessels below 15 m are rarely observed, despite the relatively high risk of bycatch on small vessels, since observer programs are costly (ICES, 2019). One further issue with on-board observers is that they have many tasks on board that they need to take care of. This can result in overlooking animals that drop out of the net before being hauled on board; additionally it is not known how many animals drop out already under water and sink before being accounted for by the observer (Trippel et al., 1996; Tregenza et al., 1997; Kindt-Larsen et al., 2012). The lack and cost of observers could be counteracted by using remote electronic monitoring systems (REM) to document and quantify bycatch (Kindt-Larsen et al., 2012; Plet-Hansen et al., 2019). On vessels that are too small to install bulky REM system, the use of a mobile app could facilitate reporting of bycatch (Merrifield et al., 2019).

In addition to the lack of quantitative bycatch data, there is a lack of understanding as of why harbor porpoises get caught in gillnets in the first place. Several gear specifications (floatline type, net height, mesh size, twine diameter, twine type) and operational factors (time of day, time of year, soak time, water depth) seem to influence bycatch, but the underlying mechanism is unclear (Northridge et al., 2017). There are both field and laboratory studies that show that harbor porpoises should be able to recognize at least parts of a gillnet, especially the highly visible floatline, and avoid gillnets at a distance (Kastelein et al., 1995b, 2000; Nielsen et al., 2012). It has been hypothesized that while they are able to recognize the net, or at least parts of it, they do not classify it as an impenetrable barrier due to the faint echo (Goodson, 1997).

They may easily recognize the floatline and attempt to dive under it, as harbor porpoises have shown to prefer diving underneath an obstacle, rather than over it (Kastelein et al., 1995a). Furthermore, even though they echolocate very frequently (Wisniewska et al., 2016; Sørensen et al., 2018), harbor porpoises have shown to remain silent (Linnenschmidt et al., 2013) or echolocate less often for several minutes, possibly during episodes associated with sleeping (Wright et al., 2017). They may also be either distracted by prey (Kastelein et al., 1995b) or exhibit a feeding behavior termed “bottom grubbing” (Lockyer et al., 2001) where they practically stand on their head and echolocate towards the bottom. As the beam of harbor porpoises is very narrow (Koblitz et al., 2012), it is vital that it is directed towards the gillnet in order to perceive it.

Masking is another issue that could impede harbor porpoises from recognizing gillnets. It occurs when the frequency of noise lies within a certain bandwidth of the signal that the porpoise is receiving. The source of masking can be anthropogenic, like boat traffic (Hermannsen et al., 2014), or environmental, such as noise from waves during heavy sea states, which lies within the hearing range of harbor porpoises (Miller and Wahlberg, 2013). Noise occurring outside the frequency spectrum of the echolocation signal can also lead to a reduced attention or reduced echolocation. Harbor porpoises have been reported to be irritated during rainfall on the water surface – even if this has typically lower sound frequencies than the echolocation signals of harbor porpoises (Miller and Wahlberg, 2013). It has also been reported that they stop foraging, and thus echolocating, due to boat traffic (Wisniewska et al., 2018).

3.4 Mitigation measures to reduce harbor porpoise bycatch

3.4.1 Fishery closure

The only way to eliminate bycatch in gillnets completely in a certain place during a specific time is to close this region to gillnet fisheries. Time-area closures can be an effective way to avoid bycatch, given that the overlap between fisheries and the presence of harbor porpoises in a certain region at a certain time is high. In areas where a high density of harbor porpoises is known, e.g. close to the island of Sylt in the North Sea (Gilles et al., 2011) or south of Gotland in the Baltic Sea during certain times of the year, spatiotemporal closures of gillnet fisheries can be a very effective tool (Carlén et al., 2018). The time-area closures of the gillnet fishery in the Gulf of Maine were not effective, as the temporal and spatial variability in bycatch as well as the displacement of the fishing effort were not taken into consideration (Murray et al., 2000). The so-called "Take Reduction Plan" (TRP) aimed at reducing the bycatch of harbor porpoises along the Northeast coast of the United States (NMFS and NOAA, 1998) by closing areas of high risk and implementing technical measures in other areas. After implementation of the TRP, the bycatch rate overall dropped initially, thanks to the fishing effort reduction observed in areas with previously large bycatches. However, bycatch rates rose again after several years, likely due to displacement of the effort outside of high-risk areas, as well as low compliance with technical measures in areas outside of the closure (Orphanides and Palka, 2013). A positive example of local gillnet fishery restrictions is documented for New Zealand, as the establishment of the Banks Peninsula Marine Mammal Sanctuary off the coast of New Zealand has increased the survival rate of Hector's dolphin (*Cephalorhynchus hectori*) (Gormley et al., 2012). In a simulation study using the inner Danish waters as a study area, van Beest et al. (2017) confirmed that a combination of time-area closures and the implementation of technical mitigation measures, such as acoustic alarms, would have a positive effect on bycatch reduction in the study area with an assumed effective range of acoustic alarms. Overall, closing fisheries is a drastic measure and the economic viability needs to be considered; often time-area closures have been regarded an incentive to further develop alternative technical bycatch reduction methods (O'Keefe et al., 2014).

3.4.2 Alternatives gears

Fishing with alternative passive gears such as large-scale traps, pots or longlines can help to reduce or halt the bycatch of harbor porpoises in some regions. A recent trial in Argentina has shown that longlines are a potentially viable alternative gear in fisheries with bycatches of Franciscana dolphin (*Pontoporia blainvillei*) (Berninsone et al., 2020). However, gillnets are low-cost and a highly efficient and easy to use gear, thus switching gears voluntarily is rare without a strong incentive. Other external factors, such as a rising grey seal (*Halichoerus grypus*) population in the Baltic Sea and the associated depredation of seals on fish captured in gillnets, have incentivized the development of "porpoise-friendly" gear like fish pots or large-scale push-up traps in Sweden and Denmark (Hemmingsson et al., 2008; Königson et al., 2015).

3.4.3 Active alarms

The most widespread mitigation measure to reduce bycatch of harbor porpoises is the use of active alarms, or so-called "pingers". Pingers emit noises that alert or scare away harbor porpoises from a hazard, such as gillnets. Pingers effectively reduce bycatch of harbor porpoises (Kraus et al., 1997; Gönener and Bilgin, 2009; Dawson et al., 2013; Larsen et al., 2013) and are mandatory in the EU on vessels of more than 12 m in length in certain areas specified in Annex XIII in Regulation 2019/1241 (EU, 2019), as well as in U.S. fisheries that are managed within the Take Reduction Plan during certain times of the year (NMFS, 2009). Due to the nature of their operating principle, pingers have a series of drawbacks. Concerns about habituation to constant signals and reduced efficiency have been raised (Cox et al., 2001; Kindt-Larsen et al., 2019), but there is also evidence of no habituation to more randomized signals within a frequency range (Kindt-Larsen et al., 2019; Omeyer et al., 2020). There is the potential for higher bycatch rates in nets with pingers compared to nets without pingers, if a subset of pingers fail or fishers do not comply with the required spacing, as the space between two functioning pingers can be seen as an "acoustic door" (Palka et al., 2008; Carretta and Barlow, 2011). Furthermore, using pingers means that an additional source of noise is introduced into an already noise-polluted environment (Simmonds et al., 2014). Another reason for concern is the potential for displacement of harbor porpoises from their habitat due to the intense sounds (Carlström et al., 2009; Kyhn et al., 2015). In addition, pinger sounds could be less effective if masked by rainfall (Kastelein et al., 2008). As far as maintenance is concerned, the batteries of pingers need to be replaced regularly and functionality needs to be ensured and enforced.

3.4.4 Increased acoustic reflectivity

The hearing capabilities of harbor porpoises should enable them to recognize the gillnet netting from a short distance (Kastelein et al., 2000; Mooney et al., 2004). A field study suggests that harbor porpoises are also able to recognize gillnets from a larger distance (Nielsen et al., 2012), but it is not clear whether they recognize the entire net or only the highly visible floatline. It has been suggested to "fill in" the acoustic gap between the floatline and the bottom to make the netting recognizable as an impenetrable object (Goodson, 1997) and prevent harbor porpoises from attempting to dive underneath the floatline (Kastelein et al., 1995a) and swim over or along the structure instead. One attempt to improve the acoustic reflectivity of gillnets was the alteration of the net filament properties by using high-density fillers such as Barium-Sulfate ($BaSO_4$) or iron-oxide (IO) (Trippel et al., 2003; Mooney et al., 2004; Koschinski et al., 2006; Larsen et al., 2007). The aim was to make use of an impedance mismatch between the filament and water. Acoustic impedance is a function of density and elasticity of a medium. If there is a high mismatch in impedance between two mediums (in this case water and the netting filament), it can lead to a high reflection of the sound given that the reflective surface is large enough to intercept the acoustic energy from the source (Simmonds and MacLennan, 2005).

Results from trials with high-density gillnets are somewhat conflicting. Trippel et al. (2003) have shown a reduction in bycatch for harbor porpoises with no decrease in target fish catches when using $BaSO_4$ nets on the East coast of Canada. However, the bycatch reduction effect was not as clear in another year within the same region (Trippel et al., 2009) and no bycatch reduction using $BaSO_4$ nets was found in trials with Franciscana dolphins in Argentina (Bordino et al., 2013). Larsen et al. (2007) showed that a bycatch reduction was achieved using IO gillnets in the Danish North Sea, but catch of target species was reduced. Target catch was also reduced in some years in the study by Trippel et al. (2009). Some studies have reported a small, but significant difference in acoustic reflectivity when comparing high-density gillnets and standard nylon nets (Trippel et al., 2003; Koschinski et al., 2006), while others have reported no such difference (Mooney et al., 2004; Larsen et al., 2007). It has been concluded that the increase in stiffness, rather than an increase in acoustic reflectivity, of the high-density gillnets was mainly responsible for the observed bycatch reductions (Larsen et al., 2007; Trippel et al., 2009).

Another way to improve the acoustic reflectivity is the use of additional reflectors. Based on the pioneering work by Hembree and Harwood (1987), a promising reflector was developed by Goodson (1997). The reflector was an air-filled, 70 mm long and 35 mm wide plastic deep-water net float. Harbor porpoises encountering several vertical lines with such a reflector would recognize it as a barrier if the reflectors were spaced close enough to each other (Kastelein et al., 1995b; Nakamura et al., 1998). The identified reflectors, however, were fairly large and thus required additional space on board and caused handling issues during fast shooting of the net, as they tended to fall through the meshes of underlying layers of net when stored. Passive reflectors that are easy to handle in gillnets seem like a promising tool to reduce bycatch of harbor porpoises, if the animals are actively echolocating.

4 AIM OF THE THESIS

As there are several populations of harbor porpoises and other small toothed whales that are under high pressure due to bycatch in gillnet fisheries, among other reasons, the need for mitigation of bycatch is high (Read et al., 2006; Reeves et al., 2013; Brownell Jr et al., 2019). So far, no gear modification fulfills the requirements of being non-intrusive, easy to handle for fishers and able to reduce the bycatch of harbor porpoises and other odontocetes substantially, while maintaining catch efficiency for target species. There is a lack of fundamental understanding of the acoustic properties of gillnets in general and modified gillnets to be more acoustically reflective in particular, and previous attempts have been largely based on a trial-and-error trials. There is no systematic approach to improve the acoustic detectability of gillnets using passive reflectors, while remaining inconspicuous to fish.

This thesis addressed the optimization of acoustic reflectivity of gillnets for harbor porpoises and at the same time, provides a comprehensive guide that could facilitate the development of modified gillnets that have the potential to reduce the bycatch of a wide range of odontocetes species, while keeping the catch efficiency constant. For this purpose, the acoustic properties of a large range of objects, including standard nylon gillnet filaments as well as of gillnet filaments with high density and high stiffness, were systematically simulated, in order to identify an ideal passive acoustic reflector (**Paper I**) across echolocation frequencies. The effect of such a reflector on the acoustic reflectivity of gillnets compared to unmodified gillnets was experimentally verified (**Paper I, Paper II**) and the bycatch reduction effect on harbor porpoises was tested in a commercial fishery (**Paper III**).

5 DETERMINATION OF OPTIMAL PASSIVE REFLECTORS

One way to mitigate bycatch of harbor porpoises and other odontocetes is to make gillnets appear like an impenetrable barrier. The study presented in **Paper I** is the first systematic approach to determine an object that can substantially increase the acoustic reflectivity of gillnets. Frequency-specific reflectors that resonate at the echolocation frequency of different odontocete species were identified. It is a comprehensive guide that provides the acoustic reflectivity of species-specific objects that increase the acoustic visibility of gillnets covering the entire frequency range of small cetaceans (1 – 200 kHz). Acoustic reflectivity is expressed quantitatively in terms of target strength (MacLennan et al., 2002) and qualitatively in form of exemplary echograms.

5.1 Requirements of the reflector

Several pre-requisites must be met by the reflector in order to successfully increase the acoustic visibility of gillnets to reduce bycatch of odontocetes and be simultaneously taken up by the fishery (Goodson, 1997). These criteria, stemming from the pioneering work on passive reflectors (Hembree and Harwood, 1987; Peddemors et al., 1991; Frady et al., 1994) as well as physical restrictions, comprise:

a) Omnidirectionality: the object needs to be acoustically visible from all angles of approach of the animal
b) Small size: the object needs to be small enough to avoid large additional storage requirements, but large enough to intercept enough acoustic energy
c) Neutral buoyancy: the object should have a similar density as seawater to avoid any influence on the hydrodynamic behavior and thus catch efficiency of the gillnet
d) Safe handling: after adding the reflectors, the gillnet needs to be safe to use and durable during operation (including shooting, hauling and clearing the gillnet)

5.2 Simulation environment, parameter ranges

To determine the acoustic properties of objects, the Helmholtz-equation must be solved either numerically or analytically. In this case, all numerical solutions were calculated using COMSOL (COMSOL Multiphysics®, 2018) a computer program used for the simulation of the acoustic properties of objects, including calculation of monostatic target strength, the visualization of the acoustic field and the visualization of eigenmodes, i.e. the shape the object takes when excited with the eigenfrequency. During all simulations, it was made sure that the thickness of the surrounding medium was large enough to allow resonance and the entire environment was surrounded by a perfectly matched layer (PML) that absorbs all incoming waves to avoid refraction from surrounding boundaries (Figure 10).

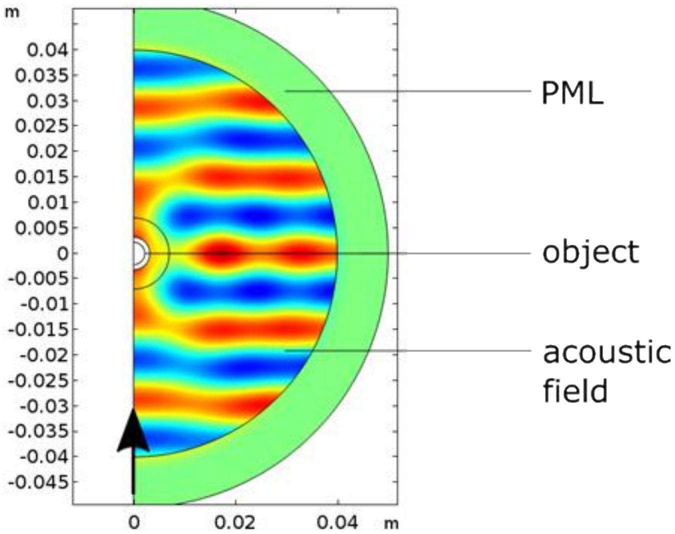

Figure 10: Visualization of the simulation environment in COMSOL, including elastic object (circle with 6.4 mm diameter in the middle, density of nylon), surrounding environment, i.e. water (blue/red visualization of the acoustic field) and perfectly matched layer (PML, green area). The arrow points in the direction of the sound propagation. Unmodified from **Paper I**

To cover the entire distribution range of small cetaceans, simulations were carried out for several combinations of water temperature (0 – 18°C) and salinity (0 – 31 psu), as these influence the speed of sound in water and hence the acoustic properties (Wilson, 1960; Del Grosso, 1974).

The large variety of elasticity in materials required simulations across a large range of Young's Modulus (0.1 GPa – 10 GPa). Furthermore, to investigate the effect of material density on the acoustic reflectivity of spheres and filaments, a range of material density (1000 kg/m³ – 8000 kg/m³) was considered.

As size played an important role in selecting the optimal reflector, simulations were carried out for spheres between 1 mm – 60 mm in diameter and filaments between 0.25 mm – 2 mm diameter, which corresponds to the filament diameter of commercially available gillnets.

5.3 Target strength simulations

5.3.1 Simulations of filaments across frequency range

The target strength of filaments was simulated across the frequency range, as well as for different combinations of filament density, filament elasticity and filament diameter. No substantial increase in target strength was detected (**Paper I**) when the density was increased. The main reason for such low values is that acoustic waves mostly bend around such small objects (Medwin and Clay, 1998), unless the object is extremely elastic (Figure 11) and even then, the field only changes slightly. An example of an elastic object of an adequate size (6.4 mm diameter) that clearly changes the acoustic field is shown in Figure 10. The highest target strength values of filaments were found for parameters that are typical for rubber materials (**Paper I**).

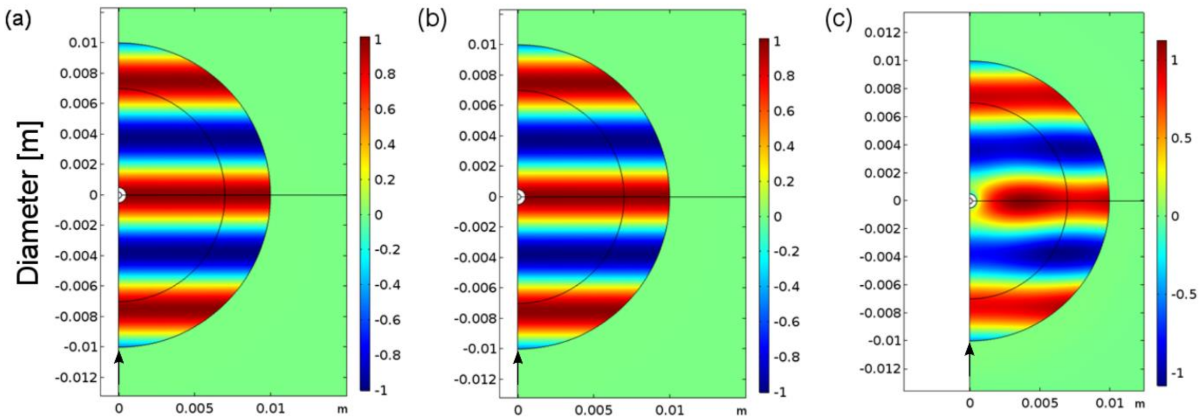

Figure 11: Normalized acoustic fields of different types of ensonified 1 mm diameter objects. Rigid (e.g. steel) (a), elastic (e.g. nylon) (b), extremely elastic (e.g. rubber) (c). The acoustic field only slightly changes even when an extremely elastic object is ensonified. The arrow points in the direction of the sound propagation.

5.3.2 Simulations of optimal reflectors across frequency range

Paper I investigated several kinds of shapes including cuboids, corner reflectors, half-spheres and domes. The best results from all angles were achieved for small spheres, which are the simplest omnidirectional objects, meeting criteria (a) and (b), leading to a thorough investigation of spherical objects of different material properties and sizes.

The oscillation of small air bubbles in water, making them appear much larger than they actually are, is a phenomenon that is known for a long time (Minnaert Sc.D., 1933) and it seemed obvious to first consider air-filled spheres. Air has the highest impedance mismatch with respect to water, as its density is extremely low compared to water. This results in a high acoustic reflectivity of air-filled objects. However, already very early work on gillnet reflectivity had pointed out, that using air-filled filaments would not lead to the desired result, since the filament itself creates a boundary layer between the water and air which leads to damping effects (Pence, 1986). The diameter of the air-filled part of the filament would need to be large in relation to this boundary layer to increase the reflectivity, which can result in handling and catch efficiency issues, due to the necessary very thick filaments. In addition, air-filled objects often did not resist rough handling on board, broke and filled up with water and failed to substantially reduce bycatch of small cetaceans (Hembree and Harwood, 1987; Jefferson and Curry, 1996). Most importantly, most air-filled structures have a considerable uplift, which would change the hydrodynamics of the gillnet, and thus alter the catch efficiency. **Paper I** investigated air-filled spheres of different wall thicknesses, but as the target strength of these spheres was not higher than solid spheres of the same size, the focus was shifted to solid spheres.

Solid spheres with high densities compared to water, e.g. steel spheres, are rigid scatterers. These are also unlikely to lead to a substantial increase in acoustic reflectivity, as their echo properties are dominated by their geometric properties (Bjørnø, 2017). Additional objects or filaments with high density would have to be very large to increase the echo of gillnets.

An alternative to air-filled and rigid spheres are elastic spheres, as they fall in a range between completely rigid and completely soft scatterers (Brill and Gaunaurd, 1987). Elastic spheres in a fluid medium can resonate when excited at their natural frequency – or eigenfrequency – (Flax et al., 1978) and exhibit larger acoustic reflectivity than their geometric properties suggest. This eigenfrequency depends on their elastic properties, i.e. the Young’s Modulus, the size of the object and on the speed of sound in the surrounding medium. Thus, the focus of **Paper I** was the investigation of acoustic properties of small, elastic spheres in different environmental conditions.

In a first step, the parameter ranges were narrowed down to the optimal compromise between density, elasticity and size to meet criteria (b) and (c) (**Paper I**). The mechanical properties are met by most polymers; the best match between simulated data and existing materials was found to be acrylic glass (PMMA), widely known under the proprietary name Plexiglas®, a transparent thermoplastic.

Subsequently, the target strength for acrylic glass spheres was calculated on a very fine scale (0.1 mm diameter increments) across the frequency range 1 – 200 kHz to cover the entire echolocation range of small cetaceans (Figure 12 a). For each frequency – and thus many species – the corresponding optimal reflector can be chosen, or, if availability of a certain sphere size is the limiting factor, the likely achievable target strength can be extracted (Figure 12 b).

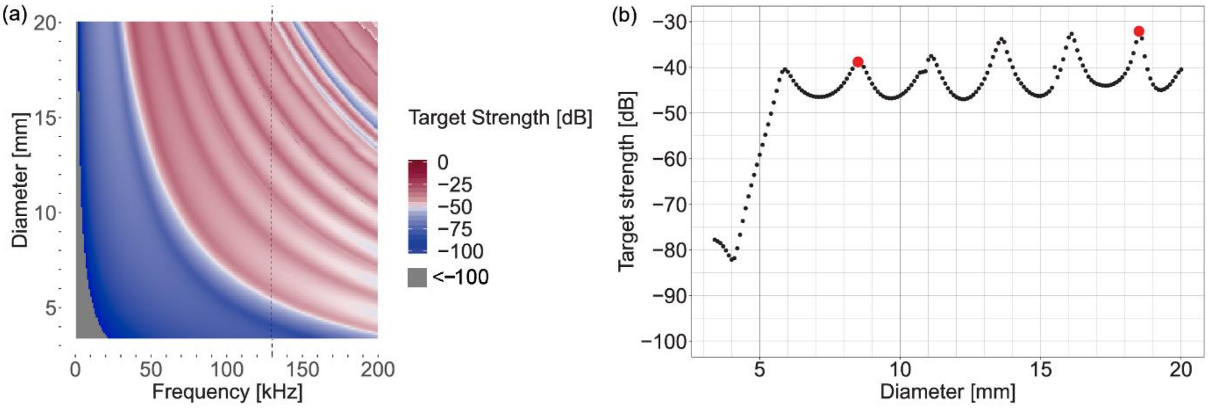

Figure 12: Target strength of acrylic glass spheres across frequency range (x-axis) and different sizes (y-axis); the white areas are values of -50 dB, the target strength of a gillnet (Kastelein et al., 2000) (a). Target strength of acrylic glass spheres exemplarily at 130 kHz, the echolocation frequency 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. Modified from **Paper I**

5.4 Experimental verification of simulation results

Experimental trials to confirm the acoustic reflectivity of the identified acrylic glass spheres were conducted in **Paper I** and **Paper II**. Firstly, the target strength of a single sphere was measured and then the acoustic reflectivity of a gillnet equipped with spheres was qualitatively assessed (**Paper I**). In **Paper II**, the acoustic reflectivity of gillnets modified with spheres was assessed quantitatively.

5.4.1 Acoustic tank experiments

The trials to measure the target strength of single spheres were carried out in an acoustic tank, i.e. a large pool that is acoustically insulated on all sides similar to a recording studio. Two types of acrylic glass spheres (6.4 mm and 9.6 mm diameter), as well as two reference objects (a table tennis ball and a steel sphere of 25.5 mm diameter) were ensonified with a broadband signal (50 – 150 kHz) and the echo was recorded (**Paper I**). The experimentally determined target strength value of the acrylic glass spheres at 130 kHz, which corresponds to the echolocation frequency of harbor porpoises (Møhl and Andersen, 1973), was similar to the simulated value and was almost as high as the target strength of the table tennis ball which is five times larger in diameter (40 mm, Figure 13). The measured and simulated target strength of a single acrylic glass sphere was higher or at least as high as the target strength of the area of a gillnet at 130 kHz (Au and Jones, 1991; Kastelein et al., 2000; Mooney et al., 2004), both in the simulation as well as in the experiments.

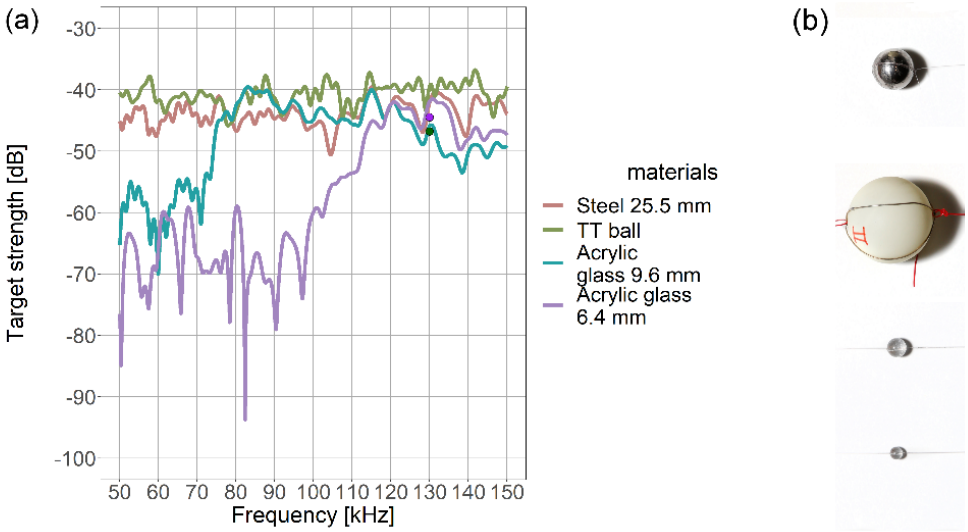

Figure 13: Target strength values (a) of various measured objects (b) of different materials. Dots in (a) indicate the corresponding simulated values at 130 kHz. Modified from **Paper I**

5.4.2 Echograms of modified gillnet

To assess the effect of the addition of acrylic glass spheres on the acoustic reflectivity of an entire gillnet, a standard gillnet was equipped with acrylic glass spheres at a 30 cm sphere-sphere interval (**Paper I**). To visualize the effect, an echogram of a standard gillnet and a modified gillnet was taken with a SIMRAD EK60 scientific echosounder onboard R/V Clupea. To this end, the gillnet was pulled underneath the vessel and the gillnet was positioned vertically in the center of the acoustic beam (Figure 14). The gillnet was ensonified with a signal frequency of 38 kHz, the frequency usually used to find fish, and 120 kHz, which lies within the echolocation frequency range of harbor porpoises. When ensonified at 120 kHz, the attached spheres became highly visible compared to the standard gillnet (Figure 15, **Paper I**).

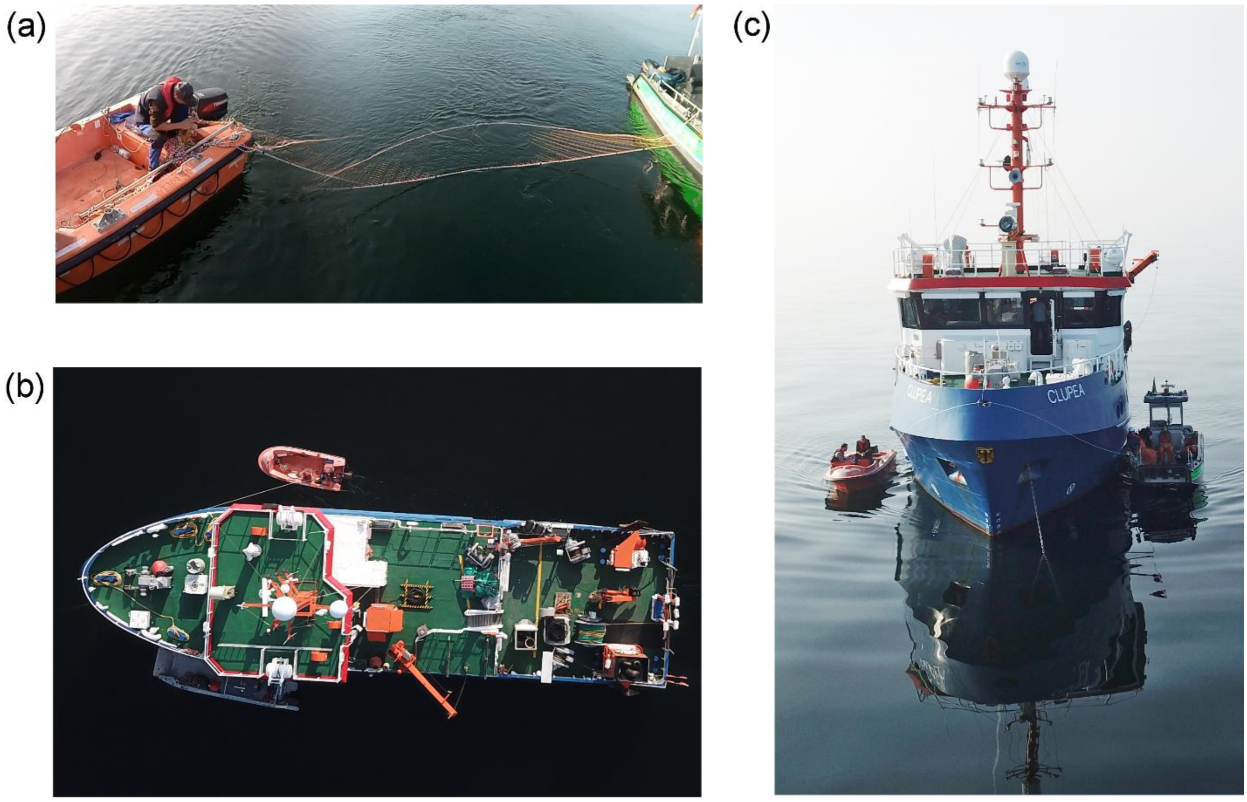

Figure 14: Gillnet is spanned between two small boats (a) and pulled underneath R/V Clupea into the center of the beam of the hull-mounted echosounder (b, c)

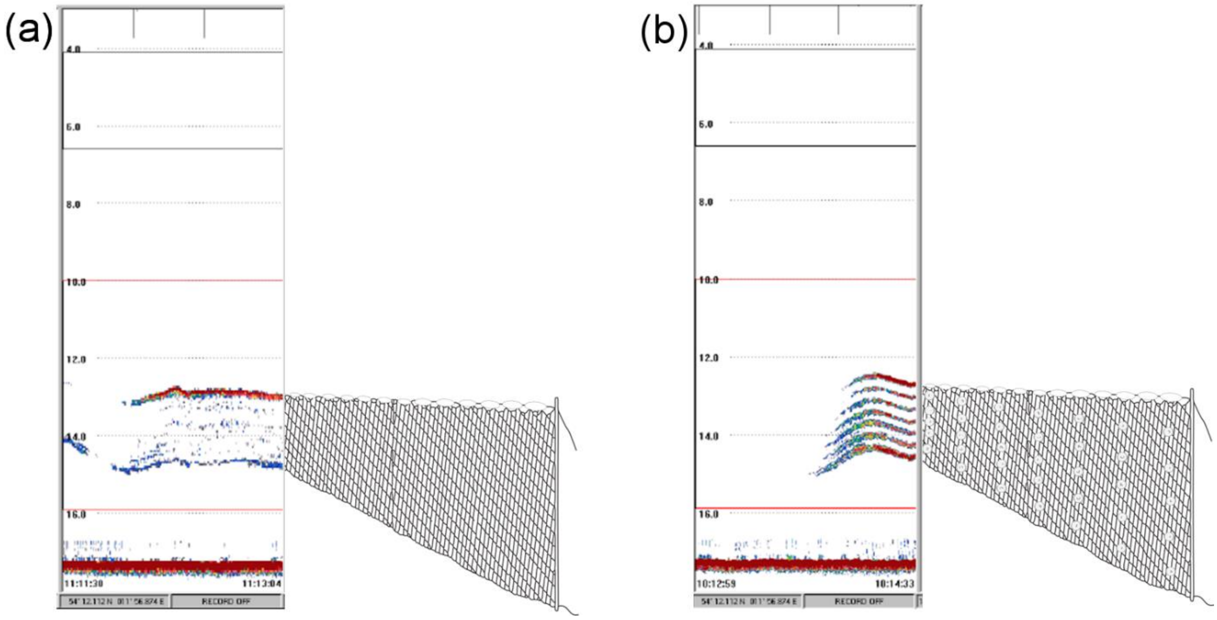

Figure 15: Echograms of a standard gillnet (a) and a gillnet modified with acrylic glass spheres (b), both taken at 120 kHz. The acrylic glass spheres are clearly visible (b) while only floatline and leadline are visible when the standard gear is ensonified (a). Modified from **Paper I**

6 ACOUSTIC REFLECTIVITY OF MODIFIED GILLNETS

Following the determination of an optimal reflector (acrylic glass sphere) in **Paper I** and the experimental verification of the acoustic reflectivity of single spheres, **Paper II** aimed at determining the influence of the acrylic glass spheres in different configurations on the acoustic reflectivity of gillnets. As acrylic glass spheres with 8 mm diameter had yielded a high target strength within the echolocation frequency of harbor porpoises (**Paper I**, Figure 12 b), several gillnets were equipped with 8 mm acrylic glass spheres at different sphere-sphere intervals (**Paper II**). The scope was to evaluate their influence on the acoustic reflectivity of gillnets with regard to a change in area backscattering strength (S_a, MacLennan et al., 2002), target strength (TS, MacLennan et al., 2002) and spatial distribution of the echoes from several angles of ensonification. Area backscattering strength and TS were calculated from the volume backscattering strength (MacLennan et al., 2002) and the volume backscattering coefficient (MacLennan et al., 2002).

6.1 Experimental set-up

All measurements took place in a 14 m x 40 m sheltered harbor berth with 8 m depth. The gillnets were ensonified one after another using a standard SIMRAD EK80 wideband echosounder in a waterproof housing (WBT Tube) with three broadband transducers (38 kHz, 70 kHz and 120 kHz centroid frequency) covering the frequency range between 35 – 170 kHz. The transducers were mounted to a wooden board and fixed at 4 m depth (Figure 16 a), with the transducers pointing in the horizontal direction. The gillnets were positioned between two pontoons and hung from a steel bar (Figure 16 b, c) at set distances from the transducers with the center of the gillnet placed in the center of the transducer beam. The gillnets were ensonified perpendicularly to the transducers and at 20° and 45° horizontal inclination relative to the transducer. Six different gillnets were used for the acoustic measurement (Table 1). One type of gillnet was a nylon net typically used in the cod fishery in the Baltic Sea ("Cod", Table 1) and the other gillnet type is typically used in the Black Sea turbot fishery ("Turbot", Table 1). The sphere-sphere intervals were chosen to determine the influence of number of spheres/m² of netting on the acoustic reflectivity and potentially find a compromise between acoustic reflectivity and necessary number of spheres. This is relevant, as the number of spheres needed is fourfold, when the distance between the spheres is halved. The maximum distance between spheres (60 cm) is the minimum distance between two objects that a porpoise is fairly unlikely to swim through (Nakamura et al., 1998).

Table 1: Properties of ensonified gillnets

Name	Material	Sphere-sphere interval [cm]	Stretched mesh size [mm]	Height of net [m]	Approx. number *n* of spheres/m² [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

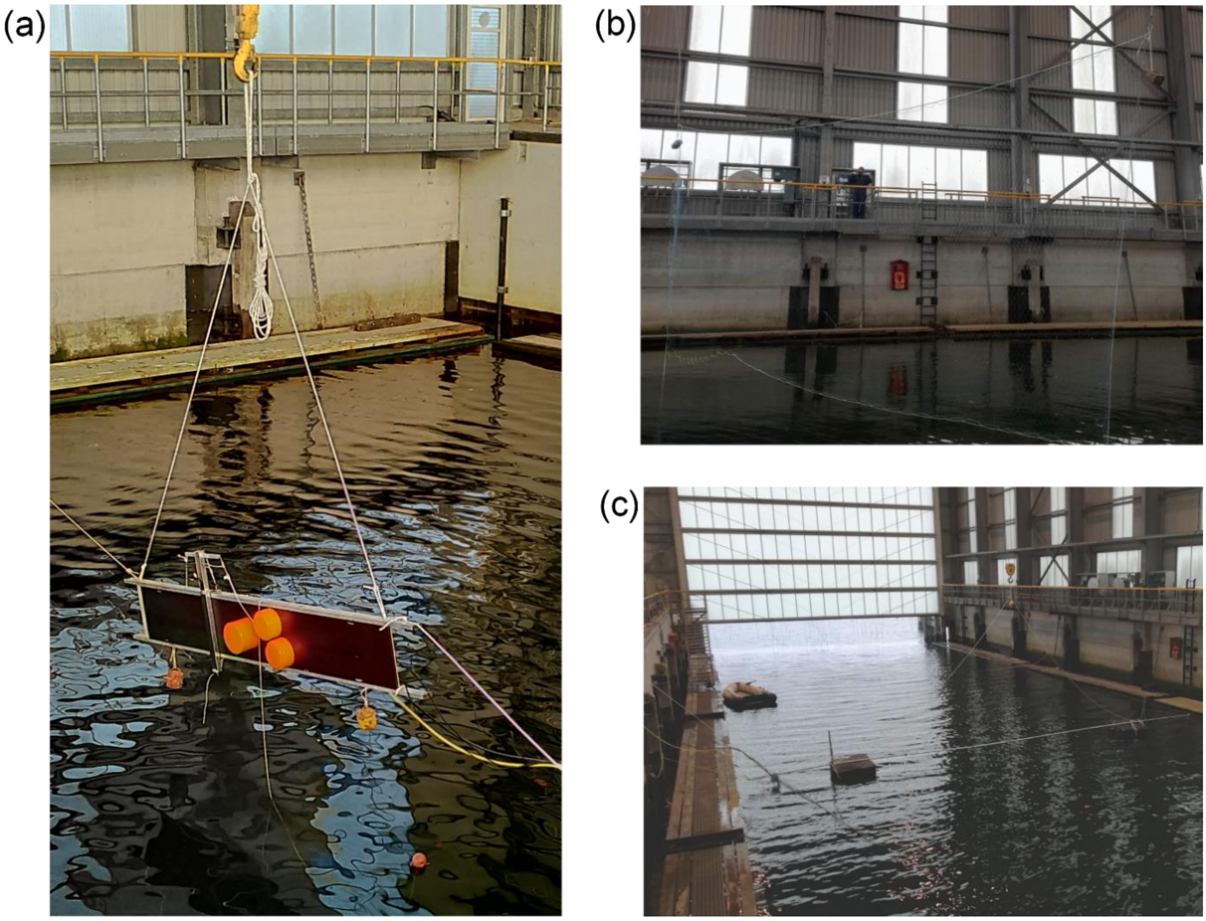

Figure 16: Set-up of acoustic measurements in sheltered harbor berth. Transducers before being set in the water (a), gillnet hanging from steel bar ready to be set in the water (b), pontoons with steel bar, gillnet is positioned underwater between pontoons (c)

6.2 Spatial distribution of echoes

The echograms at 120 kHz revealed a distinct pattern of spheres when the gillnets with spheres were ensonified, as the spheres resonated (**Paper II**). As also shown qualitatively in **Paper I**, the spheres became highly visible, especially when the gillnets were ensonified from an angle (Figure 17). The reference gillnets without spheres were not as visible and became even less visible when set at an angle relative to the acoustic beam of the transducer (Figure 17). The echo strength and the echo patterns were not as obvious when the gillnets were ensonified with frequencies outside of the echolocation range of harbor porpoises which the spheres were optimized for, as they did not correspond to the resonance frequency of the acrylic glass spheres (**Paper II**).

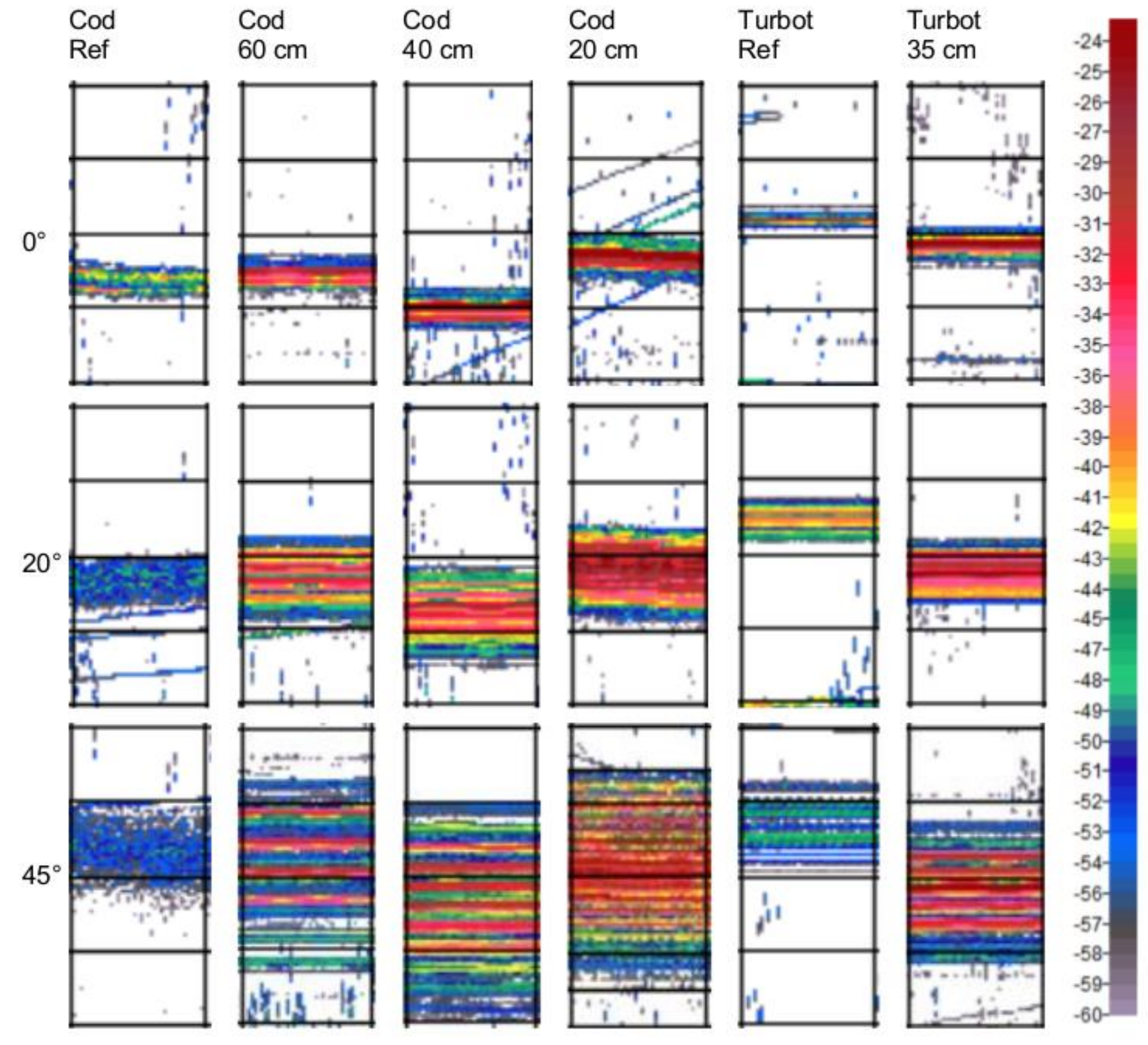

Figure 17: Echograms of standard („Ref“) gillnets and gillnets modified with different sphere-sphere intervals from three different ensonification angles (0°, 20°, 45°) using the 120 kHz transducer. Echo strength is depicted in S_v [dB] (grey: low echo, red: strong echo, see color scale). The spheres 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. Modified from **Paper II**

6.3 Backscattering strength of modified gillnets

The echo strength of the gillnets were determined in terms of area backscattering strength (S_a, Figure 18 a, b) as well as target strength (TS, Figure 18 c, d). S_a can be used to describe the integrated echo of a layer between two depths (Simmonds and MacLennan, 2005), here the distance to the transducer, which in this case corresponds to the ensonified area of the gillnet. As former research has merely provided TS values for gillnets, TS measures were determined for comparison (**Paper II**), albeit TS is a measure for single targets and thus not ideal for an area target, such as a gillnet. TS values were calculated as coherent and incoherent addition of single TS values (each point in the echograms in Figure 17 representing one single TS value), where the coherent addition corresponds to the maximum possible value and incoherent addition to the likely mean value, as it compensates for interference of the reflected acoustic waves. S_a and TS were determined for each single frequency in 1 kHz steps within the entire frequency range of the transducers and for a frequency range of 120 – 140 kHz, as harbor porpoises do not echolocate on a single frequency but across this range depending on their activity (Clausen et al., 2011). The gillnets equipped with spheres had a substantially higher reflectivity (both S_a and TS) than the standard gillnets. The increase was between 15 dB and 30 dB depending on the number of spheres per m^2 and the angle of inclination (Figure 18). The reflectivity improved even if the spheres were attached at the largest, 60 cm, sphere-sphere interval, potentially achieving a barrier effect already with a low number of spheres. Generally, the reflectivity was higher when considering the frequency range 120 – 140 kHz as the echo energy of different frequencies accumulated. The TS values of the standard gillnet were fairly low compared to other studies, but follow a similar pattern shown by previous work, i.e. dropping when ensonified from an angle (Au and Jones, 1991; Kastelein et al., 2000; Mooney et al., 2004).

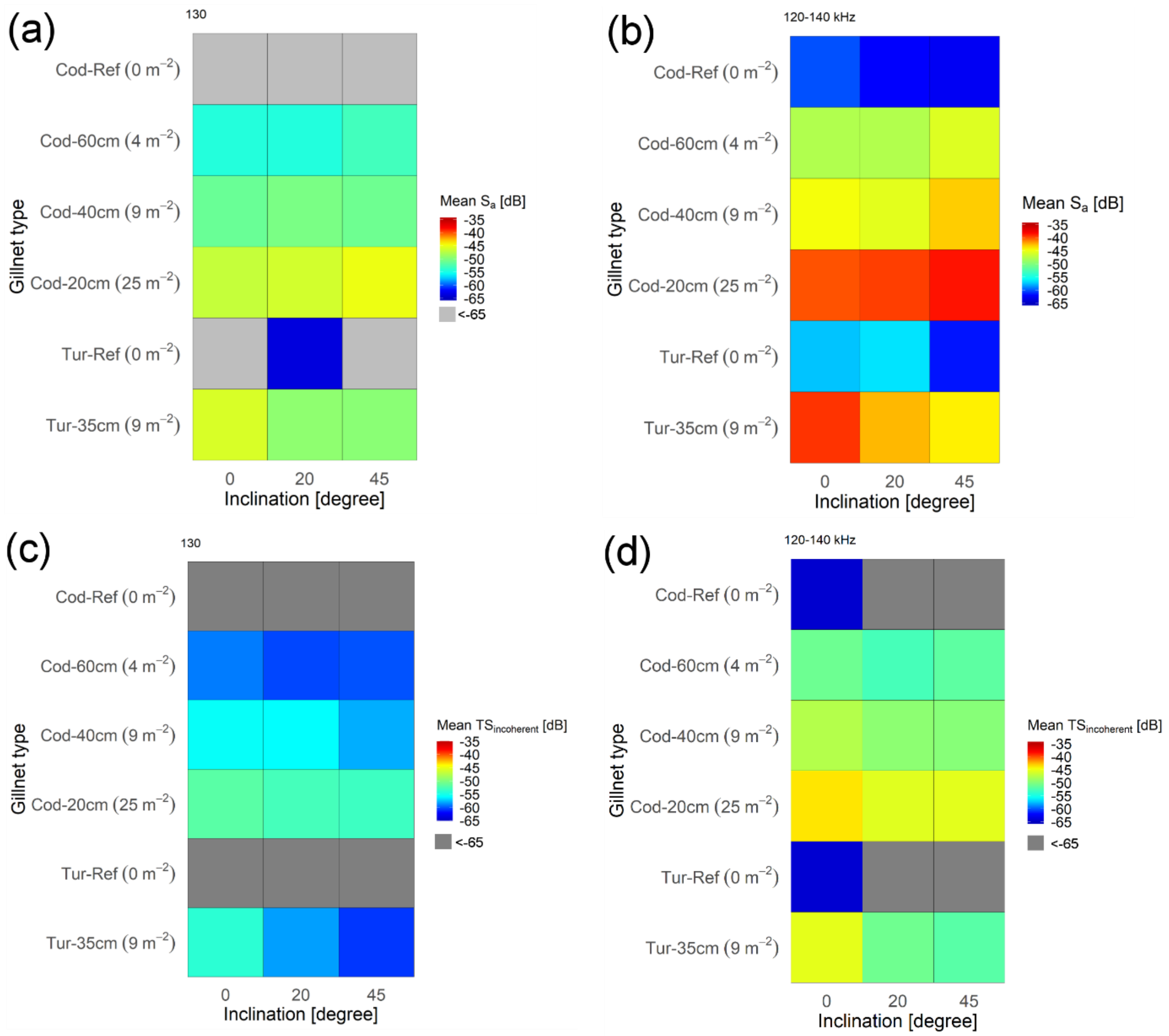

Figure 18: S_a values (a, b) and incoherent TS values (c, d) of all measured gillnets (number of spheres per m² in brackets) at 130 kHz (a, c) and in the frequency range 120 – 140 kHz (b, d). Modified from **Paper II**

7 First commercial trial using acoustically visible gillnets

In **Paper III**, the effect of an acoustically visible gillnet on the bycatch reduction of harbor porpoises was investigated in the Turkish turbot fishery. For the first time, a gillnet equipped with acrylic glass spheres was tested in a pairwise trial in a commercial fishery.

7.1 Selection of study area

To carry out a pilot trial and gather data within a short time frame, it was necessary to identify regions with high bycatch rates in combination with gillnet fisheries using relatively short net lengths. Relatively high bycatch rates in Northern Europe have been documented in the Danish bottom-set gillnet fishery in the North Sea (Vinther and Larsen, 2004), in the Celtic Sea (Tregenza et al., 1997), as well as in the Norwegian fishery for cod and monkfish (Bjørge et al., 2013). These fisheries have the disadvantage that very long nets are used and since no automated process to attach the acrylic glass spheres to the nets exists yet, it would have been beyond the scope of a pilot trial to equip more than ten kilometers of nets with spheres by manually attaching them. There are other regions where high bycatches of harbor porpoises have been observed in the past, e.g. the Bay of Fundy (Trippel and Shepherd, 2004) and the turbot fishery in the Black Sea (Gönener and Bilgin, 2009; Tonay, 2016). In the Black Sea turbot fishery nets of less than 2000 m are used, as the clearing of the nets is done manually. The high bycatch rates in combination with a manageable length of nets led to the choice of conducting the experiments the Black Sea turbot fishery. After establishing a cooperation with the University of Sinop and local fishers, ten fishing hauls were conducted off the coast of Sinop (Figure 19) during September – December 2019.

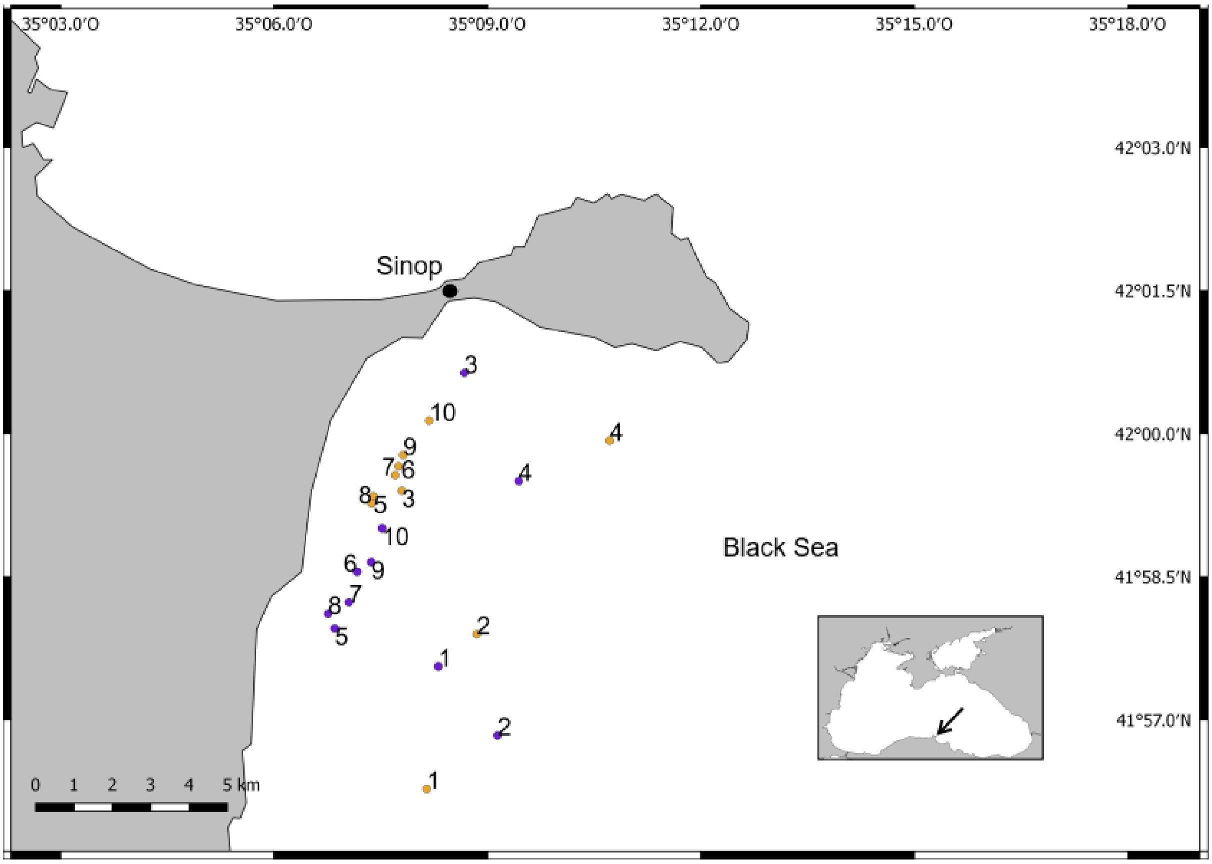

Figure 19: Study area of the commercial fishery trials and location of the ten hauls. Dots show the midpoints of the gillnets (purple = standard gillnet, yellow = modified gillnet). Unmodified from **Paper III**

7.2 Gear properties

The standard gillnet were the turbot gillnets typically used in the region. The turbot nets had a stretched mesh size of 400 mm, consisted of orange/yellow natural filament, were 5.5 meshes deep and approximately 2000 m long (**Paper III**, Figure 20). The only difference between the standard net and modified net was the addition of acrylic glass spheres on the modified net. The spheres were attached at 35 cm horizontal and 37 cm vertical distance. The distance of around 35 cm was chosen based on a study that investigated the "personal space" of harbor porpoises, i.e. the minimum distance between two objects that the porpoise would not swim through (Nakamura et al., 1998). The difference in vertical and horizontal distance was due to the mesh geometry and hanging ratio. The gillnet modified with acrylic glass spheres was acoustically visible as opposed to the standard gillnet (**Paper II**, turbot net in Figure 17).

(a) (b)

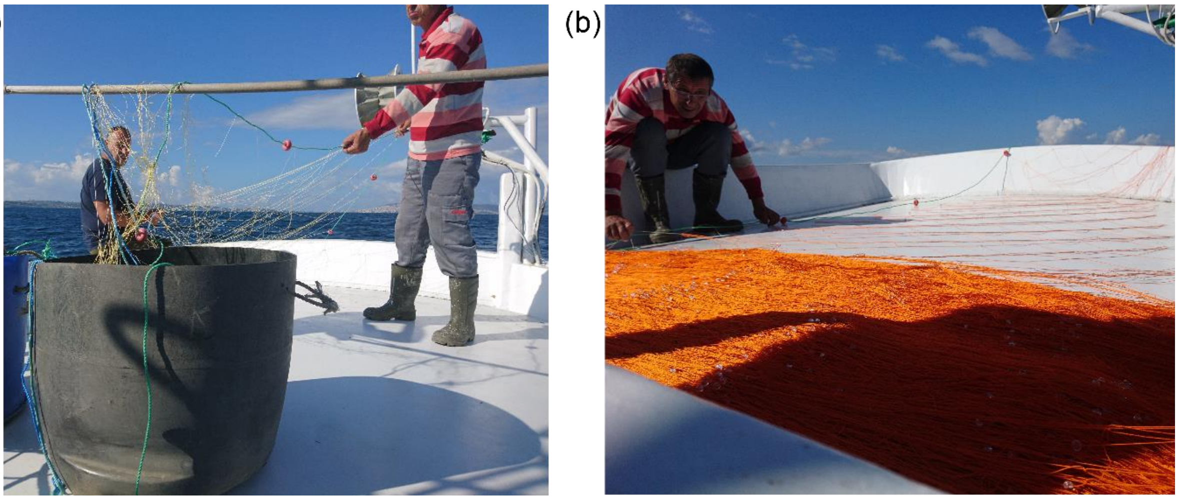

Figure 20: Setting of standard (a) and modified gillnet (b) from a commercial vessel during the trials in the Black Sea turbot fishery

7.3 Catch and bycatch

The most commonly caught fish species was thornback ray (*Raja clavata*; 195 individuals), while only four individuals of the target species Black Sea turbot (*Scophthalmus maeoticus*) were caught in all of the ten hauls. Other fish species occurred in small numbers (**Paper III**). The low catches of turbot are typical for the season. Additionally, the gillnet fishery for turbot is suffering from low turbot stocks in general and competition from trawlers. Local fishers reported that they did have some catches with a smaller – illegal – mesh size. The catch efficiency for bottom-dwelling species like *Raja clavata* did not seem to be compromised by the addition of the acrylic glass spheres.

In total, seven harbor porpoises were caught, five in the standard net and two in the modified net (Figure 21), which results in a reduction of bycatch by 60% in the modified gear, based on the raw data. The estimated marginal mean for the bycatch was 0.5 for the standard gear and 0.2 for the modified gear with wide confidence intervals (Figure 22). The generalized linear mixed model (GLMM) showed no significant difference in bycatch depending on gear ($p = 0.25$, **Paper III**). This may be attributed to the low number of trips, as a power analysis showed that with the given bycatch rate approximately 130 sets would be needed to confirm a significant reduction in bycatch with 80% power (**Paper III**). Five of the caught harbor porpoises were male, one was a female and of one of the seven individuals, the sex could not be determined, as it dropped out of the net before being hauled on board. This emphasizes the need for a quantification of drop-out rates in gillnet fisheries for the determination of bycatch rates (see Chapter 3.3), as it is unknown how many animals may have dropped out under water and sunk before being accounted for. Generally, the results indicate a positive trend in bycatch reduction and are a promising basis for a full-scale future trial in other commercial fisheries.

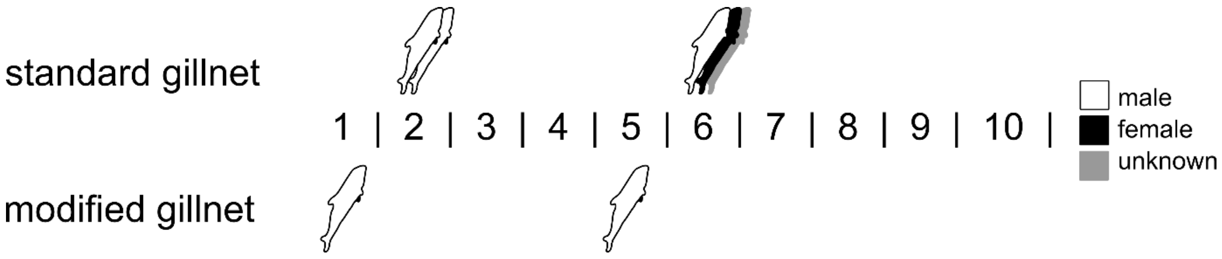

Figure 21: Overview of bycaught harbor porpoises in each haul (numbers) by gear and sex. Modified from **Paper III**.

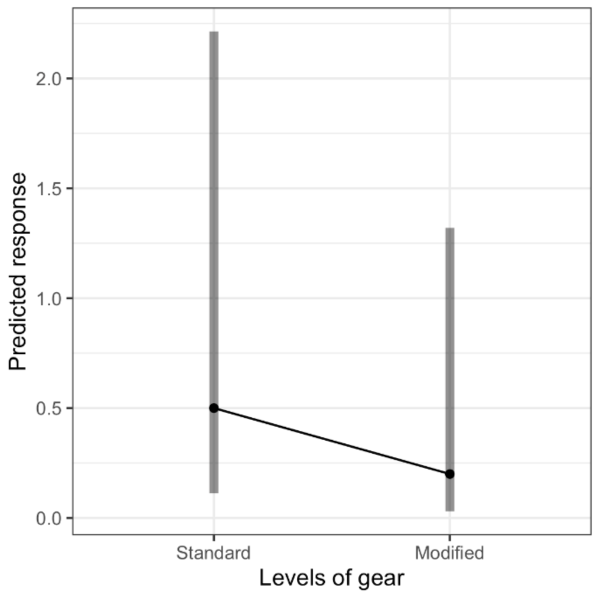

Figure 22: Estimated marginal bycatch means (black dots) according to gear with confidence intervals (grey bars). Unmodified from **Paper III**

7.4 Handling of gear

The initial preparation of the modified gillnet was labor-intensive, as all spheres had to be glued to the gillnet by hand. As this was a pilot trial, no automated process is available yet, but is a definite requirement for future development. Setting of the gear took some practice to avoid entanglement during the setting process due to the large meshes and fiber material, however there was a steep learning curve, resulting in faster handling with practice. During the first trip, the setting of the modified gillnet took an additional 45 minutes compared to the standard gillnet, while throughout the study, this additional time was reduced to 11 minutes (**Paper III**).

Hauling of the gear took place with a locally used gillnet hauler (Figure 23 a), which leads to entanglement of the gear in itself, regardless of whether the standard gear or the modified gear is used. This may have several reasons: the horizontally aligned rollers do not allow for enough space of the netting to stay untangled, the floatline is made of twisted rope which enhances wrapping of the netting around the floatline, and the floats are quite large and tend to fall through the large meshes. Additionally, the spheres sometimes fell through some underlying layers of mesh. It should be noted though, that the nets were not entangled before entering the hauler (Figure 23 a), thus the hauler could be one issue why the nets entangled. To avoid entanglement and facilitate preparation of the netting for the following trip, several improvements could be made. These improvements could comprise the use of braided rope instead of the twisted rope, the use of a hauler with vertically aligned broad rubber rollers, as commonly used in the German and Danish gillnet fishery (Figure 23 b) and the use of a net stacker to facilitate disentanglement in the last step of the clearing of the net (Figure 23 c).

(a) (b) (c)

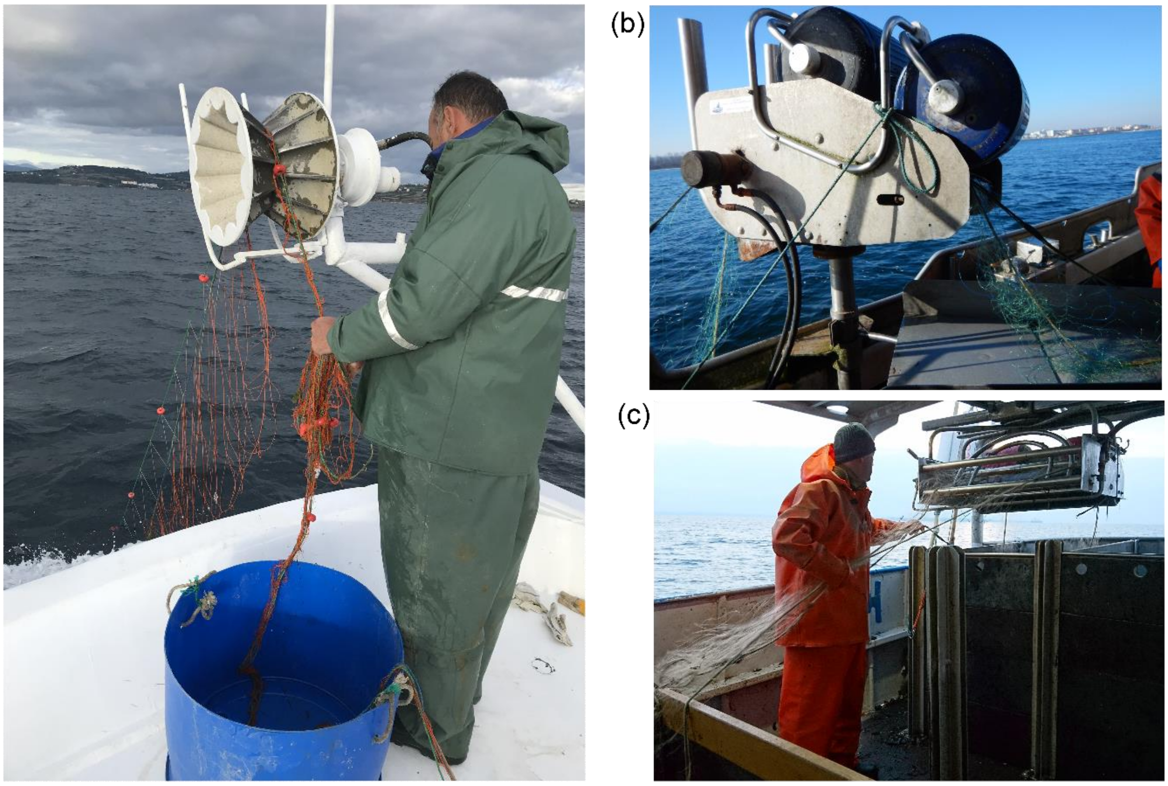

Figure 23: Gillnet hauler commonly used in the Black Sea turbot fishery (a). The gillnet is not entangled prior to passing through the white hauler (photo by Sabri Bilgin). Hauler used on Danish and German vessels with rubber rollers (b). Net stacker on a Danish vessel facilitating the clearing of gillnets prior to setting (c)

Other reasons why the net with spheres tended to get more easily entangled and was more difficult to handle could be associated with the natural fiber and the large meshes. In trials prior to **Paper III**, a prototype nylon net had been equipped with acrylic glass spheres at a similar sphere-sphere interval as the Turkish turbot net to assess potential setting, hauling and clearing issues. This net did not show any problems of entanglement, had been hauled by hand as well as a hauler used on a German vessel, and cleared successfully with a net stacker. However, the prototype gillnet was made from nylon and had smaller mesh sizes (110 mm stretched mesh size). The spheres may “slip” better over the smooth nylon surface when the net is cleared and be less likely to fall through underlying smaller meshes when stacked, as more netting is available to lie on.

7.5 Implications for future research

The results of the pilot study presented in **Paper III** show a promising bycatch reduction when using a gillnet modified with acrylic glass spheres. However, as previously mentioned, to achieve a statistically robust result with 80% power, 130 sets with the observed bycatch rate would have to be carried out (**Paper III**). If five vessels were equipped with modified gillnets, the full-scale trial could be completed within one fishing season in the Black Sea. A prerequisite is, however, that an automated process to attach the spheres is developed to be able to provide this amount of netting.

8 CONCLUSIONS AND PERSPECTIVES

Worldwide, several species of odontocetes are under severe pressure from bycatch in gillnet fisheries (Brownell Jr et al., 2019), thus the need for tools to reduce bycatch is high. The first study presented in this thesis was able to identify optimal acoustic reflectors, i.e. small acrylic glass spheres, that increase the acoustic reflectivity of gillnets and have the potential to make a gillnet appear as an impenetrable barrier and thus reduce bycatch of odontocetes (**Paper I**). In addition, the simulation of target strength of different objects showed, that adding material fillers to the netting filament itself does not increase the acoustic reflectivity, as the limiting factor is the diameter. This means, that any attempt to increase the detectability of gillnets by altering the filament itself will likely be in vain, unless a very elastic material, i.e. rubber, is used (**Paper I**). The main drawback of rubber materials is their low tensile strength, making them unsuitable for operation in gillnet fisheries. The simulations of target strength of the filaments also showed exceptionally low target strength values at 130 kHz when the material parameters were close to the material characteristic of nylon (**Paper I**). Harbor porpoise clicks are very narrow band and centered at 130 kHz with a 6 – 26 kHz 3-dB bandwidth (Teilmann et al., 2002; Villadsgaard et al., 2007), i.e. the major part of acoustic energy falls within this range (Figure 7). These click characteristics could explain why harbor porpoises are especially at risk when encountering nylon nets, as 130 kHz is the peak frequency of their echolocation range.

Gillnets equipped with small acrylic glass spheres become highly acoustically visible compared to standard nets, if the ensonification frequency and the resonance frequency of the sphere match (**Paper II**). For example, at 130 kHz, the use of 8 mm acrylic glass spheres increases the acoustic reflectivity of gillnets, potentially making gillnets appear as an obstacle. The pattern of the simulated target strength of a single sphere across frequencies (**Paper I**) follows a similar pattern as the measured area backscattering strength of a gillnet equipped with several spheres (**Paper II**) across frequencies above 100 kHz. The acoustic reflectivity did not decrease with an increase in inclination of the net relative to the transducer, owing to the fact that spheres are omnidirectional (**Paper II**). On the contrary, the acoustic reflectivity increased for some sphere-sphere intervals as more spheres were ensonified when the gillnet was set at an angle relative to the transducer. In Mooney et al. (2004), where it was aimed to determine whether a $BaSO_4$ filler would increase target strength of a gillnet, the target strength decreased with increasing inclination. Similarly, the target strength of standard nets decreased with increasing inclination in several studies (Au and Jones, 1991; Kastelein et al., 2000; Mooney et al., 2004). This is particularly important, as during operation of gillnets the angle of approach of harbor porpoises is unpredictable and detectability must be provided regardless from which direction the animal is encountering the net.

The spherical shape of the optimal reflector is complemented by the right choice of material. Aside from the resonance effect induced by the optimized combination of size and material characteristics of acrylic glass, acrylic glass has other advantages. It is transparent, thus it should be inconspicuous to fish and has the same density as sea water, which should minimize the effect on the behavior of the netting. Furthermore. as acrylic glass has a relatively low water absorption coefficient, especially compared to nylon (Abts, 2016), the acoustic properties should remain constant throughout the soak time.

This is the first study that comprehensively showed the acoustic properties of gillnets and an improvement in detectability through modifications. The detectability was improved quantitatively through an increase in absolute values and an improved spatial pattern in an acoustic beam. It is not known how harbor porpoises process their perceived images and whether they primarily rely on the absolute value of acoustic reflectivity, i.e. target strength, or the distribution of echoes to perceive barriers. In the present case both issues, a low reflectivity and the acoustic image are tackled. The absolute value of acoustic reflectivity is increased when acrylic glass spheres are attached to gillnets and the acoustic image is altered in such a way that the spheres should create the image of a barrier (**Paper I**, **Paper II**). The likelihood of a harbor porpoise to mistake the gillnets for a fish shoal should be relatively low, as the shoal has a clearly defined beginning and end, while the gillnet is an extended structure. Furthermore, harbor porpoises are more likely to be triggered by moving prey (Feldskov Hansen et al., 2017), rather than a static object. **Paper I** and **Paper II** provide the physical basis for the development of an effective bycatch mitigation method and the most optimal gillnet modification was tested during a field trial in **Paper III**. Promising results regarding bycatch reduction of harbor porpoises in a turbot gillnet fishery in the Black Sea were achieved by using a gillnet modified with the species-specific optimal reflector, i.e. the acrylic glass sphere with an 8 mm diameter (**Paper III**). The raw data suggests a potential bycatch reduction by 60 %, albeit the results were not statistically significant, which is also associated with the low number of hauls (**Paper III**). The most important prerequisite for a passive reflector to effectively reduce bycatch is that the animal is actively echolocating in the direction of the gillnet, as the reflector in itself does not have any actively alerting effects and the echolocation beam of harbor porpoises is very narrow (Koblitz et al., 2012). While harbor porpoises do echolocate frequently, they also sometimes swim in silence or echolocate towards the bottom when searching for certain prey species (see Chapter 3.3). Their inattentiveness towards the gillnet may be one reason why the highly visible gillnet caught harbor porpoises. Early research has also suggested that a combination of a “wake-up call” and improved detectability could be the most effective way to reduce harbor porpoise bycatch (Goodson, 1997). Furthermore, noise could also be either reducing the range of the perceivable signals (Hermannsen et al., 2014) or disrupt the echolocation activity of harbor porpoises (Wisniewska et al., 2018). Several mechanisms underlying the bycatch process of harbor porpoises are thus not well understood and should be subject to further investigations (see Chapter 8.1). On the other hand, the low abundance or decline of several populations of harbor porpoises are cause for immediate concern. The timely further development of the promising mitigation method developed within this thesis could be crucial to halt the decline of some odontocetes populations.

As an example, in the Eastern Baltic Sea there are approximately 500 harbor porpoises left (Amundin, 2016) and there is urgent need to provide tools that mitigate the conflict between nature conservation goals and gillnet fisheries. It has been proposed to list the Baltic Proper harbor porpoise in Appendix I of CMS (Read et al., 2019; CMS, 2020), which would drastically increase the pressure on Range States, i.e. states bordering the Baltic Sea, to take action towards a strict protection of the species. ICES has recommended i) to close gillnet fisheries in Natura 2000 sites with high detection probability of harbor porpoises and ii) to use pingers outside of Natura 2000 areas (ICES, 2020). Fishery closures can be effective when there is a high aggregation of non-target species in space or time (Hall et al., 2000). However, this bears the potential of relocating the fishing effort elsewhere (Greenstreet et al., 2009). Therefore the effect for a highly mobile species might be lower than expected. Thus, implementing technical measures to reduce bycatch of harbor porpoises is essential, especially outside of Natura 2000 areas, as the current PBR (Potential Biological Removal) bycatch limit for harbor porpoises is estimated at 0.7 animals per year (ICES, 2020). Furthermore, enforcing compliance to the regulations is a key element for bycatch reducing methods to be successful (McDonald et al., 2016). Compliance to the use of modified gillnets could be easier to enforce than the use of functioning pingers, as ensuring that pingers are functional under water can be a challenge for enforcement staff. The gillnet modification developed in the previously discussed studies could thus greatly contribute to the portfolio of measures for reducing bycatch of harbor porpoises.

Based on the results of **Paper I**, similar modification as tested in **Paper III** could be applied to other odontocetes species. In South America, the Franciscana dolphin is seriously threatened due to bycatch in gillnet fisheries (Negri et al., 2012). Trials could be carried out with similar reflectors as used in **Paper III**, as the echolocation frequency of Franciscana dolphins is similar to that of harbor porpoises (Morisaka and Connor, 2007). Most recently, the fate of the common dolphin (*Delphinus delphis*) population in the Bay of Biscay has drawn international attention and measures to protect the population have been included in the ICES advice on emergency measures to prevent bycatch (ICES, 2020). Common dolphins echolocate at approximately 112 kHz (Morisaka and Connor, 2007), thus slightly larger acrylic glass spheres would be needed to match their echolocation frequency (**Paper I**). Furthermore, trials with species-specific reflectors could be carried out for many other species threatened by bycatch (Reeves et al., 2013).

8.1 Scientific perspective

8.1.1 Behavioral experiment

To better understand the underlying causes of bycatch in gillnets, it is essential to carry out an experiment quantifying the movements and acoustic behavior of harbor porpoises around gillnets. In the past, such behavior has been evaluated in tank studies (Kastelein et al., 1995b) as well as by field studies using visual (Koschinski et al., 2006; Nielsen et al., 2012) or passive acoustic monitoring methods (Boström et al., 2013) to track the behavior. In an experiment combining both visual and acoustic tracking, one method would compensate the drawbacks of the other. Visual tracking of surfacing harbor porpoises has been successfully conducted using a theodolite (Culik et al., 2001; Koschinski et al., 2003; Kyhn et al., 2012; Schartmann, 2019), a device that registers the vertical and horizontal position of the harbor porpoise relative to the observer and enables the observer to calculate tracks from subsequent surfacing points. A prerequisite is that the observer is standing on a sufficiently high point of view to be able to track the harbor porpoises and accurately measure their position (Figure 24 b).

(a) (b)

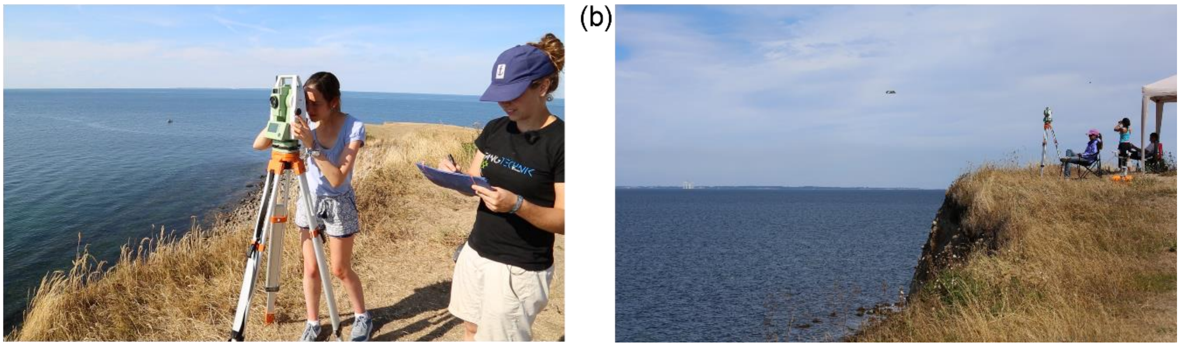

Figure 24: Two observers tracking a harbor porpoise with a theodolite (a) from a sufficiently high observation point (b). Photographs by Anne Schütz taken in Fyns Hoved, Denmark

Acoustic monitoring could either be carried out with passive acoustic devices that register presence and absence of harbor porpoises as well as some click characteristics (Koschinski et al., 2006; Boström et al., 2013), or an acoustic hydrophone array that allows to triangulate the 3D underwater movements of harbor porpoises from their click behavior (Gillespie and Macaulay, 2019). A preliminary experiment using passive acoustic devices has been carried out in Sweden (Gustafsson, 2020) and results indicate that it is less likely to encounter harbor porpoises around gillnets modified with acrylic glass spheres. This is in line with the results from **Paper III**, as fewer animals were bycaught. A behavioral experiment could also be useful in exploring the reaction to gillnets modified with acrylic glass spheres and increased acoustic reflectivity in combination with other alternative methods of bycatch reduction such as LEDs (Bielli et al., 2020) or PorpoiseALerting Devices (Culik et al., 2015; Chladek et al., 2020).

8.1.2 Selectivity and hydrodynamic behavior

As described in Chapter 2.2, the selectivity curve for gillnets is rather narrow and depends largely on the shape of the mesh. To quantify any changes in selectivity owed to the attachment of the acrylic glass spheres, it is advisable to carry out a FISHSELECT study (Herrmann et al., 2009). In addition to the morphological limitations that can be grasped using FISHSELECT, there might be an influence on the flow through the net influencing the hydrodynamic behavior. Nets with iron oxide fillers needed to be equipped with additional floats to compensate for the additional weight (Larsen et al., 2007). Despite the fact that the acrylic glass spheres should be almost neutrally buoyant and thus not change the hydrostatic behavior, the flow properties may have an influence on the overall behavior and entanglement properties. Behavior of the gillnet in waterflow can be investigated in a flume tank (Winger et al., 2006).

8.1.3 Development of an automated process to attach spheres

Prior to a large-scale fishery trial or widespread implementation of gillnets with acrylic glass spheres, it is vital to develop a method to automatically build this type of gillnet. Spheres could either be attached to the filament and then woven into a net or automatically attached to a sheet of netting. Acrylic glass has a lower melting temperature than nylon (Abts, 2016), thus it should be possible to extrude spheres directly onto the netting without destroying the filament. Since acrylic glass is a thermoplast, other ways of attaching them might be the use of heat, to induce a behavior similar to shrink sleeves. During the development of an automated process, it could be considered to use alternative materials that are also elastic, similarly to acrylic glass. Ideally, nylon spheres would be used given that they have sufficient acoustic properties. These properties would have to be evaluated prior to such a development and be monitored over a certain soak time of nylon, as it has a high water absorption coefficient and may change its echo properties over time (Abts, 2016). The reason why nylon would be the preferred material is a) the possibility for the manufacturer to use the same extrusion machine for filament and sphere and thus reduce the working steps and b) products that are made from compound plastics (here acrylic glass and nylon nets) are more difficult to recycle than products made from only one type as they need to be sorted due to their mechanical properties (Singh et al., 2017).

8.2 Commercial perspective

Gillnets modified to reduce bycatch are urgently needed in several fisheries to avoid closures of fisheries and mitigate conflicts between nature conservation and the use of marine resources. Bycatch of marine mammals is also a nuisance for fishers as it can result in increased labor and costs due to damaged fishing gear, as well as critical perception by the public. Gillnets that reduce bycatch of odontocetes without reducing catch would be a compromise that caters to both fishers and nature conservation goals.

Two conditions must be met prior to a widespread implementation of gillnets with acrylic glass spheres, both of which need a large-scale fishery trial. It needs to be documented and statistically verified that the new gear has a similar catch efficiency as standard gillnets. The pilot trials in **Paper III** showed that the catch of bottom-dwelling species was not reduced, albeit it was only confirmed for the bycatch of thornback rays and not specifically for the target species turbot. However, the mechanical entanglement process of the gillnet with acrylic glass spheres does not seem to be compromised. Trials testing for catch efficiency should be carried out throughout a fishing season preferably for several target species to include seasonal and species-specific effects.

The second condition is the statistically robust assessment of the bycatch reduction when the gillnet with acrylic glass spheres is used in direct comparison with the standard gillnet. Depending on the region, the scale of such a trial may be different. In the Black Sea, where bycatch rates are seasonally high (Bilgin et al., 2018), less than 130 sets would be needed to verify the bycatch reduction achieved in **Paper III**. In other parts of the world like, e.g., the Baltic Sea, where bycatch rates are much lower, a substantially higher number of sets would be needed to achieve a statistically robust result. Other large-scale trials investigating bycatch reducing methods have carried out up to 864 sets in order to gain a robust data set (Gearin et al., 2000; Carlström et al., 2002; Mangel et al., 2013; Bielli et al., 2020). A large-scale bycatch trial would need to be carried out in a region with potentially high bycatches, and a large harbor porpoise population, e.g. in the North Sea, in the Western Atlantic, or in the Icelandic lumpsucker fishery to be able to gather data in a relatively short period.

Implementing the use of new gears on a voluntary basis has proven to be exceptionally difficult (Eayrs and Pol, 2019). A co-management process involving fishers and other stakeholders could facilitate the implementation (Bruckmeier and Höj Larsen, 2008). This participatory approach could include educational measures to increase awareness of the impacts of bycatch on a population level as well as practical improvements of the gear to make it commercially viable. The modified gillnet developed in this study could greatly benefit from such a co-management process and even more contribute to sustainable gillnet fisheries.

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Paper I

frontiers in Marine Science

ORIGINAL RESEARCH
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Determination of Optimal Acoustic Passive Reflectors to Reduce Bycatch of Odontocetes in Gillnets

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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. 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 results. 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. We simulated the acoustic reflectivity of a wide range of materials in different shapes, sizes, and environmental conditions, with a focus on polymer materials. We verified the simulation results experimentally and calculated detection distances of the selected modifications. For example, if 8 mm acrylic glass spheres are attached to the net at intervals smaller than 0.5 m, the spheres have the same target strength (TS) at 130 kHz as the most recognizable part of a gillnet, the floatline. Modifications of the netting material itself, e.g., using barium sulfate additives, do not substantially increase the acoustic reflectivity of the net.

Keywords: bycatch, odontocetes, resonance, target strength, acrylic glass, gillnet

INTRODUCTION

At least since Biblical times, whales, or cetaceans, have been an order of animals fascinating to humans. Over time, the focus has shifted from hunting to coexistence and onto conservation of these marine mammals (Harrop, 2003). Nowadays, cetaceans are protected by national and international agreements (Marine Mammal Protection Act, 1972; ASCOBANS, 1992; EEC, 1992; Accobams, 2001), and only a small number of countries still practices commercial whaling. In addition to humankind's ethical obligation to avoid their unintentional killing, whales are often top predators and thus support the resilience of ecosystems (Estes et al., 2011). To keep ecosystems stable, as well as ecosystem services that provide us with food, security, and general well-being (Millennium Ecosystem Assessment, 2005), it is necessary to provide suitable protection for top consumers. The many reasons that threaten whales include climate change, habitat degradation, increased aquatic noise, pollution, and overfishing (Reeves et al., 2003; IWC, 2019). Furthermore, unwanted bycatch of marine megafauna, including whales, has been pinpointed as one of the driving forces in species reduction (Lewison et al., 2014). The International Whaling Commission has acknowledged bycatch as the "greatest immediate threat for cetaceans globally" (IWC, 2018).

Static fishing nets, such as gillnets, belong to the most frequently used fishing gears owing to their low cost, easy handling, and their practicality on the large number of small fishing vessels (He, 2010). Despite being highly size selective, having little direct impact on the seabed (Savina et al., 2018), and being more fuel efficient than active gears, gillnets have been criticized for the bycatch of higher taxa species, especially birds and aquatic mammals. They are considered to be one of the drivers in severely reducing the number of individuals of some cetacean species (Burkhart and Slooten, 2003; Crespo, 2018) and even driving them to the verge of extinction (D'agrosa et al., 2000; Turvey et al., 2007).

Cetaceans are divided into two groups: toothed whales (odontocetes) and baleen whales (mysticetes). Both groups use sound as a communication tool, but only for odontocetes has it been proven that they echolocate actively, which could allow them to avoid gillnets. Despite their echolocation ability, it is still unknown why odontocetes entangle in gillnets in the first place. At least harbor porpoises (*Phocoena phocoena*, L.) are able to detect gillnet structures from a distance in quiet conditions (Nielsen et al., 2012). There are several hypotheses why odontocetes entangle: (a) they do not echolocate continuously (Dawson, 1991); (b) they echolocate in a different direction or lock in on another target (Au and Jones, 1991; Mackay, 2011); (c) they mistake gillnets, owing to the gillnets' faint echo, for an object they can penetrate and fail to recognize it as an obstacle (Goodson, 1997); and (d) the echo of the net is masked. In this study, we follow the hypothesis that odontocetes are able to detect gillnets from a short distance, but do not realize they are an obstacle. We aim to improve both the perceived image as well as increase the detection range to avoid collision.

There have been several attempts to develop gillnets that reduce the bycatch of odontocetes with mixed and sometimes contradictory results. Studies have demonstrated reduced target catch (Larsen et al., 2007), decreased bycatch for certain species (Perrin et al., 1994; Trippel et al., 2003; Larsen et al., 2007), but also no decrease in bycatch for other species (Perrin et al., 1994; Bordino et al., 2013). Many attempts have been based on trial-and-error approaches without sufficient understanding of the acoustic properties of the modified gears and the requirements of the fishery. For instance, lower target catches or impeded handling and safety hazards caused by modifications (Hembree and Harwood, 1987; Peddemors et al., 1991) hamper the voluntary uptake of modified gillnets.

There are two options to modify the acoustic reflectivity of gillnets: changing the netting itself by using a different kind of filament, and adding objects with strong echo properties. If the latter option is chosen, the object needs to fulfill certain requirements to succeed in reducing bycatch and be adopted by the fishery. The object needs to be acoustically omnidirectional, not impede handling of the net, and have little or no effect on net behavior; the last is essential to keeping fish catches constant. Therefore, a spherical object is suitable, because spheres have the same properties from every direction and the density of the object is preferably close to seawater to avoid an increase or decrease in buoyancy of the net. Furthermore, the object must be relatively small to facilitate handling and minimize the need for additional storage space, especially on board small vessels.

These requirements suggest several possible gillnet modifications. Consequently, a systematic approach to the issue is a valuable alternative to a large-scale, trial-and-error field trial. Here, for the first time, we systematically simulated the target strength (TS) of potential modifications to gillnets that can substantially increase the acoustic visibility of gillnets, such as modified filaments and added objects. In a parametric study, we have simulated a large number of different objects to identify the ideal objects that would allow odontocetes to perceive gillnets early on and classify them as obstacles. We simulated the acoustic characteristics of the objects in a wide range of frequencies to cover many odontocete species and thus allow the identification of optimal objects for different species, resulting in a wide application of the modification. Selected simulations were confirmed by measurements in an acoustic tank. Furthermore, a standard gillnet was equipped with one of the promising objects, and sonar images were taken of both a modified and a standard gillnet. We used harbor porpoises as a model species for odontocetes, because they are affected by gillnet fisheries worldwide (Trippel et al., 1996; Vinther and Larsen, 2004; Read et al., 2006; Koschinski and Pfander, 2009; Tonay, 2016) and are a well-studied species. Thus, in the third part of the study, we predict the distance at which harbor porpoises, an endangered species in the Eastern Baltic Sea (Helcom, 2013), should be able to perceive a modified net.

MATERIALS AND METHODS

Simulation of Target Strength

Target strength is one of the standard parameters used to describe the acoustic reflectivity of different objects, including nets (Pence, 1986; Au and Jones, 1991; Mooney et al., 2004). It can be defined as:

$$TS = 20 \times \log_{10} \left(\frac{p_r}{p_i} \right) \quad (1)$$

where p_r is the sound pressure of the object relative to 1 m from the target, and p_i is the incident sound pressure of the signal at the target. The unit is dB re 1 m (MacLennan et al., 2002; Mooney et al., 2007).

We used the software COMSOL Multiphysics (Comsol Multiphysics®, 2018) to conduct a parameter study. We numerically solved the Helmholtz equation, which is used to describe the acoustic pressure field in fluids, and derived TS values for a large variety of objects and sound frequencies under different environmental conditions. The simulation environment was surrounded by a perfectly matched layer

(PML), which absorbs all outgoing waves without reflection (see **Supplementary Information**). The simulation environment can be reduced to 2D, because cylinders and spheres are rotationally symmetric.

The following parameter categories were modified in the simulation: the geometry of the object, material characteristics of the object, characteristics of the surrounding medium, and sound frequency (**Table 1**). The geometrical characteristics of the objects included shape (solid and hollow spheres, cylinders, cuboids, radar reflectors, half spheres) and size (diameter, wall thickness). Here, we present only results for solid and hollow spheres as well as cylinders, because other shapes do not fulfill the defined requirements, especially omnidirectionality and small size.

The material characteristics of the object are Young's modulus (E) as a measure for elasticity and density (ρ) of the material. Although the object density should ideally be close to seawater, we have used a much larger range of densities to evaluate a broad range of possibilities. We chose material densities starting at 1000 kg/m^3, because synthetic materials less than 1000 kg/m^3 are usually foams, which are inhomogeneous and thus difficult to simulate. The alternative material with densities less than 1000 kg/m^3 are wooden products; these are usually anisotropic, so they have different characteristics depending on the direction. Furthermore, their mechanical properties are difficult to control, because the properties of natural materials change with the environmental conditions they grow in, making it virtually impossible to ensure the same characteristics for each object.

The characteristics of the surrounding medium are density and speed of sound, which act as a proxy for the environmental conditions in water, i.e., temperature and salinity. Generally, speed of sound and medium density were approximated at 1500 m/s and 1000 kg/m^3, respectively, unless otherwise specified in **Supplementary Information**.

Verification of Selected Simulation Results

To verify the simulation results, we experimentally measured the acoustic properties of selected objects [table-tennis ball (TT ball), steel sphere 25.5 mm, acrylic glass spheres 6.4 and 9.6 mm] in an acoustic tank (5 m × 5 m × 3 m). These objects were attached to a fishing line and consecutively suspended from the surface to be placed at 1.50 m depth and at an approximate distance of 1 m from the acoustic transducer. The objects were ensonified using a B&K 8105 spherical hydrophone; the signals were received using a Reson TC4014 spherical hydrophone (sampling rate 4 MS/s with a 200 kHz low-pass Besselfilter; amplification + 50 dB). The signal was a sweep between 60 and 120 kHz (184 dB re 1 μPa source level).

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/m^3
Salinity (Sal)	0–31	psu
Temperature (T)	0–18	°C

Sonar Imaging of Standard and Modified Nets

To visualize the potential effect of small objects with high acoustic reflectivity attached to a gillnet, we took an acoustic image using a standard scientific echosounder (SIMRAD EK60) of both a modified and a standard gillnet. We glued 8 mm acrylic glass spheres to a standard gillnet (140 mm stretched mesh size, 2 m rigged height) at a distance of 0.3 m between the spheres. Both the modified gillnet and the standard gillnet without spheres were stretched consecutively between two small boats, and the net was placed in the center of the sonar beam underneath RV Clupea. Echograms were made using 38 and 120 kHz hull-mounted transducers. Sonar data were visualized in SonarData Echoview (Echoview Software Pty Ltd, 2015).

Potential Detection Distances

The applicability of gillnet modifications depends largely on their effect on echolocating odontocetes. We modeled the potential detection distances of the modified net using the harbor porpoise as a model. In this case, we used 8 mm acrylic glass spheres as the modification and virtually distributed them over a gillnet at different distances between spheres. The sphere-sphere distances ranged from 0.1 to 0.7 m.

First, we calculated the maximum possible TS of spheres in an ensonified area of 0.36 m^2 for each sphere-sphere distance. This area was chosen to stay consistent with Kastelein et al. (2000), who determined TS and detection ranges for various gillnets and gillnet components when 0.36 m^2 are ensonified using echosounder with a similar beam angle as a harbor porpoise. The number of spheres that are simultaneously ensonified depends on the distance between spheres in a given area. For each distance between spheres, we fit the maximum number of spheres in the ensonified area while maintaining equal distance between the spheres. For example, applying a distance of 0.1 m between the spheres, results in 37 spheres in the ensonified area, whereas 0.7 m distance results in a single sphere in the ensonified area.

To calculate the maximum possible TS for a given number of spheres, we solved Equation 1 for p_i/p_r:

$$TS_{n\ spheres} = 20 \times \log_{10}\left(n \times \left(\frac{p_i}{p_r}\right)\right) \quad (2)$$

which results in:

$$TS_{n\ spheres\ coherent} = 20 \times \log_{10}(n) + TS_{single\ sphere} \quad (3)$$

where n is the number of spheres and TS_{single_sphere} is the TS of one sphere. This corresponds to the coherent addition of the TS of n spheres, which is the maximum possible value. In addition to the maximum, we also calculated the most likely mean TS by incoherent addition (Kinsler et al., 2000):

$$TS_{n\ spheres\ incoherent} = 10 \times \log_{10}(n) + TS_{single\ sphere} \quad (4)$$

Detection distances were modeled based on the method described in Kastelein et al. (2000). We calculated potential detection distances for an ensonified area of 0.36 m^2 with different distances (0.1–0.7 m) between spheres. The distance between spheres determines the number (n) of spheres that are simultaneously ensonified. The following equation was solved for R:

$$40 \times \log_{10} R + 2 \times \alpha \times R + TS_{n\ spheres} = 40 \times \log_{10} R_{ref} + 2 \times \alpha \times R_{ref} + TS_{ref} \quad (5)$$

where R is the distance at 90% detection probability for the investigated object. The reference 90% detection range (R_{ref}) for an object with reference TS (TS_{ref}) is given by Kastelein et al. (1999). Here, we assumed an acoustic absorption coefficient of seawater α = 0.038 dB/m (T = 8°C, Sal = 35 ppt, ph = 8, depth = 50 m, Ainslie and McColm, 1998).

RESULTS

Simulation of Target Strength

Identification of Relevant Parameters, Narrowing Parameter Ranges

First, we simulated the TS of spheres in a large range of diameter (5–60 mm), elasticity (0.1–9.6 GPa), material density (1000–8000 kg/m^3), and combinations thereof in order to identify the relevant parameters and their ranges to obtain maximum TS at small sphere size for given frequencies.

Figure 1 shows the TS of solid spheres depending on the elasticity (Young's modulus) and material density, exemplarily at 130 kHz. In **Figures 1A–C**, spheres between 5 and 60 mm are shown for three exemplary densities (1000, 1180, 8000 kg/m^3), representative of the extreme ends of the parameter range and an approximation of seawater density. **Figures 1D–F** show the interplay between material density and elasticity for three sizes of small spheres (5, 10, 15 mm). Other densities and frequencies are found in the **Supplementary Information**.

Target strength is positively correlated with diameter of the sphere (**Figures 1A–C**). Nevertheless, the overall pattern is not homogeneous. Resonance and extinction effects can be seen for many parameter combinations resulting in outstandingly strong and weak TS for given parameter combinations. For instance, relatively high TS can be achieved for small spheres (10 mm sphere, 3.6 GPa, 1180 kg/m^3, 130 kHz), whereas large spheres can have very weak TS owing to extinction (40 mm sphere, 4.6 GPa, 1180 kg/m^3, 130 kHz). Sphere size combined with the material properties are crucial to identifying optimal reflectors. High TS of small spheres ($d < 20$ mm, **Figures 1A–C**) is achieved for a Young's modulus between approximately 2.5 and 4.5 GPa. This range of elasticity for small spheres is also suitable over the entire frequency range used for echolocation by many odontocetes (50–150 kHz; see **Supplementary Information**).

If existing standard materials are considered, the material density cannot exceed 3000 kg/m^3, because Young's modulus and density are positively correlated (**Figure 2**). Even if a material existed with a high density and low Young's modulus, the increase in density would not necessarily positively affect TS of small spheres (**Figures 1D–F** for 130 kHz; additional figures in **Supplementary Information**). Based on these general investigations over a broad range of parameter characteristics, suitable echo targets could be chosen for any desired application.

To find additional objects to be mounted on gillnets to increase the acoustical detectability of these gillnets, we further investigated spheres of a density close to seawater. This narrows potential materials to polymers (**Figure 2**, reddish area). Several polymers are in the suitable parameter range and therefore could be used for gillnet modification. We chose to concentrate our effort on acrylic glass (PMMA) because it best fits the simulated parameters and has further advantages, such as transparency and being easily attachable to a gillnet with an acrylic adhesive with the same material properties as the sphere itself. In the additional simulations, we identified a minimum sphere size needed to obtain resonance effects, resulting in high TS at a specific frequency and simulated spheres on a higher diameter resolution scale. This simulation approach was conducted for a large range of frequencies, allowing us to identify species-specific resonators.

In the literature, the Young's modulus for acrylic glass is given as approximately 3.3 GPa (Abts, 2016); this value, however, does not account for changes in Young's modulus at high frequencies. Therefore, we have adapted the value to 4.8 GPa, based on our own measurements at high frequencies.

Minimum Size for Resonance Effect at Different Frequencies

For small spheres, resonance effects, rather than pure geometrical reflection, are responsible for high TS, especially at low material densities (**Figure 1**). This effect can lead to large differences in TS, even if the object parameters change little. Because of the large variation in TS resulting from changes in sphere diameter, the TS was simulated at a finer resolution of the diameter range across frequencies for acrylic glass (**Figure 3**). This allows the determination of the minimum size of a sphere with resonance characteristics and the exact size of a sphere that would be the ideal resonator at the main echolocation frequency of a given odontocete species. The TS reference used and illustrated in **Figure 3** is -50 dB, which corresponds approximately to the TS of gillnets (Au and Jones, 1991; Perrin et al., 1994; Kastelein et al., 2000; Mooney et al., 2004). Furthermore, at least harbor porpoises could detect nets with -50 dB TS from approximately 5 m (Kastelein et al., 2000). As a rule of thumb, the TS of an additional object needs to be greater than the reference TS to improve the acoustic detectability and so to potentially increase the detection range of gillnets for odontocetes.

The graphs (**Figure 3**) are shown for both the literature value of elasticity for acrylic glass (**Figures 3A,B**), and the adapted

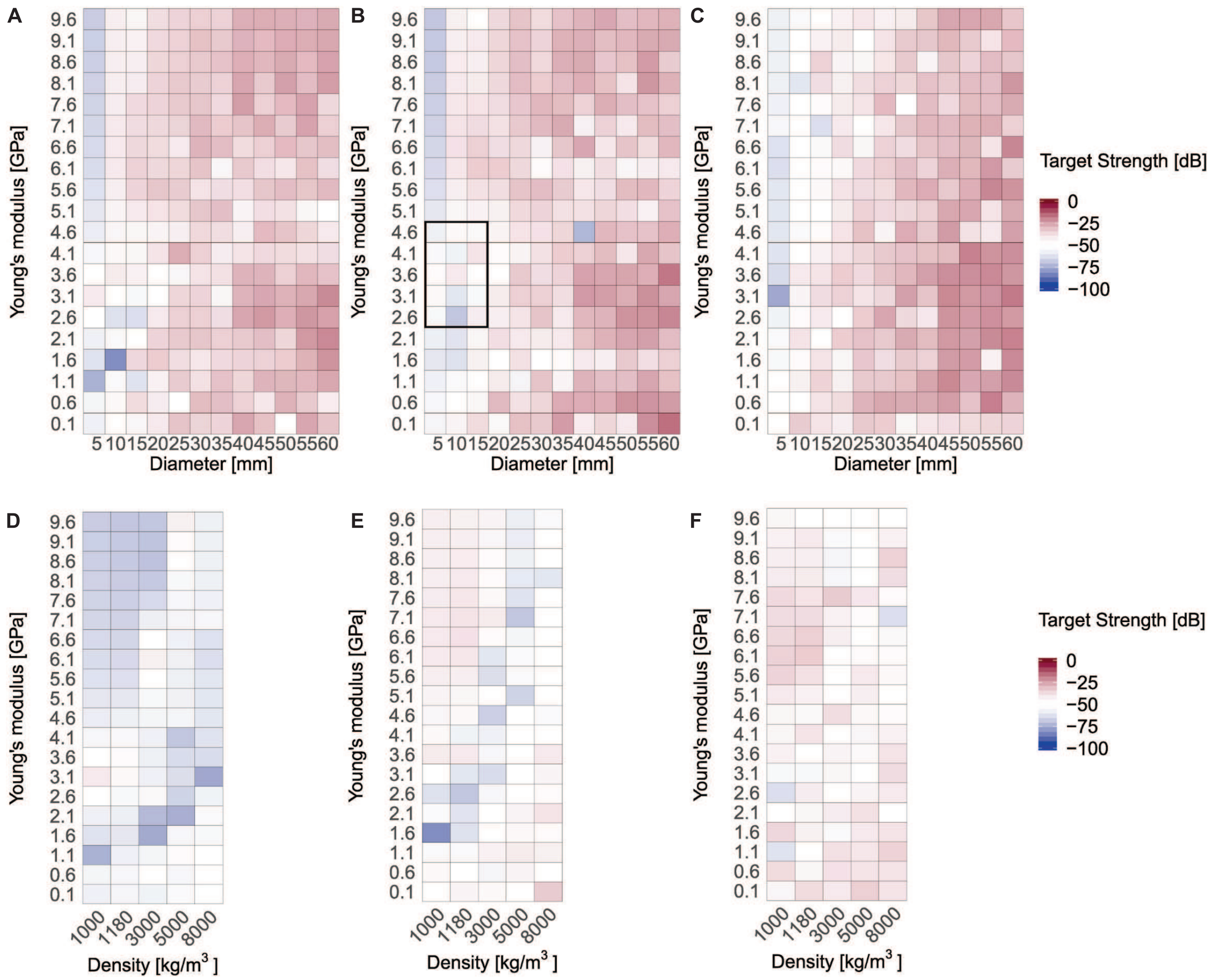

FIGURE 1 | (A) Target strength of solid spheres at ρ = 1000 kg/m^3; **(B)** ρ = 1180 kg/m^3; and **(C)** ρ = 8000 kg/m^3 at 130 kHz. Each cell represents one simulation, color ranges from strong echo (red) to low echo (blue). The box in **(B)** shows the most promising region of objects: small, relatively large echo, and density of seawater; **(D–F)** show the interaction between material density and elasticity for three small sphere sizes: **(D)** 5 mm, **(E)** 10 mm, **(F)** 15 mm. Additional frequencies and material densities are available in **Supplementary Information**.

high-frequency elasticity value (**Figures 3C,D**). **Figure 3** is given in two different color scales. **Figures 3A,C** uses the same color scale (0 to -100 dB) used by **Figure 1** for reasons of comparison. Additionally, the color scale was adapted to highlight resonance peaks (**Figures 3B,D**; red areas), and areas of acoustic extinction with very low TS (**Figures 3B,D**; blue areas), and easier identification of the reference TS (**Figures 3B,D**; white areas).

Spheres smaller than 3.4 mm in diameter have no potential to improve the TS of a gillnet (TS < -50 dB), even at higher frequencies. Additionally, to get resonance effects at frequencies lower than 32 kHz, a sphere larger than 20 mm is required.

Effects of Salinity and Temperature on Target Strength

Odontocetes occur in many bodies of water across the world. Therefore, we simulated the influence of salinity and temperature on TS of solid acrylic spheres by adapting the density and sound speed of the surrounding medium according to the parameters specified in the **Supplementary Information**. We calculated the TS for spheres between 5 and 12 mm in 1 mm increments and frequencies between 10 and 200 kHz. For example, the TS for an 8 mm acrylic sphere (E = 4.8 GPa) at 130 kHz, where the maximum difference in TS for this sphere size is 1.10 dB and the mean difference 0.44 dB (Table in **Supplementary Information**). At 130 kHz, across all diameters and simulated environmental conditions, the maximum difference in TS was 3.22 dB and occurred within the 10 mm spheres.

TS of Sphere With Small Cut for Attachment to Net

One potential way to attach a sphere to a net is to cut it to the middle and attach it to the net using an acrylic glass adhesive, using the same material the sphere is made of. To quantify

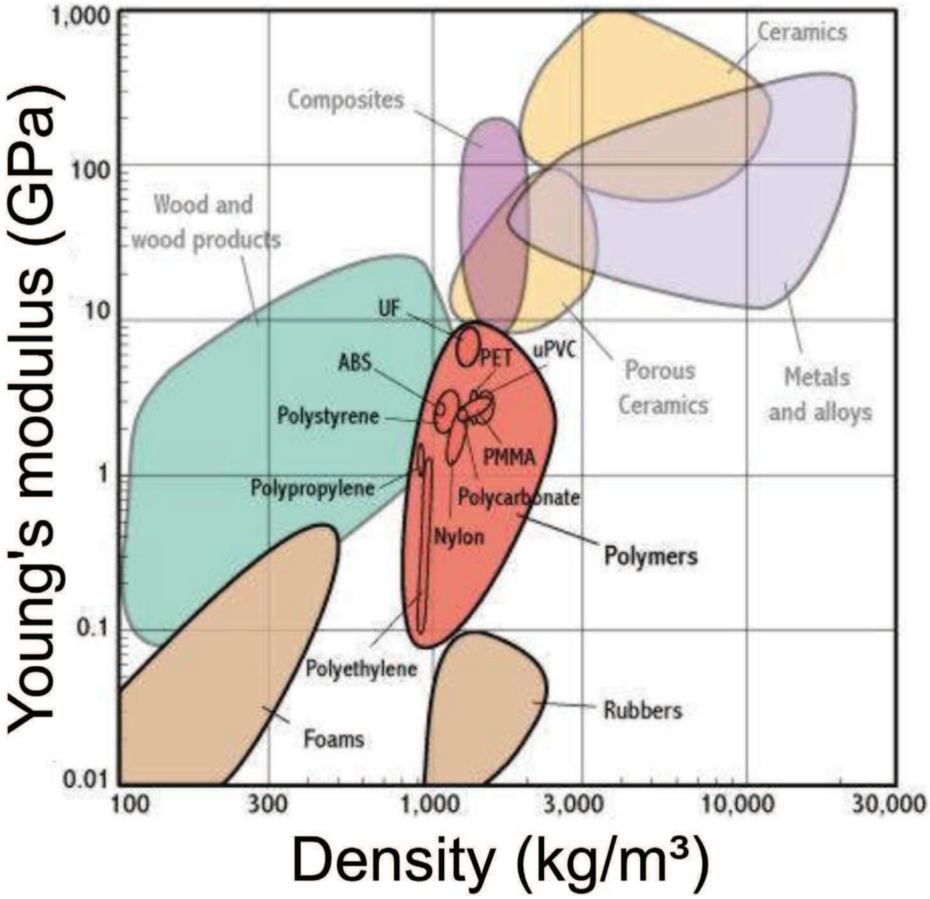

FIGURE 2 | The correlation between Young's modulus and density. Modified and permission granted by Lovatt et al. (2000).

the influence of this attachment method for a given sphere, we simulated the change in TS when a PMMA sphere is cut. The worst-case scenario that could reduce the TS would be if no adhesive is filled in the missing space caused by the cut. **Figure 4** shows the influence of a cut on the TS of a sphere (diameter 8 mm; cut width 0.8 mm) compared with a solid sphere. When a sphere is cut, it is no longer omnidirectional. Thus, the TS value changes greatly with the direction from which the sphere is ensonified. The cut leads to a strong reduction in TS at 130 kHz when the sphere is ensonified perpendicularly to the cut (x-axis in **Figure 4A**). In the other directions, the effect is less pronounced and leads primarily to a shift in resonance peak compared with the solid sphere.

Using a 3D model led to long computation times, which were necessary in this case because the sphere is no longer rotationally symmetrical. Therefore, we simulated the frequency band only between 100 and 150 kHz. Several odontocetes fall in this spectrum, including harbor porpoises, which are an exemplary species throughout the manuscript.

Air-Filled Spheres

As reverberation caused by air bubbles is a widely known issue in sonar imaging, we simulated TS for air-filled spheres. To examine a realistic thickness that could resist pressure, spheres were between 5 and 60 mm in diameter with wall thickness between 1 and 28 mm. Target strength of air-filled spheres is shown at 130 kHz (**Figure 5**; additional figures in the **Supplementary Information**), the centroid frequency of a harbor porpoise. Compared with small (<20 mm diameter) solid acrylic glass spheres (**Figure 3**), air-filled spheres made from acrylic glass do not perform better regarding TS values. For easier comparison, the relevant information of **Figures 3**, **5** are extracted and presented in **Figure 6**.

Alternative Twine Materials

Previous research has attempted to increase the detectability of gillnets by using new types of net materials, especially additives that increase the material density of the net filament. As these nets demonstrated little to no difference in TS measurements in the past (Larsen et al., 2007; Mooney et al., 2007), we simulated the TS of thin cylinders as a proxy for net filaments (**Figure 7**). The diameter of filaments of standard nets is typically 0.5 mm or thinner, and gillnets are rarely constructed from twine (which can consist of several filaments) thicker than 1 mm. Overall, the TS is low across all densities and simulated diameters. A potentially relevant exception are cylinders with a very low

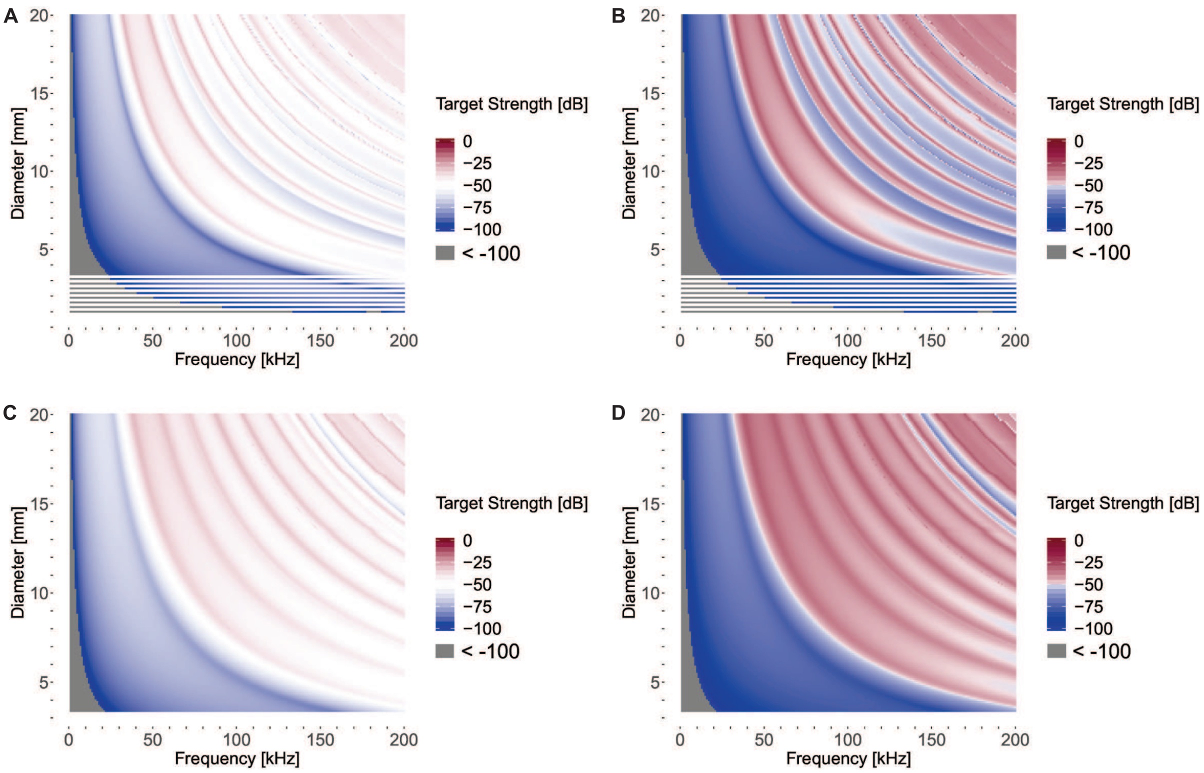

FIGURE 3 | Target strength of acrylic glass (PMMA) spheres at different diameters (increment = 0. 1 mm) across frequency spectrum (increment = 1 kHz) of echolocating odontocetes. **(A,B)** Young's modulus = 3.3 GPa, **(C,D)** Young's modulus = 4.8 GPa; At less than 3.4 mm, spheres have TS < -50 dB across all frequencies; gray area has TS values lower than -100 dB. Graphs are shown at two different color scales for illustration purposes. The raw data are given in **Supplementary Information**.

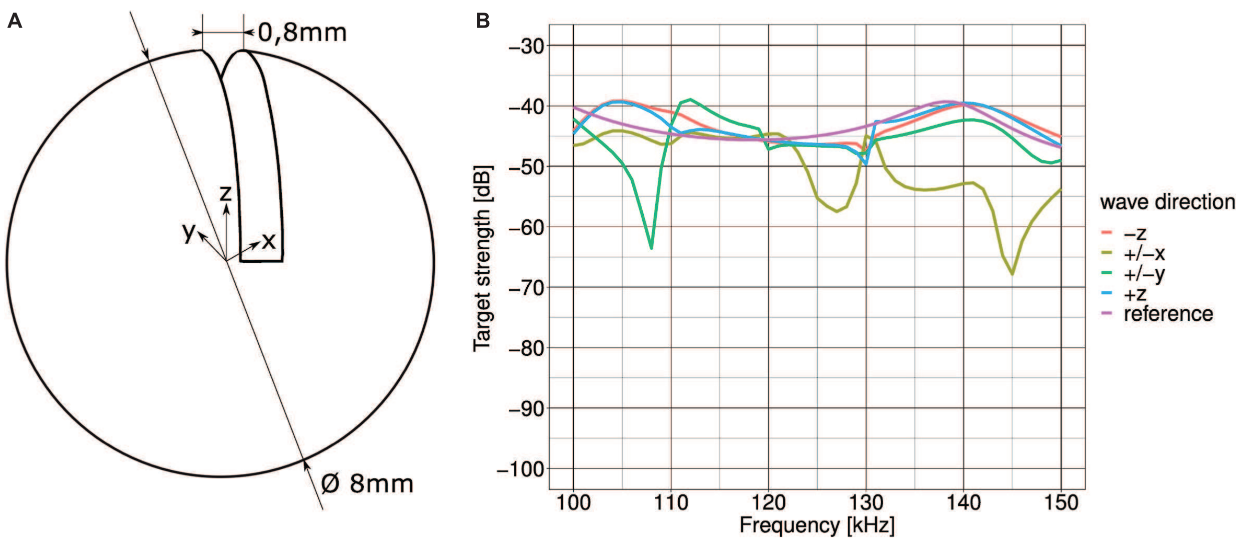

FIGURE 4 | (A) Drawing of a sphere with a cut; **(B)** TS of 8 mm acrylic glass (PMMA) sphere with a cut. Wave direction is the direction of the propagating sound corresponding to the arrows in **(A)**; "reference" is a solid sphere of 8 mm.

elasticity (Young's modulus), i.e., 0.1 GPa (**Figure 7**, undermost row in all graphs). Materials with this Young's modulus belong to the material class rubber (**Figure 2**). Additionally, few parameter combinations also resulted in relatively high TS; for instance, the highest TS value is achieved at 120 kHz, at a material density of 4000 kg/m^3, diameter of 1.75 mm, and a Young's modulus

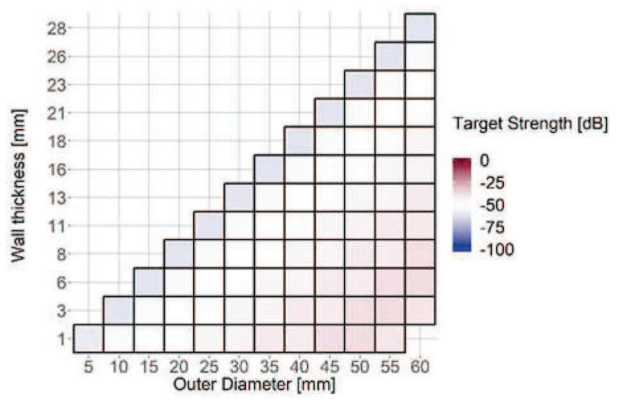

FIGURE 5 | Target strength of hollow spheres made from acrylic glass (PMMA), exemplarily at 130 kHz.

of 1.1 GPa (not shown in **Figure 7**). However, such a material currently does not exist because Young's modulus is positively correlated with density (**Figure 2**).

Identification of Optimal Spheres for Selected Odontocete Species

Many odontocete species are taken as bycatch (Reeves et al., 2013). For the 10 species most frequently taken as bycatch, as well as the species taken as bycatch that are classified as "Critically Endangered" or "Endangered" according to the IUCN Red List (IUCN, 2019), we calculated the acrylic glass sphere size with the highest TS depending on the centroid frequency of their echolocation signals (**Table 2**). Because the ideal spheres would be small, we extracted the optimal sphere sizes less than 20 mm diameter, as well as less than 10 mm diameter from **Figure 3**. We used -50 dB as a threshold and marked spheres with a lower TS in bold. The TS values were extracted for the closest frequency-bin (1-kHz increment). For some species, especially delphinids, who use several signal types, we noted the frequency used for foraging. **Figure 8** shows the values for TS vs. diameter for harbor porpoises.

Verification of Selected Simulation Results

We experimentally verified the TS simulation results for selected spheres using a sweep signal in an acoustic tank. **Figure 9** shows measurements of the two selected acrylic glass sphere sizes, both experimental and simulated data. Target strength was simulated for the standard literature value for Young's modulus of PMMA (3.3 GPa) as well as for the value adapted to high frequencies (4.8 GPa). For comparison, we also measured the TS of two reference objects, i.e., a TT ball (essentially air) and a steel sphere (high density, high Young's modulus = low elasticity; **Figure 10**). For some frequencies, the PMMA spheres perform almost as well as the larger objects.

Sonar Imaging of Standard and Modified Net

The addition of acrylic glass spheres aims to (a) increase the TS of the gillnet to increase the detection distance of the nets for odontocetes, and (b) change the acoustic image so that it is perceived as an obstacle. To qualitatively confirm that the addition of acrylic glass spheres will substantially increase the echo of a gillnet and alter its acoustic image, a prototype net was built (**Supplementary Figure 6**) and sonar images were taken by ensonifying both a standard and a modified net with a 38 kHz and a 120 kHz sonar aboard RV Clupea. Both nets were subsequently placed underneath the vessel. **Figure 11** shows the echograms taken. At 38 kHz, both standard and modified nets show only the floatline and leadline, whereas at 120 kHz, the attached spheres are almost as visible as the floatline. For comparison, **Supplementary Figure 7** shows typical pillar shaped schools of sprat (*Sprattus sprattus*) taken on RV Solea (SIMRAD EK80, 120 kHz).

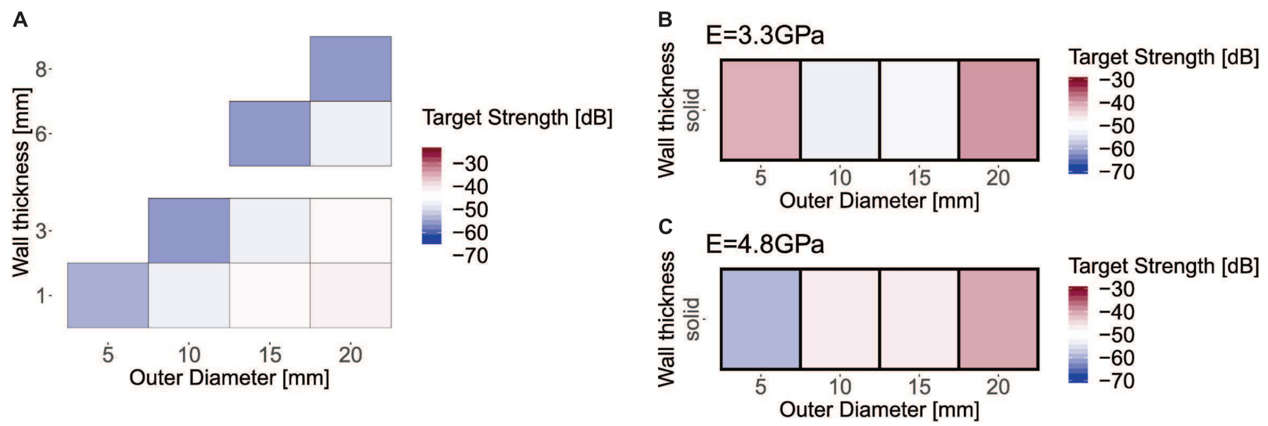

FIGURE 6 | Target strength of acrylic glass (PMMA) spheres with different outer diameter and wall thickness at 130 kHz. **(A)** air-filled PMMA spheres; **(B,C)** solid PMMA spheres (top: Young's modulus 3.3 GPa; bottom: Young's modulus adapted to high frequencies 4.8 GPa).

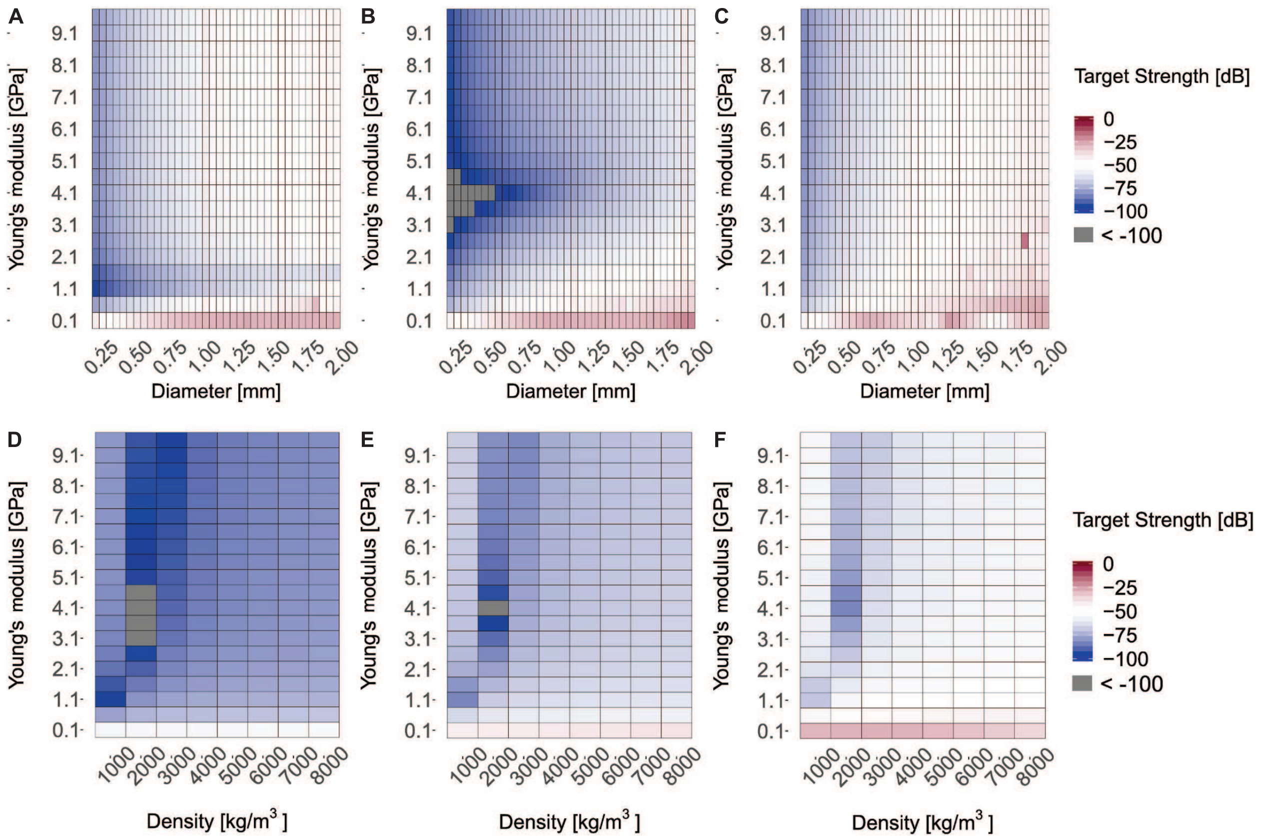

FIGURE 7 | (A) Target strength of solid cylinders at ρ = 1000 kg/m^3; **(B)** ρ = 2000 kg/m^3; and **(C)** ρ = 8000 kg/m^3 at 130 kHz. Each cell represents one simulation; colors range from strong echo (red) to low echo (blue). **(D–F)** Show the interaction between material density and elasticity for three cylinder diameters: **(D)** 0.25 mm, **(E)** 0.5 mm, **(F)** 1 mm. Additional frequencies and material densities are available in **Supplementary Information**.

TABLE 2 | Optimal sphere sizes of acrylic glass (PMMA) spheres to increase the reflectivity of gillnets for different odontocete species.

Species	Centroid frequency [kHz]	Sphere size [mm] ≤ 20 mm (TS [dB])	Sphere size [mm] ≤ 10 mm (TS [dB])	Reference for frequency
Lissodelphis borealis	18.2	**20 (−61.68)**	**10 (−75.65)**	Rankin et al., 2007
Delphinus delphis	112	18.6 (− 31.36)	9.9 (− 37.43)	Morisaka and Connor, 2007
Phocoena phocoena	130	18.5 (− 32.08)	8.5 (− 38.78)	Villadsgaard et al., 2007
Lagenorhynchus obliquidens	94.6	18.5 (− 31.08)	8.1 (− 37.78)	Morisaka and Connor, 2007
Phocoenoides dalli	133	18.1 (− 32.22)	8.3 (− 38.97)	Morisaka and Connor, 2007
Neophocaena phocaenoides	125	19.2 (− 32.03)	8.9 (− 38.47)	Morisaka and Connor, 2007
Stenella coeruleoalba	40	19.1 (− 30.26)	**10 (−67.60)**	Kastelein et al., 2003
Pontoporia blainvillei	130	18.5 (− 32.08)	8.5 (− 38.78)	Morisaka and Connor, 2007
Tursiops truncatus ponticus	80	18 (− 33.38)	9.6 (− 36.28)	Wahlberg et al., 2011
Lagenorhynchus obscurus	73.8	19.5 (− 32.73)	10 (− 38.04)	Morisaka and Connor, 2007
Phocoena sinus	132	18.2 (− 32.54)	8.4 (− 38.86)	Morisaka and Connor, 2007
Phocoena phocoena relicta	presumably 130	18.5 (− 32.08)	8.5 (− 38.78)	
Platanista gangetica	64.4	17 (− 32.72)	**10 (−53.14)**	Jensen et al., 2013
Orcaella brevirostris	94.6	18.5 (− 31.08)	8.1 (− 37.78)	Jensen et al., 2013
Inia geoffrensis geoffrensis	101.2	17.2 (− 31.85)	7.5 (− 38.38)	Ladegaard et al., 2015
Cephalorhynchus hectori	124	19.4 (− 31.61)	8.9 (− 38.41)	Thorpe and Dawson, 1991

*The two sphere sizes refer to overall highest TS (left) among spheres ≤ 20 mm, and highest TS among spheres ≤ 10 mm in diameter (right); TS values are given in brackets, spheres marked in bold have TS lower than -50 dB at the corresponding frequency; we considered the Young's modulus adapted for high frequencies, i.e., 4.8 GPa; the optimal sphere sizes for other frequencies can be extracted from raw data underlying **Figure 3**, which are given in **Supplementary Information**.*

TABLE 3 | Comparison of TS for different types of gillnets with and without additives in the netting material; IO, iron oxide in nylon filaments; $BaSO_4$, Barium Sulfate in nylon filaments.

Diameter [mm]	Frequency [kHz]	Net material	TS [dB]	References
0.59	130	Nylon netting	−53	Larsen et al., 2007
0.59	130	Nylon netting + IO	−53	Larsen et al., 2007
0.65	130	Nylon netting	−48.5	Kastelein et al., 2000
0.5	230	Nylon filament	−61	Pence, 1986
0.51	120	Nylon netting	−52	Mooney et al., 2004
0.51	120	Nylon netting + $BaSO_4$	−53	Mooney et al., 2004
0.49	120	Nylon netting	−58.8	Au and Jones, 1991

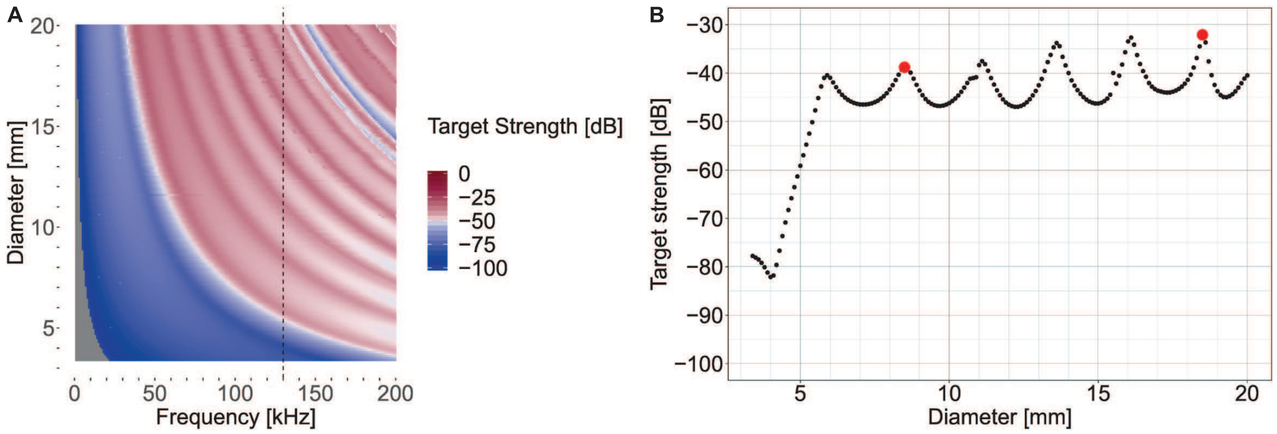

FIGURE 8 | (A) Figure 3, all simulated frequencies, diameters and corresponding TS for acrylic glass spheres (Young's modulus 4.8 GPa for high frequencies); straight line indicates frequency of harbor porpoise *(P. phocoena)*; **(B)** TS values for different diameters at 130 kHz (frequency of *P. phocoena*); red dots mark maximum noted in **Table 2**; other odontocete frequencies are available in the **Supplementary Information**.

Effect on Potential Detection Distances

In addition to altering the perceived image of the gillnet, it is essential that the net be detected as early as possible, allowing the animal to react in time to avoid the obstacle. For some species, target detection experiments have been conducted, and detection ranges for various targets estimated (Au et al., 2007). We exemplify the effect of adding objects with strong echo properties on the potential detection distances for harbor porpoises by modeling the potential detection distances for 8 mm acrylic glass spheres in several modification options, i.e., different numbers of spheres per area netting (**Figure 12**). The overall TS depends on how many spheres are ensonified simultaneously, which is related to the number of spheres per net area as well as the direction from which the animal is approaching the net. If the animal is swimming perpendicularly (0° angle) to the net, it will most likely ensonify more spheres simultaneously than when it swims at an angle. At angles, echoes from different spheres are received by the animal at subsequent points in time owing to runtime differences. Extinction effects may occur when the reflected waves interfere with each other as a result of phase shifts. Therefore, we calculated both the maximum detection range (coherent addition of TS) and the most likely mean detection range (incoherent addition). Incoherent addition statistically accounts for TS-reducing factors, such as angle of incident or distance between emitter and receiver (in this case, the emitter is the melon, and the receiver is the jaw of the odontocete). The calculated TS of net area covered with additional spheres determines the detection range. To compare the detection range with previous experimental data, we used an ensonified area of 0.36 m^2. The equal detection range of spheres either 0.5 or 0.6 m apart is the result of the distribution within the circular area. When a standard gillnet is equipped with spheres approximately 0.3 m apart, an ensonified area of 0.36 m^2 should be visible from at least 12 m and could be visible up to 17 m, which is as far as 0.68 m of floatline. This in turn means that, if harbor porpoises are able to detect the equivalent TS of a floatline, the entire netting area should appear as strong as the floatline as well. If spheres were attached at a much smaller distance, the detection distance of an area of 0.36 m^2 could increase up to 40 m. Regardless of whether one or more spheres are ensonified, the spheres outcompete all netting materials that have been considered previously.

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 (Murray et al.,

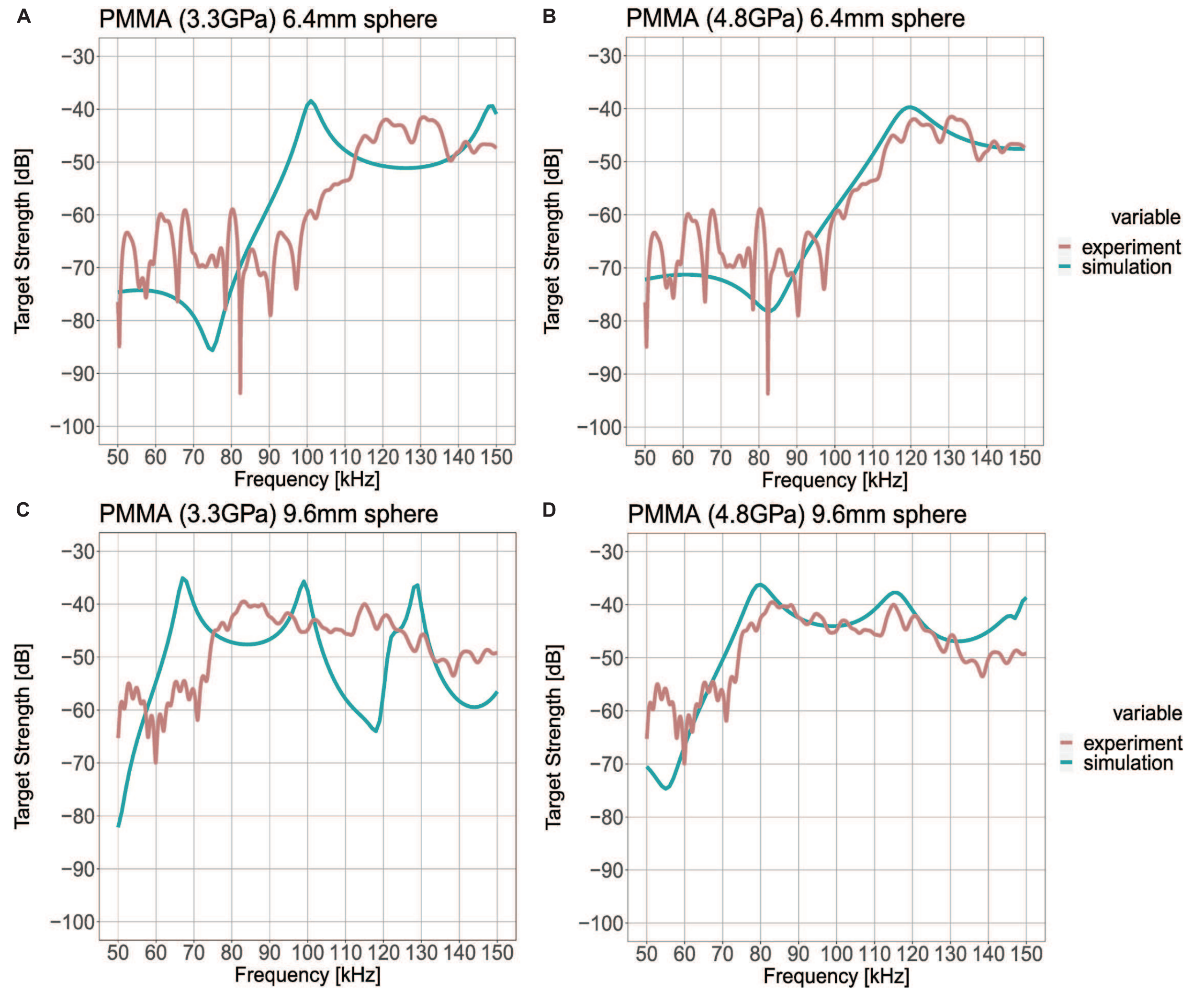

FIGURE 9 | Comparison of experimental and simulated TS of two different acrylic glass (PMMA) spheres. Left **(A,C)**: simulation with a standard value for Young's modulus at 3.3 GPa; right **(B,D)**: Young's modulus adapted to high frequencies (4.8 GPa)

2000; Gormley et al., 2012), the use of acoustic deterrent devices (pingers), and experiments with supposedly acoustically enhanced nets (Kraus et al., 1997; Larsen et al., 2007; Bordino et al., 2013; Dawson et al., 2013; Mangel et al., 2013; Larsen and Eigaard, 2014). The drawbacks of pingers over passive reflectors include potential habituation (Cox et al., 2001), potential exclusion from habitat (Carlström et al., 2009), higher bycatch rates if a subset of pingers fail (Carretta and Barlow, 2011), and a possible "dinner-bell" effect for other species (Bordino et al., 2002). So far, studies of acoustically enhanced nets have produced inconclusive results.

One major issue is the trial-and-error-approach to select gillnet modification for acoustical "enhancement" of gillnets without an understanding of the fundamental acoustic properties of such modifications.

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.

In a first step, we identified the requirements for potential modifications: The object has to be (a) omnidirectional, (b) small, and (c) neutrally buoyant in order to avoid changes to the behavior of the net. Similar requirements for passive acoustic reflectors were also identified by Goodson (1997). As spheres meet the demand of omnidirectionality, we concentrated on simulating spherical targets. Spheres are also used as standard targets in many sonar applications (MacLennan, 1981; Foote, 1982, 1983; Sheng and Hay, 1993; Atkins et al., 2008). In his consideration of spherical acoustic targets as passive reflectors to decrease bycatch of odontocetes, Goodson (1997) remarks

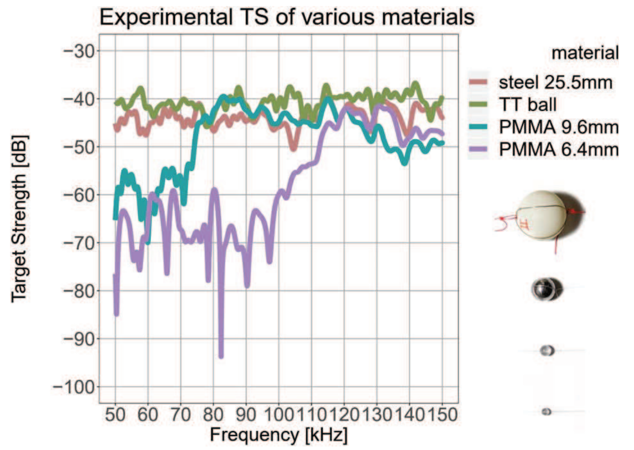

FIGURE 10 | Experimental TS measurements for different objects, including steel sphere, a table-tennis ball (TT ball) and two acrylic glass (PMMA) spheres of different sizes; objects are shown underneath legend.

that, as a consequence of Rayleigh scattering, any sphere as a passive reflector would have to be several centimeters in size. Similarly, other potential shapes for acoustic targets such as radar reflectors, which could very well channel the incoming sound waves and reflect them back to the source, would have to be larger, because they operate on geometrical reflectivity (Perrin et al., 1994). These considerations do not consider the potential use of resonance effects. Resonance effects can occur when using objects with greater elasticity (lower Young's modulus) than rigid objects. A non-rigid object can exhibit resonance effects when ensonified with its natural frequency (eigenfrequency); the sphere will oscillate and move the surrounding medium (Sullivan-Silva, 1989). These resonating properties depend largely on elasticity (Sheng and Hay, 1993). The identification of the optimal elasticity in relation to size led to the conclusion that several polymers could be suitable material. We chose acrylic glass as a suitable material, as it best matched the simulated parameters and has further advantages for the application in fisheries, such as:

(a) density close to seawater (1180 kg/m^3, Abts, 2016) making it almost neutrally buoyant and thus less likely to change net behavior;
(b) high transparency in water, which could make it less visible to fish;
(c) low melting temperature compared with nylon, resulting in potential attachment techniques that allow the acrylic glass to be molded directly onto the net, because many nets are made of nylon;
(d) low water absorption coefficient, thus the acoustic properties should stay constant throughout the entire soak time of the gillnet;
(e) wide availability;
(f) manufacture possible in all sizes;
(g) can be glued using liquid acrylic glass adhesive.

Figures 1, **2** show that 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.

Air-filled spheres did not outperform solid spheres made of PMMA. This may be because the TS is not determined by the air inside the spheres, but mostly by the properties of the shell material (Welsby and Hudson, 1972).

Some early work has been done on passive reflectors, which resulted in promising objects that may have been clearly acoustically visible to odontocetes, but failed to meet the requirement of being easy to handle (Hembree and Harwood, 1987; Peddemors et al., 1991). The acrylic glass spheres described here are not only made from a polymer that inherently eliminates the issue of rusting as described in Peddemors et al. (1991), but they are also small enough to avoid the necessity for additional storage space for the nets.

We have identified optimal sphere sizes for odontocetes species that are commonly taken as bycatch or listed as vulnerable (**Table 2**). For all species with echolocating frequencies above 40 kHz, spheres smaller than 20 mm in diameter were identified with TS > -50 dB. For most of these species, spheres smaller than 10 mm were identified, as well. The threshold of -50 dB that was used is approximately the TS of a gillnet (Au and Jones, 1991; Perrin et al., 1994; Kastelein et al., 2000; Mooney et al., 2004). This threshold is lower than the threshold suggested by Goodson (1997). However, he considered larger spacing between objects to be attached to gillnets to avoid the need for additional space on small boats. The smaller the spheres, the more additional objects could be attached to gillnets without impeding usability.

In this study, we attached the spheres to the gillnet by cutting them in half and gluing them to the net filament using fluid acrylic glass adhesive. The simulation results reveal that a small cut in the sphere can potentially lead to a drop in TS at the desired frequencies. This effect is more pronounced if the odontocete echolocates from a certain direction. In practice, however, this is counteracted by filling the cut with an acrylic glass adhesive. Further compensation of potential reduction in TS at different directions is achieved through random orientation of the spheres at the net and movement of the gillnet underwater.

The experimental verification of the TS calculations for acrylic glass indicated that the measurements in the tank are in good agreement with the modeled data, when the Young's modulus (material elasticity) is adapted from literature values of approximately 3.3–4.8 GPa. One reason for the change in Young's modulus could be that the TS measurements were taken at high frequencies, whereas the Young's modulus is usually determined at quasi-static conditions, usually in tensile testing. However, the Young's modulus of polymers changes when exposed to high frequencies (Pritz, 1994; Dauchez et al., 2002), thus, the exposure to high frequency acoustic waves is more comparable to dynamic testing of the Young's modulus. The dynamic Young's modulus is slightly higher than the static Young's modulus (Sabbagh et al., 2002; Popov and Sabev, 2016). The TT ball used as a reference target had a similar TS as previous measurements of this target (Welsby and Hudson, 1972).

In addition to the attachment of additional objects to enhance the acoustic visibility of gillnets, a common approach so far has been to increase the density of the gillnet filament itself.

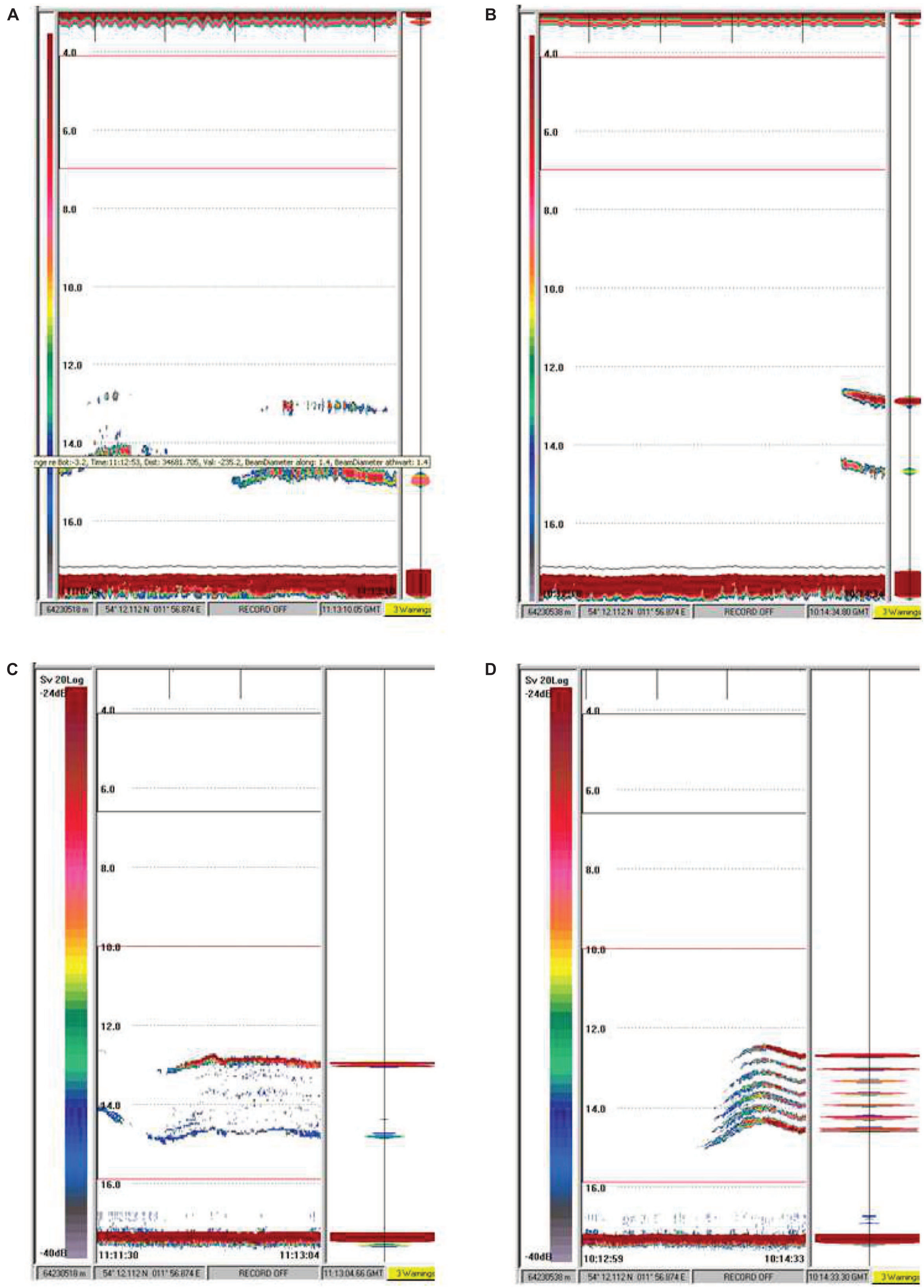

FIGURE 11 | Left: **(A,C)** echograms of standard gillnet; right: **(B,D)** modified gillnet at 38 kHz (upper: **A,B**), and at 120 kHz (lower: **C,D**). The added spheres are clearly visible at 120 kHz **(D)**, but not at 38 kHz **(B)**, whereas the standard gillnet is hardly visible, independent of the frequency.

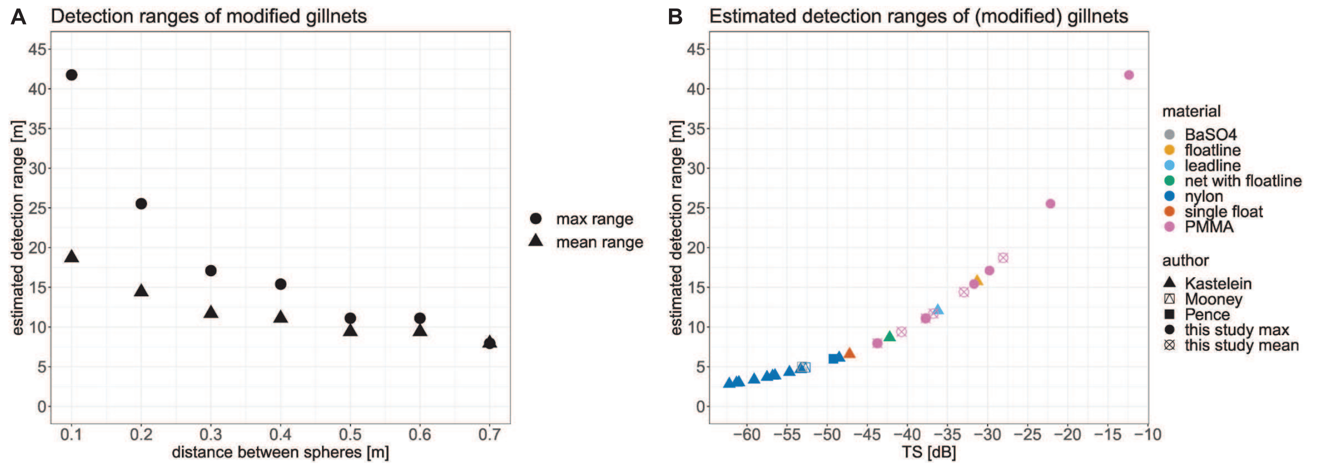

FIGURE 12 | Estimates of potential detection ranges for harbor porpoises. **(A)** Maximum and mean estimated detection ranges for gillnets equipped with 8 mm acrylic glass (PMMA) spheres in an ensonified area 0.36 m^2 at different distances between spheres. **(B)** comparison of gillnets with 8 mm spheres at different distances (open circle = mean, filled circle = maximum) to ranges determined from literature values (Pence, 1986; Kastelein et al., 2000; Mooney et al., 2004). Colors encode the material/object, and shapes encode the source of information.

Therefore, we have investigated the acoustic properties of a wide range of thin cylinders, as a proxy for gillnet filaments.

In general, the TS of thin, infinite cylinders (or filaments), irrespective of material properties, was very low. The calculated results presented here are similar to the theoretical values calculated by Pence (1986). The TS hardly differs between material densities within a given diameter of the cylinder, especially when density differences are small. In previous studies of gillnets with added BaSO4 and iron oxide (IO), the material density was increased by only 8 and 11%, respectively (Mooney et al., 2004; Larsen et al., 2007). Target-strength measurements of such acoustically enhanced gillnets are in line with the simulation results, because they do not reveal a significant difference between standard and modified gillnets (**Table 3**). One reason for the small difference in TS is that there is a geometric – and mass – threshold of the target object that needs to be exceeded in order to initiate an interaction between object and sound wave. Therefore, Goodson (1997) did not regard denser netting materials as an option. The TS of several meshes of netting is, in the best case, equivalent to the TS of a single 8 mm acrylic glass sphere. Thin cylinders with a diameter of 0.5 mm, material density of 2000 kg/m^3, and Young's modulus of 4.1 GPa at 130 kHz have very low TS values. These material properties are close to the properties of nylon, which could explain the very low TS values of monofilament gillnets and thus their poor acoustic visibility. Nevertheless, these results need further experimental verification. Because the TS of gillnet netting cannot be substantially increased by increasing the density of the net material itself, any further trials in this direction will most likely be in vain.

The only way to obtain high TS of thin cylinders is through the use of a cylinder with very low Young's modulus, i.e., rubber material (**Figures 2**, **7**). The strength of standard rubber material is too low to be used as netting material, an option could be to attach rubber strings to the net. The drawback of using a cylindrical shape is the loss of omnidirectionality. Additionally, we lack the information about a minimum length of such additional rubber filaments to be effective as acoustic targets. In case this modification is considered in future studies, further exploration would be needed to determine the minimum cylinder length via modeling and subsequently verify these results in an acoustic tank.

Detection Distances/Ecological Significance

In a parametric study, we have simulated a large number of different objects to identify the ideal objects that might allow odontocetes to perceive gillnets early on and classify them as an obstacle. We simulated a wide range of frequencies to cover many odontocete species and allow us to identify optimal objects for different species, and so ensure a wide application of the modification.

The main reason for odontocete bycatch in gillnets is assumed to be the faint echo of gillnet netting, which is not recognized as an obstacle (Goodson, 1997). Although, odontocetes are most likely able to detect parts of gillnets, such as floatlines, from a distance (Nielsen et al., 2012), they are taken as bycatch in gillnets.

Therefore, the overall goal of this study was to identify passive reflectors that substantially improve the acoustical visibility of gillnets within the frequency range of echolocating odontocetes. This is the basis to increase the potential detection distance of gillnets and alter the acoustic image of the gillnet to be recognized as an obstacle by odontocetes.

Because gillnets' floatline has a much higher TS than the netting itself, the received echo of floatline and netting may not be perceived as an obstacle. It is known that harbor porpoises and Dall's porpoises are more likely to swim underneath rather than over an obstacle (Frady et al., 1994; Kastelein et al., 1995). Furthermore, there is field evidence that some odontocetes have demonstrated avoidance to objects that have a similar TS as a floatline, but they tend to dive underneath such structures (Perrin and Hunter, 1972; Norris and Dohl, 1980; Perrin et al., 1994; Goodson and Mayo, 1995; Kastelein et al., 1995). Therefore, these animals may attempt to swim underneath the floatline and consequently get caught in the netting. If the entire netting was as obvious as the floatline, this could deter odontocetes from attempting to swim through the gillnet.

To put the identification of ideal resonators into perspective with conventional gillnets, the potential detection distances of modified gillnets were calculated. These models are based on several assumptions and serve mainly to be able to compare previous measurements to potential applications of the ideal reflectors. The spheres identified in this study, exhibit a similar TS as the floats of a gillnet and have, at least when attached close enough to each other, the same detection distance as the equivalent length of a floatline. Therefore, the spheres have the potential to make the whole netting area as obvious as the float- and leadlines. To achieve this, the distance between the spheres should be smaller than 0.5 m for odontocetes echolocating around 130 kHz. In this model, we considered consistently the same ensonified area (0.36 m^2) in order to be comparable to previous work (Kastelein et al., 2000). Due to the nature of an area target, such as a gillnet, the ensonified area would increase with increasing distance. This, in turn, renders the TS larger as more spheres can be ensonified simultaneously. As this is a recursive process, the ensonified area was kept constant to be comparable to previous work, where the same issue is present. However, when the porpoise gets closer to the net, fewer spheres are ensonified, rendering it less visible. This counterintuitive circumstance is met by keeping the area constant to get be able to compare the nets. Therefore, in reality, the gillnet equipped with spheres will be even more acoustically visible than shown here, as more spheres are ensonified simultaneously.

When taking into account that the animal is not always perfectly perpendicular to the net when it echolocates, the TS decreases, but is still higher than regular gillnets. It is possible to improve the acoustic visibility of gillnets with small and neutrally buoyant spheres for a broad range of echolocating frequencies. The main challenge is now to identify optimal attachment patterns of these objects in the gillnet (e.g., distance between spheres) to be detected as an impenetrable obstacle. Increased detection ranges aside, another important goal of modifying gillnets with acrylic spheres is to alter the perceived acoustic image of the net in such a way that it resembles a wall-like structure. To prevent the animal from swimming through two objects adjacent to each other, the objects should be less than 0.5 m apart (Nakamura et al., 1998).

Klinowska et al. (1991) has already used acoustically reflective objects to “fill in” the space between floatline and leadline, which was visualized using side-scan sonar. Nevertheless, in this case the objects were large (max length 67 mm, diameter 33 mm) and spaced at a rather large distance (2 m). The sonar images (**Figure 11**) of a gillnet with 8 mm acrylic spheres attached at a distance of 0.3 m demonstrate clearly the improved visibility of the gillnet structure with spheres compared with standard gillnets. The echo of the attached spheres is almost as strong as the echo of the gillnet’s floatline and leadline.

For the first time, an object was systematically identified and experimentally verified that substantially increases the detectability of gillnets, while meeting basic practical requirements for a low-tech fishery, such as small size and neutral buoyancy. Therefore, we see much potential in using small, acoustically reflective spheres to reduce the bycatch of several odontocetes species.

Nevertheless, the effectiveness of a passive reflector requires that odontocetes echolocate frequently – including in the direction of the net – and that they do not mistake the additional objects for prey. When comparing the sonar image of a gillnet to the sonar image of a shoal of fish (**Figure 11** and **Supplementary Figure 7**) the porpoise might be unable to distinguish between the gillnet and the shoal of fish in individuals pings. However, harbor porpoises scan their environment with head movements and should thus be able to determine the beginning and end of a fish shoal, while the gillnet with acrylic spheres is a wall-like structure with a likely artificial image that they can swim along or swim over. Additionally, echograms from vessels are taken from a driving ship viewing toward the bottom, while the porpoise would be swimming perpendicularly to the shoal, thus the perceived image might be different compared to the view from the surface. While it may still be the case that individual spheres attached to the netting are mistaken for food, the entire image is unlikely to be mistaken for a large shoal of fish. Additionally, harbor porpoises have shown to react strongly to moving prey while foraging (Feldskov Hansen et al., 2017), which is not the case with a static net. How porpoises ultimately perceive their environment remains unclear, thus it is vital to investigate their reaction to modified gillnets through behavioral experiments.

Despite the fact that harbor porpoises forage, and thus echolocate, almost continuously (Wisniewska et al., 2016), there might be also periods of silence and other odontocete species might echolocate more frequently than others (Dawson, 1991; Akamatsu et al., 2007; Sørensen et al., 2018). To improve the effectiveness of gillnets with improved acoustic visibility, it might be necessary to combine the passive reflectors with active devices that send a “wake-up” call to the odontocete (Goodson, 1997). Such devices are currently being developed and tested for harbor porpoises in the Baltic Sea (Culik et al., 2015).

As demonstrated, it is possible to identify an optimal sphere with a diameter smaller than 20 mm for species that echolocate at frequencies higher than 40 kHz. For other species, the sphere size needs to be larger.

Several further steps are required prior to a widespread application of gillnets modified with acrylic glass spheres in the commercial gillnet fishery. Nevertheless, this study provides the essential basis for further development. Therefore, the next logical steps would be:

(a) the experimental verification of the estimated TS of a gillnet with acrylic spheres. Ideally, these experiments account for different attachment patterns of spheres to the gillnet, as well as different acoustical angles of approach and the aperture of the sonar beam;

(b) a behavioral experiment to describe the difference in reaction of odontocete species in relation to modified and standard gillnets. These experiments require both visual and acoustic observation in order to describe the changes in swimming path and echolocating behavior;
(c) tests of net behavior with acrylic pearls attached, e.g., in a flume tank;
(d) a catch and bycatch comparison experiment in the commercial fishery;
(e) the development of automated processes to produce gillnets with spheres to provide cost-effective modified gillnets to the commercial fishery.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

IK, IS, AS, JC, and DS acquired the data via simulation, modeling or measurements. All authors wrote the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00539/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Paper II

Angle-dependent acoustic reflectivity of gillnets and their modifications to reduce bycatch of odontocetes using sonar imaging

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ABSTRACT

Incidental capture in gillnets is the most pressing threat for small cetaceans worldwide. One reason why small, echolocating cetaceans entangle in gillnets may be their inability to acoustically detect gillnets and classify them as obstacles. To increase the overall acoustic reflectivity as well as alter the perceived image to simulate an impenetrable barrier, small reflective objects – 8 mm wide acrylic glass spheres – were attached to standard gillnets. This study investigates the acoustic reflectivity of standard gillnets and modified gillnets with different numbers of spheres/m², at several angles of ensonification across a large frequency range. The acoustic reflectivity of standard gillnets is very low and decreases with angle of ensonification. Gillnets equipped with the spheres have substantially higher acoustic backscattering strength, and exhibit a positive relation between backscattering strength and inclination, i.e. gillnets ensonified from an angle have an even larger echo than when ensonified perpendicularly. Gillnets with sphere-sphere distance of 20 cm perform best, while the acoustic backscatter of gillnets with 40 cm and 60 cm sphere-distances is similar. The acoustic image (echogram) of the gillnet with spheres demonstrates a distinct highly visible acoustic pattern, potentially rendering the spheres an effective way to reduce bycatch of small cetaceans.

Keywords: acoustic visibility, area backscattering strength, bycatch mitigation, gillnet fisheries, marine mammals, target strength

1. INTRODUCTION

A major threat to various cetacean species worldwide is bycatch in gillnets (Reeves et al., 2013) with some species facing extinction or already been eradicated due to bycatch (CIRVA, 2019; Turvey et al., 2007). As an example, the incidental capture of harbor porpoises (*Phocoena phocoena)* is an issue taking place throughout their distribution range (Berggren, 1994; Kindt-Larsen et al., 2016; Koschinski and Pfander, 2009; Read et al., 2006; Reeves et al., 2013; Skóra and Kuklik, 2003; Tonay, 2016; Trippel et al., 1996; Vinther and Larsen, 2004).

On way of mitigating bycatch is the use of acoustic deterrent devices – so-called pingers – which is mandatory in some fisheries (Council of the European Union, 2004). Despite effectively reducing bycatch of harbor porpoises (Kraus et al., 1997; Larsen and Eigaard, 2014; Palka et al., 2008), pingers have a series of drawbacks, including potential habituation (Cox et al., 2001), catch damage due to the "dinner bell" effect for other marine mammals (Gilman et al., 2019), and potentially higher bycatch rates when a number of pingers in a series of pingers attached to gillnets fail (Carretta and Barlow, 2011). Furthermore, pingers require continuous maintenance to fulfill their task.

Despite long-term interest in the matter, it remains unclear why the animals get entangled in the first place. Whereas harbor porpoises are thought to be able to acoustically detect at least parts of the gillnet, i.e. the highly acoustically visible floatline, from a suitable distance (Kastelein et al., 2000; Nielsen et al., 2012), they are regularly bycaught in gillnet fisheries around the world. Assuming harbor porpoises echolocate regularly (Wisniewska et al., 2016), one explanation for entanglement could be their failure to detect the netting itself and hence to classify the net as an obstacle. Furthermore, studies have shown that some species of toothed whales (odontocetes), including harbor porpoises, tend to dive underneath objects they want to avoid (Kastelein et al., 1995; Silber et al., 1994). This, in turn, could make them prone to attempt to dive underneath the highly visible floatline and subsequently be caught in the less visible netting. Modifying the gillnet netting in such a way that it appears as an impenetrable object could thus be an alternative to pingers to reduce bycatch of echolocating marine mammals. Several trials with acoustically enhanced netting material or the addition of objects to the netting have produced negative or at best inconclusive results (Bordino, Mackay, Werner, Northridge, & Read, 2013 ; Dawson, 1991; Larsen, Eigaard, & Tougaard, 2007). Only one study showed both a bycatch reduction and stable catch of target species (Trippel et al., 2003). This is partially owed to a lack of fundamental understanding of the acoustic properties of the modified nets, resulting in modifications of the netting filament which led to little or no increase in acoustic reflectivity (Larsen et al., 2007; Mooney et al., 2007).

To develop an acoustically visible, yet catch efficient gillnet, small, highly acoustically reflective objects that could be attached to a gillnet with only small effects on its hydrodynamic properties were systematically identified for a large range of frequencies and therefore echolocating species (Kratzer et al., 2020). For harbor porpoises, echolocating in a narrow frequency range around 130 kHz (Villadsgaard et al., 2007), an 8 mm diameter sphere made from acrylic glass was identified as optimal object, as it resonates at around 130 kHz. A spherical object was chosen as the echo properties are independent from the angle of ensonification which is the precondition to allow detection at all aspect angles of incidence.

In this study, two different kinds of gillnets were equipped with spheres at different sphere-sphere intervals to systematically determine the dependency of acoustic reflectivity on the number of spheres per m² and potentially identify a compromise between number of spheres needed to substantially increase the echo of the gillnet and effort of net production. The echo properties were measured with the acoustic beam perpendicularly to the net as well as at two angles of incidence, to investigate any possible effect of that angle on the backscattering strength.

2. MATERIALS & METHODS

The experimental trials were conducted in a sheltered harbour berth at the Bundeswehr Technical Center for Ships and Naval Weapons, Maritime Technology and Research (WTD 71) in Kiel, Germany with a dimension of approximately 40 m by 20 m and a depth of 8 m. Acoustic measurements were conducted with a SIMRAD EK80 scientific wide-band echosounder in a waterproof housing (WBT Tube) operated with three SIMRAD transducers (ES38-18DK, ES70-18CD, ES120-7C). Acoustic reflectivity was measured in a frequency range from 35 kHz to 170 kHz, with the range between 46 and 54 kHz not covered. The transducers were calibrated using a

38.1 mm tungsten carbide sphere (Demer et al., 2015). The echosounder was operated in FM-mode (frequency modulated, i.e. broadband mode) with a pulse duration of 0.512 ms. Nets were ensonified for approximately 180 s at each angle at a ping rate of 1 s^{-1}. All tested gillnets were 10 m long and the specifications are given in TABLE 1.

TABLE 1: Characteristics of tested gillnets. Spheres are attached at the given interval across the entire height and length of the net

Net name	Abbreviation	Material	Sphere-sphere interval [cm]	Stretched mesh size [mm]	Height of net [m]	Approximated number *n* of spheres/m² [m^{-2}]	Hanging ratio
Cod reference	Cod-Ref	Nylon	N/A	110	3.6	0	0.5
Cod 60cm	Cod-60cm	Nylon	60	110	3.6	4	0.5
Cod 40cm	Cod-40cm	Nylon	40	110	3.6	9	0.5
Cod 20cm	Cod-20cm	Nylon	20	110	3.6	25	0.5
Turbot reference	Tur-Ref	Natural fiber	N/A	400	2	0	0.33
Turbot 35cm	Tur-35cm	Natural fiber	vertical: 37; horizontal: 35	400	2	9	0.33

To investigate the relationship between acoustic backscattering strength and number of spheres per m² of netting, a standard cod gillnet made from nylon was equipped with spheres at different sphere-sphere intervals. A second gillnet type usually used in the Turkish turbot fishery was also investigated, as this net has been used in a commercial fishery trial (Kratzer et al, in review). The main focus, however, was on the cod net. The modification of the gillnets with 8 mm spheres was based on the simulated resonance peaks between 90 – 150 kHz (Kratzer et al., 2020; FIGURE 1).

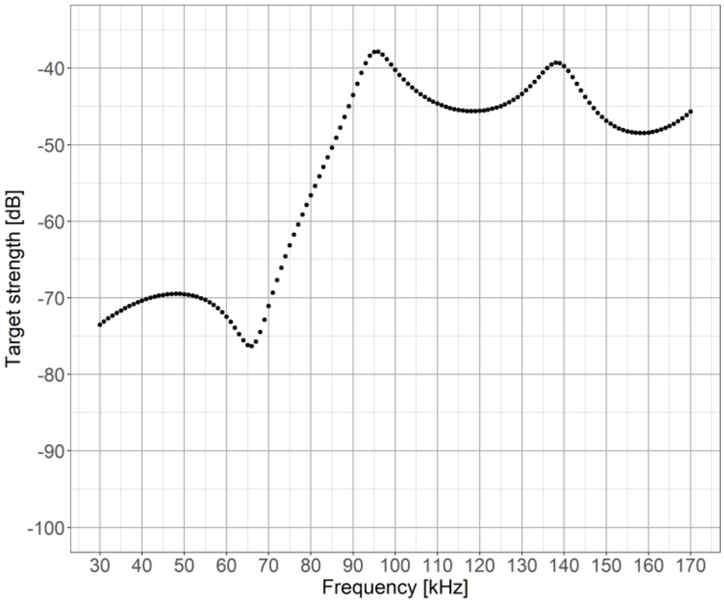


FIGURE 1: Simulated target strength (TS) of an 8 mm diameter acrylic glass sphere across the frequency range measured in this study

2.1 Set-up and ensonified area

The transducers were mounted at a depth of approximately 2 m looking horizontally towards the gillnet. The gillnets were placed into the acoustic beam of the transducers with both vertical and horizontal center of the gillnet centered in the acoustic beam. To ensure that the same area of gillnet netting was ensonified at a 0° angle, the cod gillnets were set at 5 m (ES38-18DK, ES70-18CD) and 13.1 m (ES120-7C) from the respective transducers to accommodate differences in beam angles of the transducers (18° for ES38-18DK/ES70-18CD and 7° for ES120-7C). The turbot gillnets were set at 2 m and 5 m respectively to avoid ensonification of leadline and floatline, as they were lower in height compared to the nylon nets. Each net was measured at 0°, 20° and 45° relative to the perpendicular axis of the transducer. As the nets are inclined relative to the transducer, the ensonified area changes as does the absolute number of spheres that are ensonified and the number of columns of spheres that should become visible as rows in the echogram (TABLE 2, FIGURE 2).

TABLE 2: Transducer types, aspect angle of ensonification of net, resulting approximate ensonified area and approximate number of ensonified columns of spheres. Ensonified area is related to the distance from the transducer given in the text.

Transducer type	ES38-18DK			ES70-18CD			ES120-7C		
Transducer Center frequency	38 kHz			70 kHz			120 kHz		
Angle [°]	0	20	45	0	20	45	0	20	45
Ensonified area [m²]	2.01	2.15	2.92	2.01	2.15	2.92	2.01	2.14	2.85
No. columns Cod-20 cm		9	12	0	9	12		9	12
No. columns Cod-40 cm		6	76	0	6	7		5	6
No. columns Cod-60 cm		3	4	0	3	4		3	4
No. columns Tur-35cm		5	8	NA	5	8		5	8

As the net is turned to a certain inclination, the minimum and maximum distance from the transducer changes, which becomes visible as a "height" of the gillnet (FIGURE 2), i.e. the vertical axis in the echogram corresponds to the distance of the gillnet from the transducer in the transducer beam. This in turn means that spheres that are attached horizontally adjacent to each other (columns) become visible as spheres on top of each other (rows), since they are inclined in the transducer beam and thus at different distances from the transducer (FIGURE 2). At 0° the transducer ensonfies all of the netting area from almost the same distance, which means that the rows of spheres cannot be resolved as the image shows all spheres at almost the same distance level. The net appears as a thin line in the echogram. At 0° the "height" of the net when ensonified perpendicularly is a result of the longer distance of the netting on the edges of the acoustic beam compared to the center of the beam.

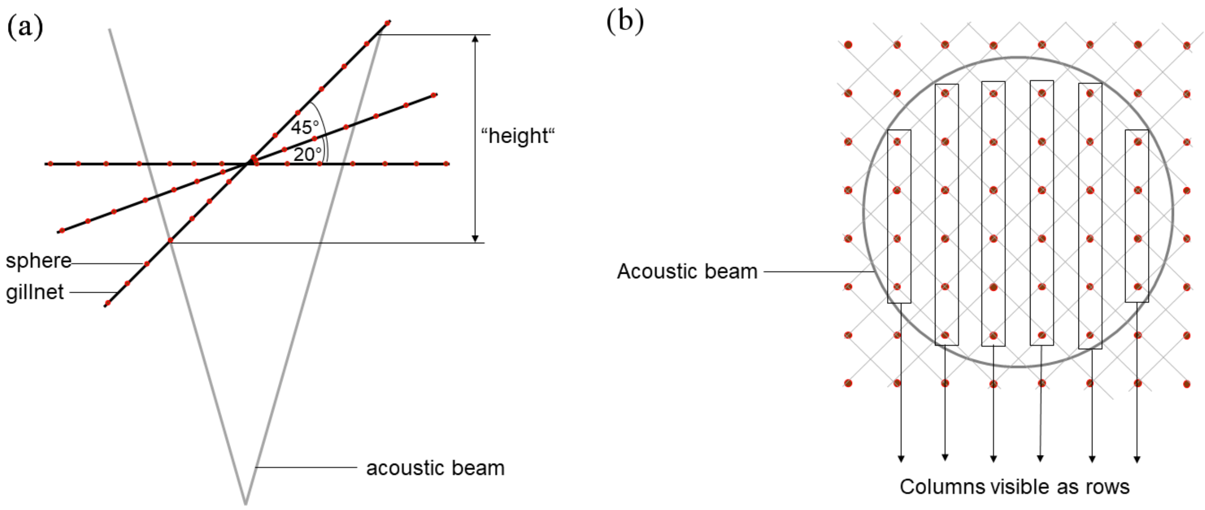


FIGURE 2: (a) Top view of the experimental set-up from above. Red dots mark the location of sphere columns attached to the gillnet, i.e. underneath each red dot there is a column of spheres mounted at equal distances between the floatline and the leadline. Range between maximum and minimum distance from echosounder is termed "height" as it becomes visible as a "height" in the echogram; (b) front view of the experimental set-up, the columns become visible as rows in the echogram, when the gillnet is ensonified from an angle

2.2 Determination of area backscattering strength (S_a) and target strength (TS)

In previous studies measuring the acoustic reflectivity of gillnets (Kastelein et al., 2000; Mooney et al., 2004), target strength was used as the measure for acoustic reflectivity, albeit target strength is more suitable for single targets rather than area targets. As gillnets are area targets, the area backscattering strength (S_a; MacLennan et al., 2002) of tested gillnets was primarily used to describe the acoustic properties, relevant for echolocating whales. S_a-values were determined across a large frequency range (35 kHz to 170 kHz). Additionally, target strength (TS; MacLennan et al., 2002) of the gillnets were calculated to be able to compare our measurements to previous studies.

Echodata from the EK80-echosounder were post-processed and analyzed with EchoView 10 software (*Echoview Software Pty Ltd*, 2019) and the minimum threshold was set to –60 dB when viewing the echograms. For all pings during the ensonification, volume backscattering strength (S_v, MacLennan et al., 2002) and target strength (TS) were exported for each single frequency as well as the frequency range between 120 – 140 kHz, which corresponds to the frequency range used by harbor porpoises (Miller and Wahlberg, 2013). Sections containing echoes of fish or fish schools swimming around the gillnet were marked as “bad data” and excluded from the analysis.

To automatically separate gillnet echoes from noise and to correct for net movements during each measurement series, an algorithm was applied to determine the first and last S_v or TS value larger than –65 dB for each acoustic ping during the measurement of each net/angle combination. This threshold was chosen based on previous work (Au and Jones, 1991; Kastelein et al., 2000; Mooney et al., 2007). As not all pings had values larger than the threshold, the running minimum and maximum distance from the transducer was determined for 10 pings and subsequently the running mean was determined over 50 pings.

For both reference nets (Cod-Ref and Tur-Ref) start and end of the net were determined at a threshold of –70 dB, as some combinations of net and degree did not have enough pings with values above –65 dB to be able to distinguish the netting from noise.

From the exported S_v values, the corresponding volume backscattering coefficients s_v were calculated:

$$s_v = 10^{\frac{S_v}{10}} \tag{1}$$

To gain the area backscattering coefficient s_a the s_v values for each ping were integrated using a spline function in R (R Core Team, 2019):

$$s_a = \int_{minimum\ distance}^{maximum\ distance} s_v \tag{2}$$

The area backscattering strength S_a is calculated as:

$$S_a = 10 * \log_{10}(s_a) \tag{3}$$

To be able to compare the results of this study with previous studies, an equivalent target strength (TS) value was determined. The TS for the full gillnet was determined by both coherent and incoherent (following (Simmonds and MacLennan, 2005) addition of the TS values across the “height” *m* for each ping.

$$TS_{coherent} = 10 \log_{10}(\textstyle\sum_m \sigma_{bs_m}) \tag{4}$$

$$TS_{incoherent} = 10 \log_{10}(\sqrt{\textstyle\sum_m (\sigma_{bs_m})^2}) \tag{5}$$

Coherent addition is the maximum possible TS, where incoherent accounts for possible factors reducing TS such as extinction, small movements of the net or small deviations from perpendicularity. It is the likely mean of the TS of the gillnet.

2.3 Modelling area backscattering strength

The experimental variation in the average area backscattering was modelled as:

$$S_{a_{ij}} = \mu_0 + \alpha_i \times angle_i + (\beta_0 + \delta_i) \times n_{ij}^k + g(a, f_{ij}, n_{ij}) + \epsilon_{ij} \quad (6)$$

In Equation 6, μ_0 is the model intercept representing the average area backscattering strength for the reference gillnet (Cod-Ref) at the reference angle of ensonification (0°). Parameters α_i are deviations from the average, caused by the two additional angles of ensonification tested $i \in \{20°, 45°\}$, entered in the model as categorical levels. The parameter β_0 accounts for the effect of increasing the number of spheres (n_{ij}) per m² attached to the gillnet at reference angle of ensonification. To account for potential non-linear relationship between n_{ij} and $S_{a_{ij}}$, different transformations of the identity n_{ij} (k= 1) were considered, including square root (k = 0.5), quadratic (k= 2) and cubic (k= 3) transformations. Models with quadratic and cubic transformations of n_{ij} also incorporated lower order ($1 \leq k \leq 3$) transformations as polynomial basis. Parameters δ_i are interaction terms representing deviations of β_0 caused by the two additional angle of ensonification i. Further, $g(a, f_{ij}, n_{ij})$ denotes a smooth-by-factor interaction (Roca-Pardiñas et al., 2006) between the tensor product of cubic splines smoothing the effect of transducer frequency (f_{ij}) and number n_{ij} of the spheres per m², and the angle of ensonification $a \in \{0°, 20°, 45°\}$, therefore:

$$g(a, f_{ij}, n_{ij}) = \begin{cases} g^{0}(f_{ij}, n_{ij}) \text{ if a=0°} \\ g^{20}(f_{ij}, n_{ij}) \text{ if a=20°} \\ g^{45}(f_{ij}, n_{ij}) \text{ if a=45°} \end{cases} \quad (7)$$

Note that for this analysis the range of frequencies were restricted to values between f = 100 kHz and f = 160 kHz, as this is the frequency range that the spheres were designed for and thus require an in-depth analysis. The last parameter $\varepsilon_{ij} \sim N(0, \sigma^2)$ in Equation 6 are the model residuals. The model in Equation 6 has a semi-parametric form that involves parametric terms (μ_0 ,α_i, β_0 and δ_i) from standard linear model regressions, and non-parametric terms ($g(a, f_{ij}, n_{ij})$, Equation 7) which require specific algorithms to control the degree of smoothing of each individual smooth term . Therefore, the model was fitted using the P-IRLS algorithm established for generalized additive models, using the mgcv package (Wood, 2006) available in R (R Core Team, 2019).

3. RESULTS

The wideband echograms (FIGURE 3) revealed a clearly visible difference in echo structure of the different types of gillnets in the different inclinations. The height of the gillnet in the echogram corresponds to the distance from the transducer resulting in a broader echo at the 20° and 45° angle, as the gillnet is rotated around its center which is aligned with the center of the transducer beam. At 0°, the netting area inside the acoustic beam is ensonified simultaneously and the small “height” results from the edges of the transducer beam being further away from the center and the fact that the net, despite being strung tightly was never positioned absolutely perpendicular to the acoustic beam, but often rather hung like a slightly wavy curtain. The vertically aligned spheres, or columns of spheres, are visible as distinct rows, as some columns are closer to the transducer than others (FIGURE 2). The spheres are particularly visible when measuring with the 120 kHz transducer as the spheres resonate within the frequency range of that transducer. The number of red rows corresponds to the predicted columns in TABLE 2 for 40 cm and 60 cm at 120 kHz. The echoes of the rows in the 20 cm cod net overlap, thus it is not possible to count the individual rows. The turbot gillnet with spheres (Tur-35cm) only shows five columns of spheres instead of the predicted eight.

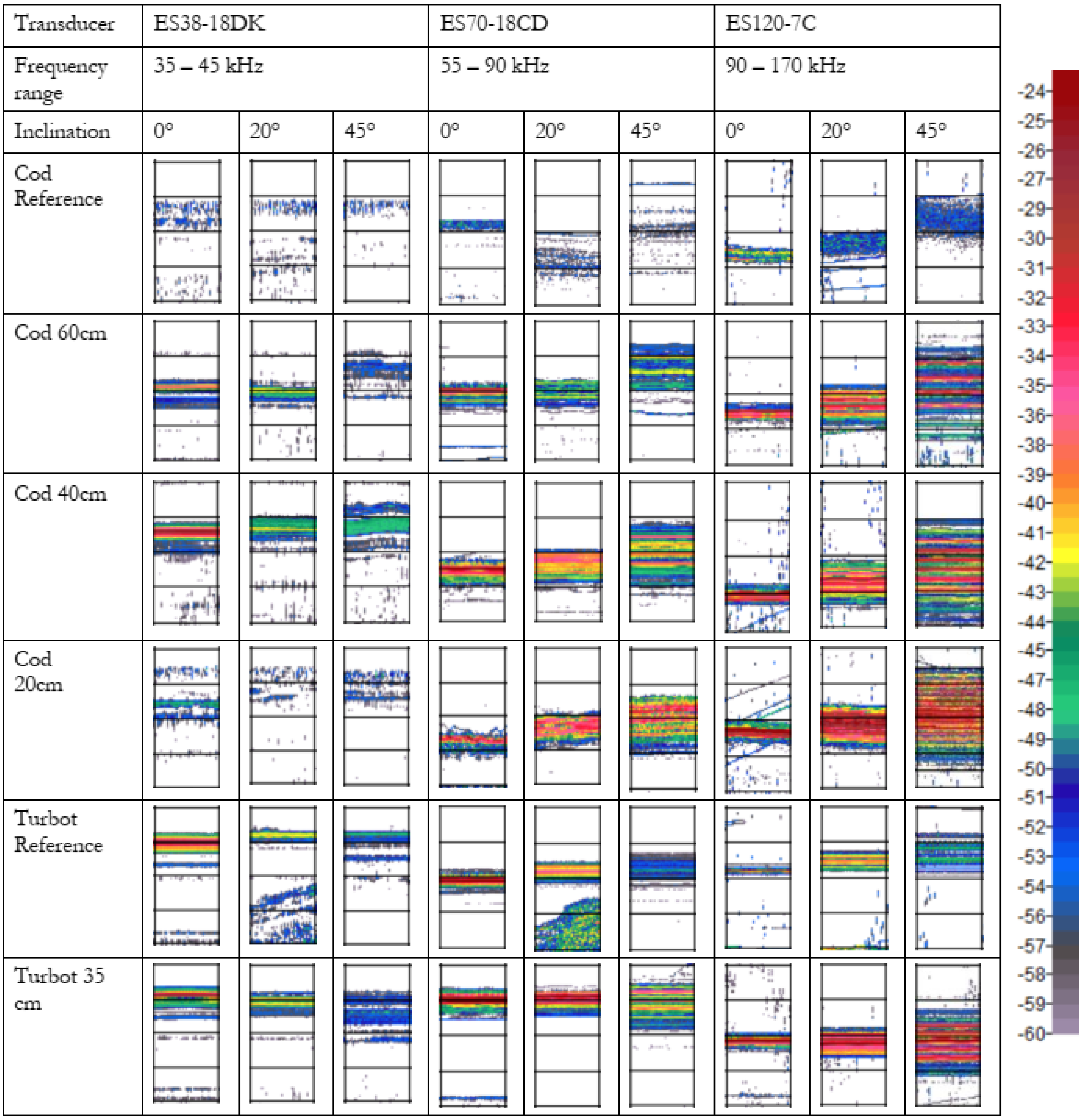


FIGURE 3: Wideband echograms of all measured gillnets at three different angles of incidence from the transducer. Scale indicates S_v in dB at each pixel. Distinct rows are the columns of spheres. The x-axis represents the sequential pings, while the distance from the transducer face is depicted in the y-axis. Noise such as fish schools are not removed from the echogram for visualization.

3.1 Area backscattering strength

3.1.1 General comparison of area backscattering strength measurements

From the wideband echogram data, S_v was extracted for each pixel, corresponding to the visualization of each data point, and values were integrated over “height” of the gillnet to determine the area backscattering strength (S_a) per ping and then shown as the mean S_a for all pings per frequency (FIGURE 4). The cod reference net made from nylon (Cod-Ref) has the lowest S_a across all frequencies. The turbot net made from natural fiber (Tur-Ref) has slightly higher S_a values, but the echo values are low especially in the high frequency range and when ensonified at a 45° angle, The nets with spheres outcompete their respective reference nets at frequencies above 100 kHz, as this is the frequency range where resonance of the spheres occurs and follow a similar pattern as in the simulated data (FIGURE 1), albeit not being comparable in terms of echo strength, due to the difference in measure (measured S_a vs simulated TS). The values drop for all nets near the edges of the measurable frequency ranges of each transducer, due to the physical limitations of the transducer.

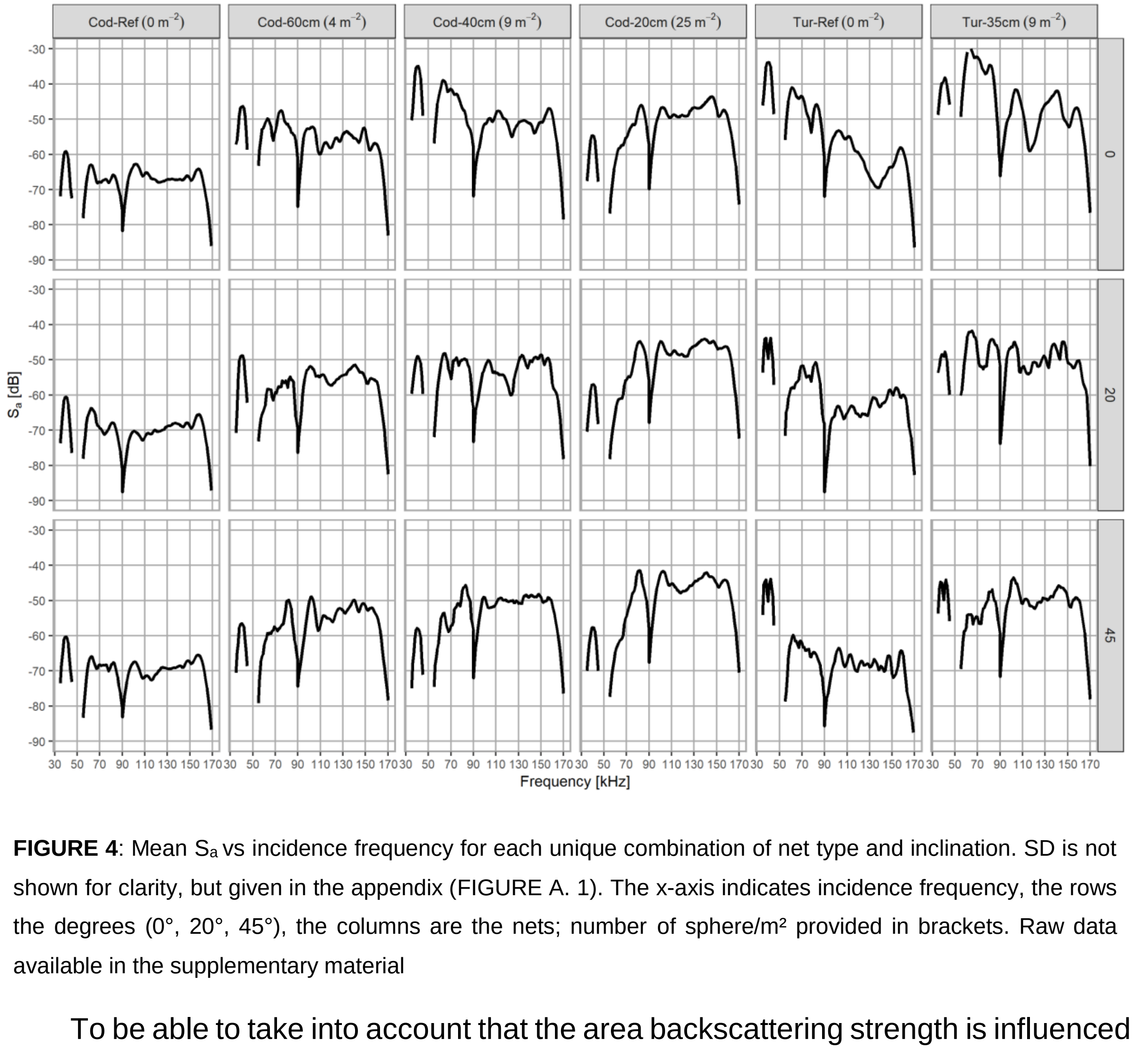


FIGURE 4: Mean S_a vs incidence frequency for each unique combination of net type and inclination. SD is not shown for clarity, but given in the appendix (FIGURE A. 1). The x-axis indicates incidence frequency, the rows the degrees (0°, 20°, 45°), the columns are the nets; number of sphere/m² provided in brackets. Raw data available in the supplementary material

To be able to take into account that the area backscattering strength is influenced by the ensonified area, FIGURE 5 shows the mean s_v value of each "height" averaged over all pings in each frequency. While S_a can stay the same with an increase in inclination as more but smaller s_v values are integrated, mean s_v decreases with an increase in inclination, as the echoes are distributed over a larger range.

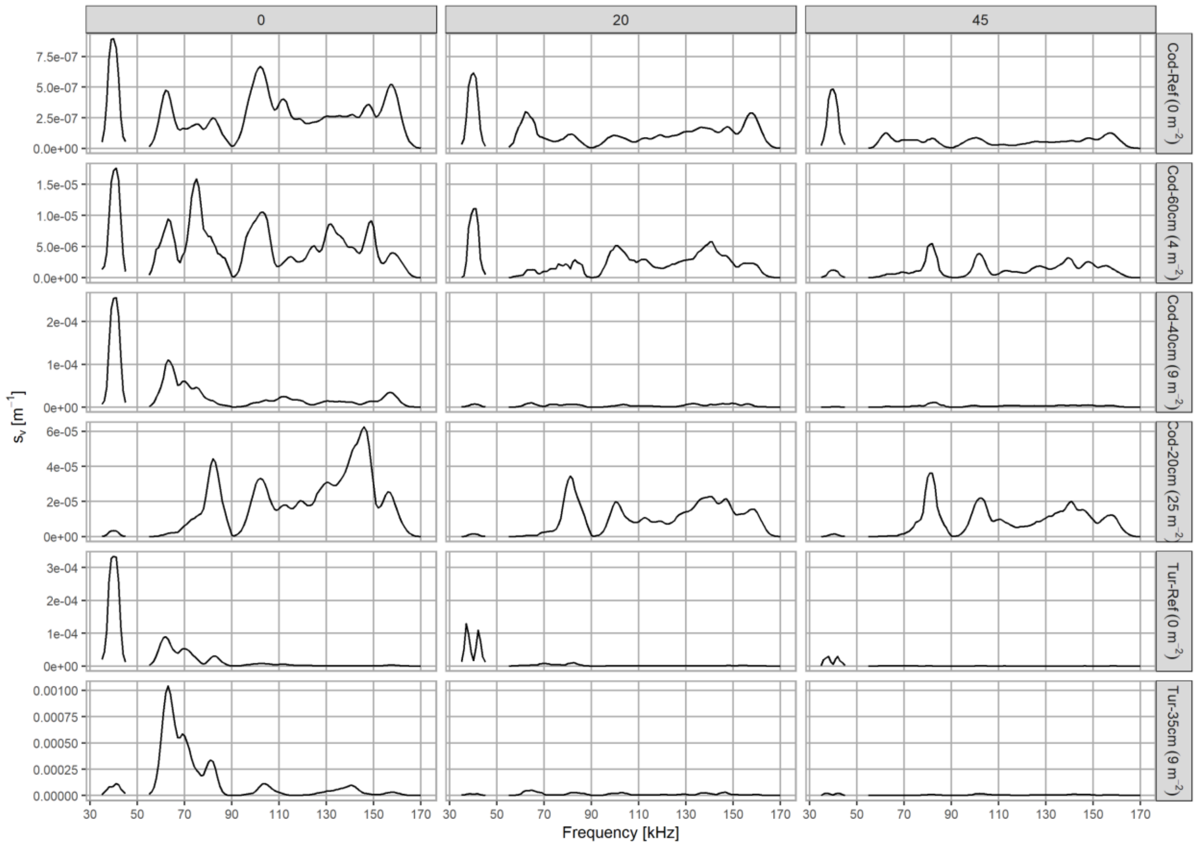


FIGURE 5: Mean volume backscattering coefficient s_v for each frequency and inclination/net combination. The s_v of each ping were averaged over "height". The x-axis indicates incidence frequency, columns represent inclination (0°, 20°, 45°), and the rows represent the corresponding nets; number of sphere/m² provided in brackets . Note the difference in y-scale for each net (same scale in each net across degrees).

3.1.2 S_a value for single frequency (130 kHz) vs frequency range (120 – 140 kHz)

The S_a for the single frequency value of 130 kHz differ between net types, i.e. modified nets have a higher S_a than their respective reference net (FIGURE 6a). The S_a of nets with spheres also differ between Cod-20 cm, as Cod-20cm has a higher S_a than Cod-40cm and Cod-60cm, which are similar. The S_a values are similar between inclinations within each net type at 130 kHz, except for Cod-20 cm and Tur-35cm between 0° and 45° with higher S_a values at 45° for the Cod-20 cm net and the opposite for the Tur-35cm.

Here, the S_a values are also shown for a frequency range between 120 – 140 kHz, as this corresponds to the echolocation range of harbor porpoises. The S_a values of the frequency range 120 – 140 kHz show a similar behavior as the S_a values of the single 130 kHz frequency, with generally higher values than the single frequency (FIGURE 6b). This is due to the fact that the echo energy of different frequencies is accumulated. Still, the reference nets have significantly lower S_a values compared to the nets with spheres. The cod nets with 40 cm and 60 cm sphere-sphere distance have similar S_a values. This in turn means that if the reflectivity of the Cod-60 cm net is enough to alert harbor porpoise to the obstacle and they do not attempt to swim through the individual objects, there is no need to increase the number of spheres, also shown in the predictive model results (FIGURE 9). That is especially relevant, as e.g., halving the distance between spheres means a fourfold increase in number of spheres required. Similarly to the single frequency of 130 kHz, there is a positive correlation between S_a and inclination for the 20 cm, 40 cm and 60 cm cod nets when comparing 0° to 45° and a negative correlation for the turbot net with spheres as well as both reference nets. The turbot reference net has a higher reflectivity than the reference cod nylon net at 0° and 20°. However, this difference is not apparent at 45°.

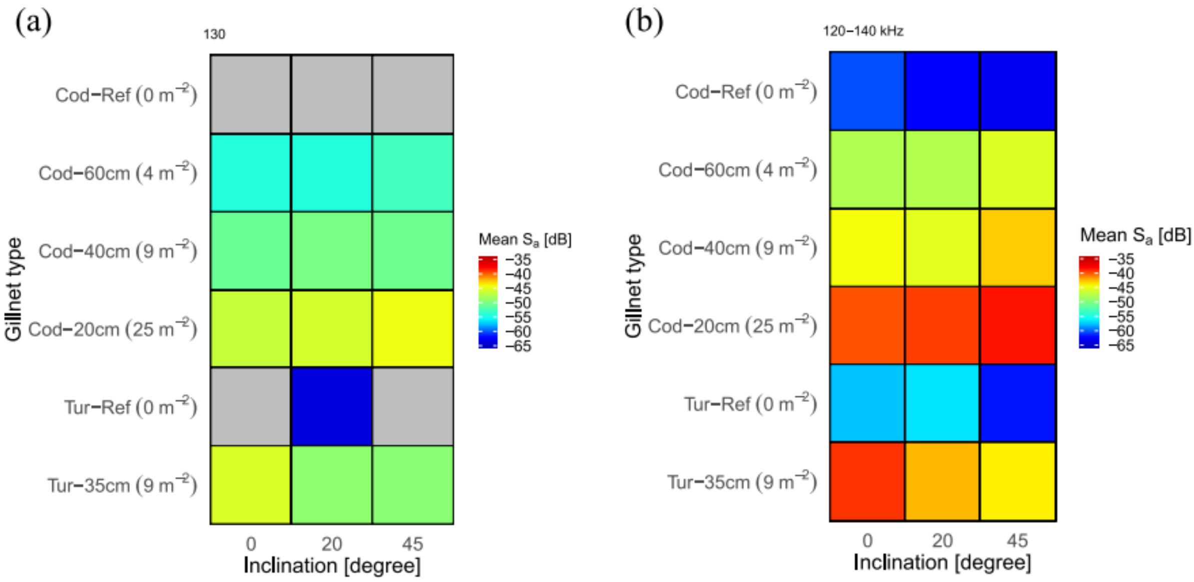


FIGURE 6: Mean Acoustic Backscattering Strength (S_a) at 130 kHz (a) and for a frequency range 120 – 140 kHz (b). Grey areas (Tur-Ref and Cod-Ref (a) represent S_a values below –65 dB. S_a for other frequencies is given in the appendix (FIGURE A. 2). Number of sphere/m² provided in brackets

3.1.3 Models for area backscattering strength

Prediction modelling was conducted for the cod nylon nets in the frequency range between 100 – 160 kHz. This selection is based on the fact that the spheres were designed to improve the acoustic visibility in the high frequency range (above 100 kHz), as this is the echolocation range of harbor porpoises. The cod nets were chosen as they provide a stepwise increase in number of spheres per m² while the turbot nets were measured for the sake of completeness as they already had been used in a commercial fishing trial.

The model candidates to assess the additive and combined effect of angle of ensonification of the gillnet, number of spheres per m² and frequency on the observed area backscattering strength were successfully fitted (TABLE 3). Fit statistics from the model using the square root transformation of number of spheres per m² (model 1) were equal to those from the models involving quadratic and cubic polynomial basis (models 3 and 4). The high R^2 achieved demonstrates that models 1, 3 and 4 captured and explained most of the variation of the experimental data ($R^2 = 0.92$, FIGURE 7, FIGURE 8, TABLE 4). Model 1 had however a simpler structure than model 3 and 4 (6, 9 and 12 parametric linear predictors, respectively), therefore model 1 was selected and subsequently used for the analysis.

TABLE 3: Fit statistics of the candidate models ranked by AIC (Akaike, 1974) and number of parametric terms applied to model the main effect of number of spheres per m² and its interaction with angle of ensonification of the gillnet.

Model	k	Linear predictors (n)	Deviance	AIC	R^2
1	0.5	6	938700	744720	0.92
3	2	9	938700	744720	0.92
4	3	12	938700	744720	0.92
2	1	6	1586693	829678	0.87

TABLE 4: Model summary of the predictive model 1

Parametric coefficient	Estimate	Smooth term	edf	Reference
μ_0	–66.73±0.125***	$g^0(f_{ij}, n_{ij})$	84.55***	103.2
α_{20}	–19.97±0.189***	$g^{20}(f_{ij}, n_{ij})$	86.70***	105.7
α_{45}	–19.09±0.189***	$g^{45}(f_{ij},n_{ij})$	85.82***	104.7
β_0	4.62±0.047***			
δ_{20}	7.45±0.071***			
δ_{45}	7.68±0.072***			

An inspection of predictions from the selected model 1 shows its capability to describe the experimental data (FIGURE 7, FIGURE 8, FIGURE 9), capturing sufficiently well even local patterns that occurred throughout the range of transducer frequencies assessed (FIGURE 8).

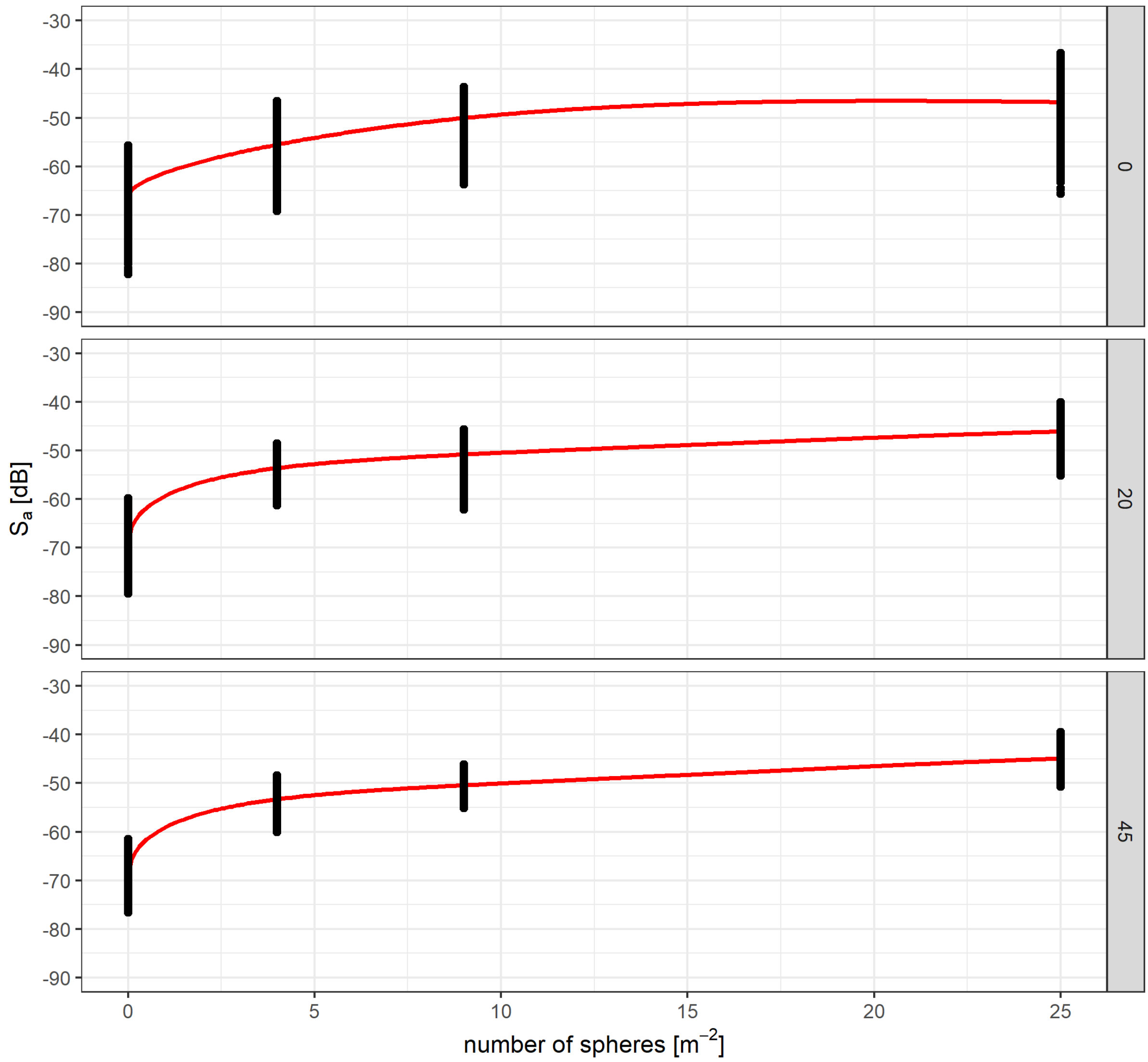


FIGURE 7: Predicted S_a values (solid line) and experimental values (black marks) depending on the number of spheres *n* per m² of netting, exemplarily at 130 kHz

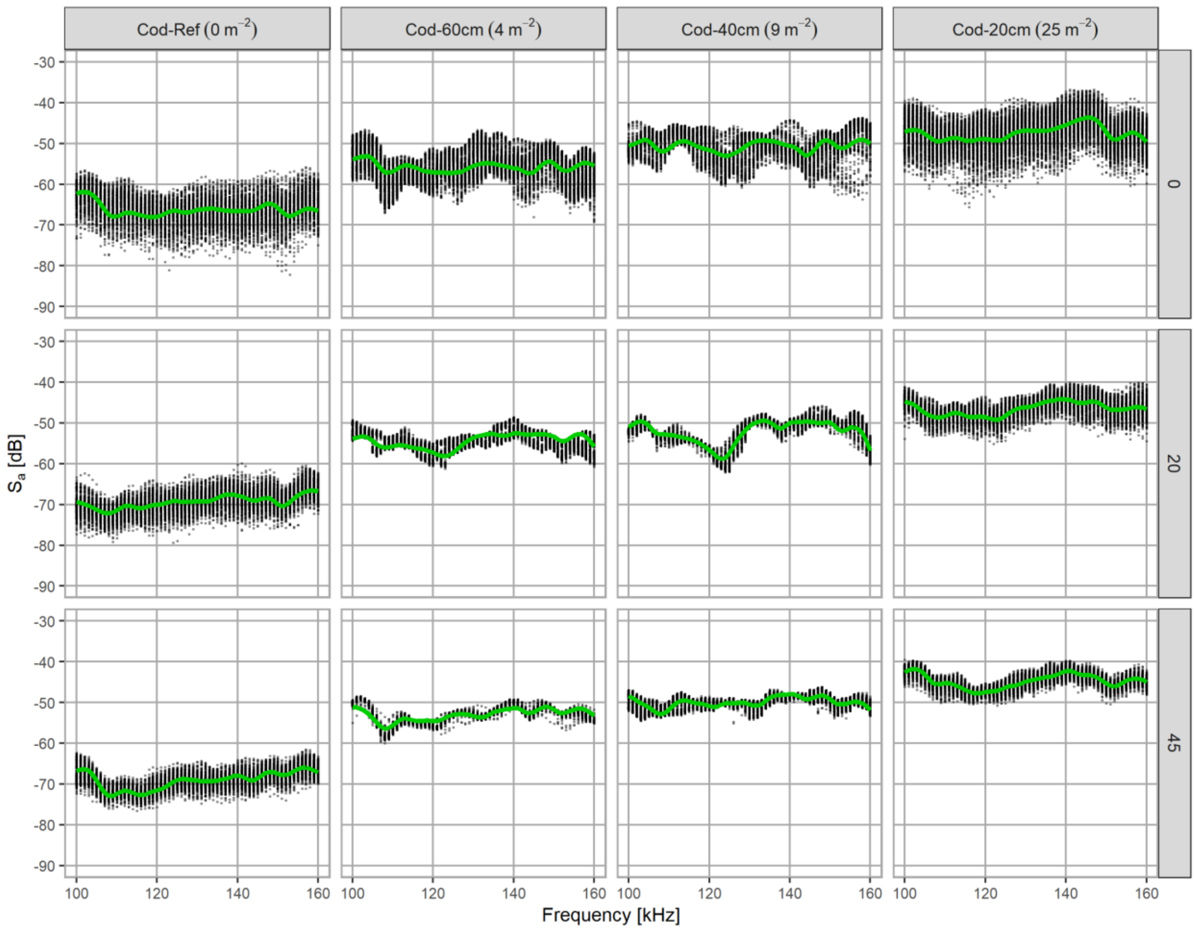


FIGURE 8: Predicted S_a values (solid line) across frequency range 100 – 160 kHz and experimental data (black marks) for each combination of net/inclination; number of spheres/m² provided in brackets.

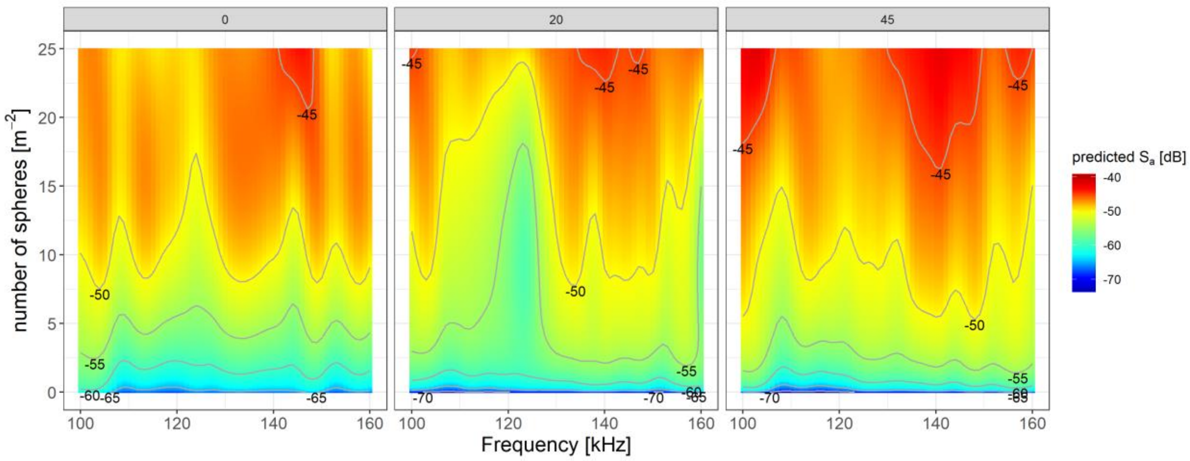


FIGURE 9: Predicted S_a values (colors) across the frequency range 100 – 160 kHz (x-axis) depending on the number of spheres per m² (y-axis) of cod gillnet for each angle of inclination (0°, 20°, 45°)

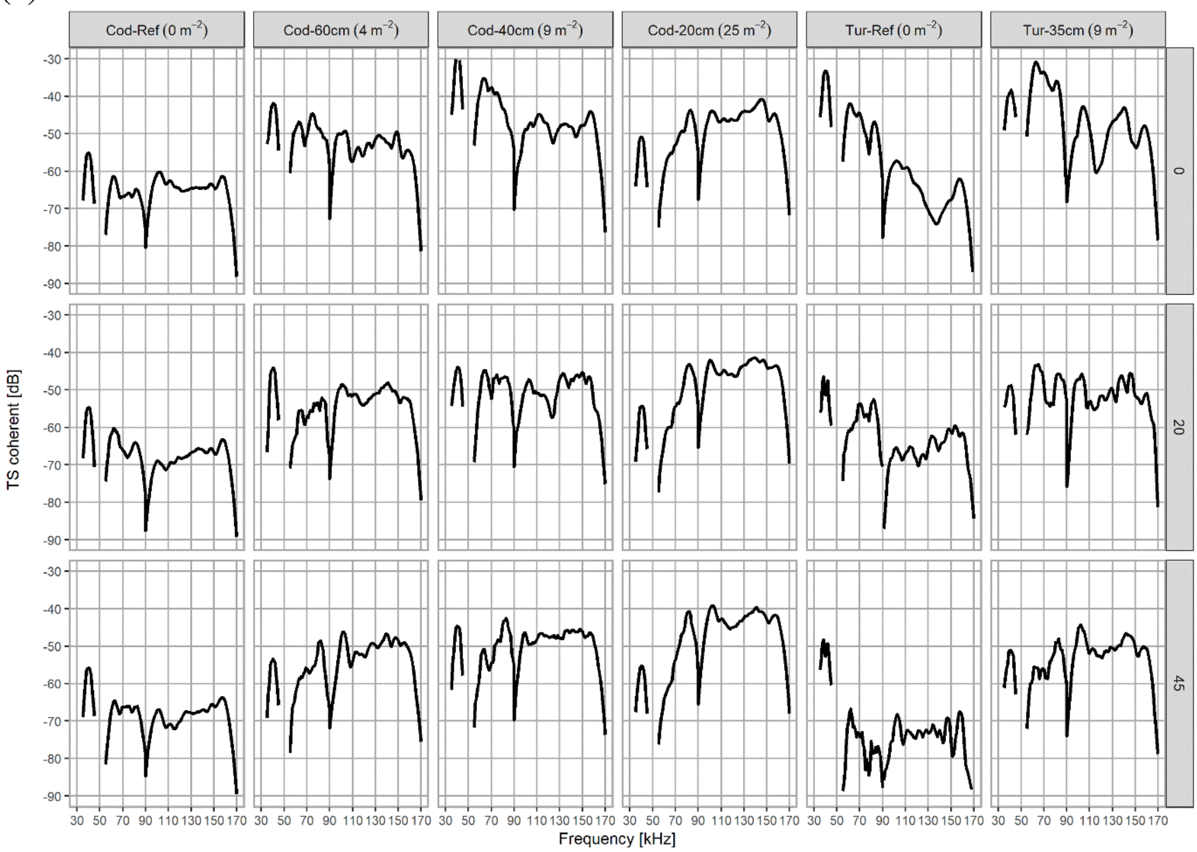
The predicted values of S_a (FIGURE 9) show a similar trend as the experimental data (FIGURE 4), i.e. an increase in S_a with increasing number of spheres per area of netting. The increase in inclination respective to the transducer face leads to an increase in overall S_a in nets with spheres across all high frequencies. The S_a value of the reference net (Cod-Ref) decreases with an increase in inclination. Even with a low number of spheres (9 m²) the acoustic backscattering strength increases substantially compared to the reference net when ensonified perpendicularly and at 45°.

3.2 Target strength

3.2.1 General comparison of target strength measurements

The echo data were transformed into TS values per data point using EchoView and subsequently exported for all single frequencies as well as the frequency range 120 – 140 kHz. Both coherent (FIGURE 10a) and incoherent (FIGURE 10b) addition of single TS values were calculated, values are shown without SD for clarification (see appendix for individual nets with SD). The values of both coherent and incoherent single frequency TS values follow the same pattern as the S_a values. Predictive modelling was not applied to the TS values, as S_a is a more representative measure of an area target as opposed to TS. The TS values are presented mainly for comparability to other studies.

(a)



(b)

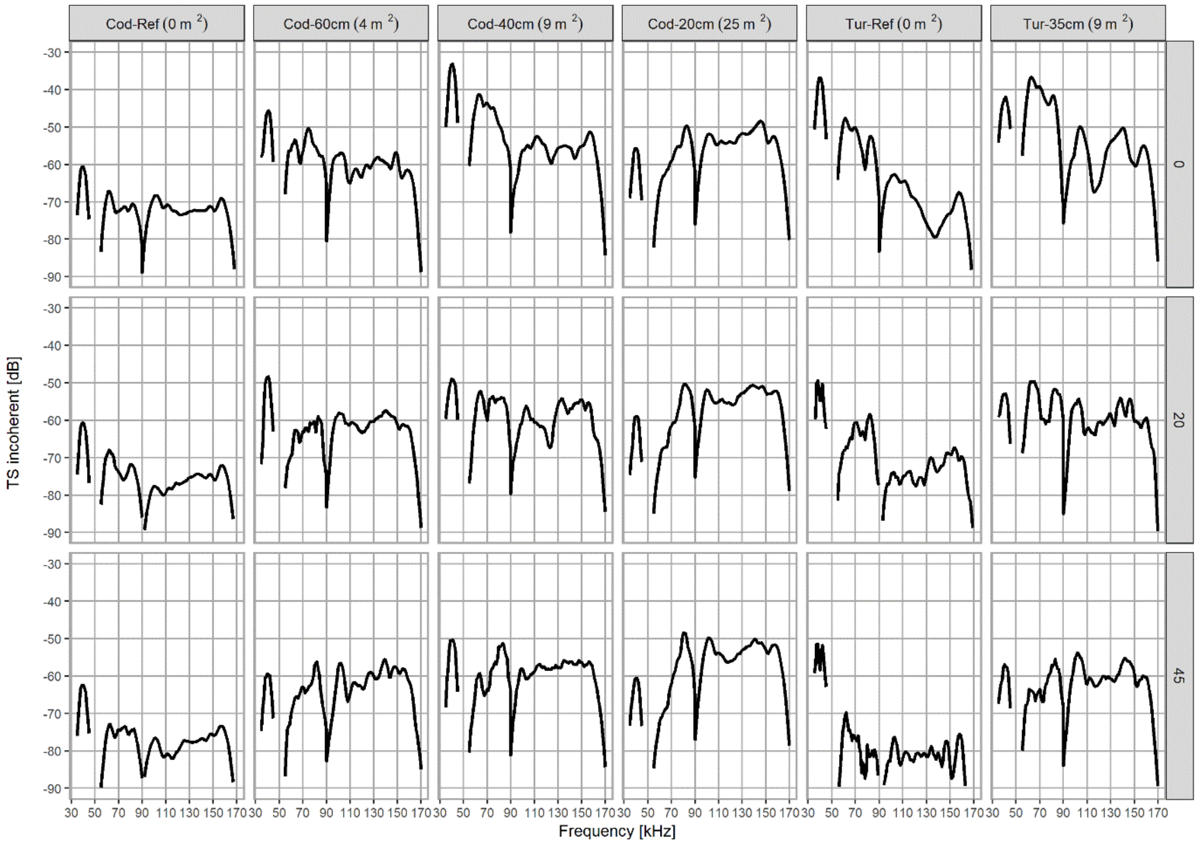


FIGURE 10: Mean coherent (a) and incoherent (b) TS vs frequency for each unique combination of net type and inclination; number of sphere/m² provided in brackets. SD is not shown for clarity, but given in the appendix (FIGURE A. 3; FIGURE A. 4). Raw data available in the supplementary material

3.2.2 TS value for single frequency (130 kHz) vs frequency range (120 – 140 kHz)

The TS values are compared between 130 kHz (FIGURE 11a, c) and the frequency range 120 – 140 kHz (FIGURE 11b, d). Similarly to the S_a values, the single frequency and frequency range TS values differ for both coherent and incoherent addition between the nets, but largely not between inclinations within one net (FIGURE 11a, c and b, d). Overall, the net with 20 cm sphere-sphere distance has the highest incoherent TS, regardless of inclination.

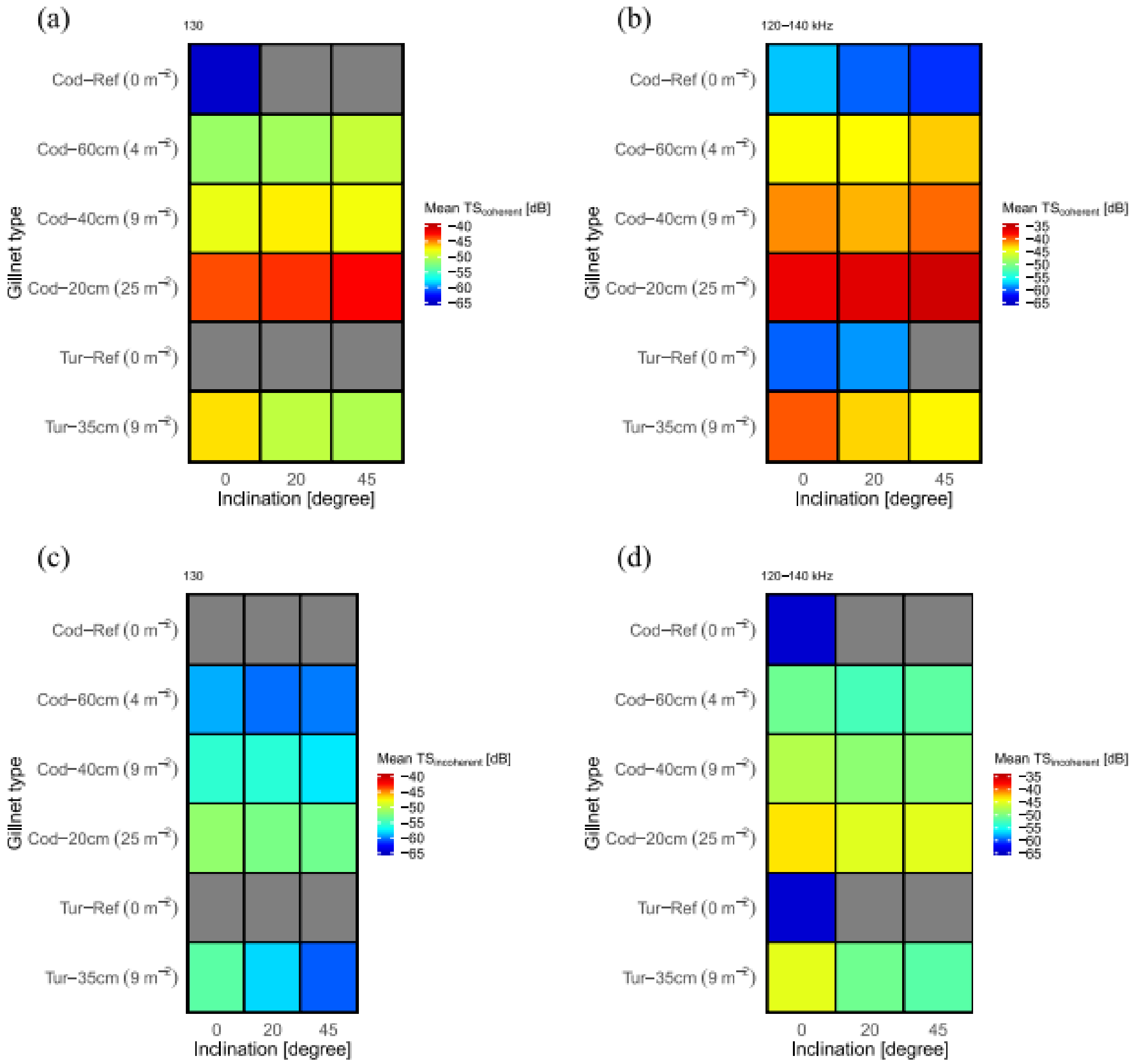


FIGURE 11: Mean coherent (a, b) and incoherent (c, d) target strength (TS) at 130 kHz (a, c, same color scale) and for a frequency range 120 – 140 kHz (b, d, same color scale). Grey areas (Tur-Ref and Cod-Ref) represent TS values below –65 dB; number of sphere/m² provided in brackets. TS for other frequencies is given in the appendix (FIGURE A. 5; FIGURE A. 6)

4. DISCUSSION

Developing effective bycatch reduction measures for toothed whales (odontocetes) has been a challenging task for the past 50 years since the IWC first recognized bycatch as an emerging problem for small cetaceans (IWC, 1972). In this study, the acoustic visibility – and hence detectability – of gillnets has been substantially improved by attaching small acrylic glass spheres to the netting, especially in the frequency region above 110 kHz that the spheres were optimized for. Additionally, the acoustic image of the gillnet was altered, i.e. the spheres become highly visible at an angle and the overall pattern of the gillnet is more visible, as the echoes are distributed within the acoustic beam. This could greatly reduce bycatch of echolocating odontocetes as it could enable them to recognize the net as an obstacle and thus avoid entanglement. Harbor porpoises are used as an exemplary species, as they are well studied and are endangered in the Eastern Baltic Sea (Hammond, 2008) as well as in the Black Sea (Birkun and Frantzis, 2008), due to bycatch among other reasons. Based on a simulated study (Kratzer et al., 2020), the gillnet was acoustically enhanced for a frequency range between 120 – 140 kHz, which is the echolocation range of harbor porpoises (Miller and Wahlberg, 2013).

Porpoises constantly move their heads when scanning their environment (Wahlberg et al., 2015) and it is presumed that they perceive nets as areas. Thus, acoustic reflectivity is primarily regarded in terms of area backscattering strength (S_a), as gillnets are more accurately represented as an area target rather than a single target. Nevertheless, target strength values are also presented for comparability to previous studies (Au and Jones, 1991; Kastelein et al., 2000; Larsen et al., 2007; Mooney et al., 2004).

Two types of gillnets were used as reference nets: a nylon gillnet used in the Baltic Sea cod fishery (Cod-Ref) and a gillnet made from natural fiber (Tur-Ref), usually in use in the Black Sea turbot fishery. The gillnet made from natural fibers has a higher reflectivity than the nylon net, possibly due to the larger diameter of the filament, but also due to the material characteristics of natural fibers. A more likely reason for higher S_a values of the turbot net compared to the cod net is the entrapment of air bubbles in the filament strands, which have a high target strength if excited at their resonance frequency (Medwin and Clay, 1998). It should be noted that the bubbles are likely to disappear over the usual soak time of turbot nets (usually several days; (Bilgin et al., 2018; Vinther, 1999), likely resulting in a substantial drop in acoustic visibility. Bycatch rates have been associated with long soak times (Northridge et al., 2017), which could, aside from an increase of capture probability through prolonged effort, be caused by an decrease in acoustic visibility of gillnets when they are soaked in water. Below 100 kHz the spheres do not strongly affect the acoustic reflectivity of the nets. At frequencies above 100 kHz, the S_a of nets equipped with spheres is substantially higher than nets without spheres, as it is within the frequency range where the spheres have several resonance peaks (Kratzer et al., 2020). When the nets are set at an angle relative to the transducer, the echo broadens, as some parts of the gillnet are further away from the transducer within the acoustic beam than others. While the echo appears to be wider and thus stronger on the echogram, there is only a small increase in S_a for the nets with acrylic spheres and a decrease of S_a for the reference net. The increase in S_a is attributed to an increased number of ensonified spheres when the nets are set at an angle relative to the transducer. Effects such as runtime differences, refraction and small interference effects are possible causes of a decrease in S_a of the reference nets.

As the S_a value is obtained by integration of s_v values, the small increase of S_a with increasing inclination of nets with spheres is also reflected in the area under the s_v-splinefunction, which has several smaller peaks, likely from the resonating spheres, when the net is at an angle compared to a single large peak at 0° (exemplarily shown in FIGURE A. 7). That means that at an angle many small s_v values are integrated as opposed to a few larger ones at 0°. This is especially relevant as it is not known whether porpoises integrate the echoes over an area and thus the overall echo strength is crucial or whether they are able to resolve the pattern of echoes in an area target. This means, it remains to be determined whether the S_a values, i.e. value integrated over the entire height, are more relevant or whether the distribution of S_v values will influence the behavior of the porpoise. In either case, the spatial and temporal distribution of the echoes (as shown in the echograms) as well as the echo strength (S_a) are greatly improved at any given angle when spheres are attached to the gillnet. In fact, as the S_a of standard nets decreases with an increase in inclination, the effect of the spheres is even more relevant when the porpoise would be approaching from an angle.

As the S_a turbot net with spheres decreases with inclination, a possible explanation is the challenging experimental set-up required for the turbot nets. Due to the reduced net height compared to the nylon nets (2 m vs 3.6 m), the nets had to be placed very close to the transducer. As the nets were inclined, the net may have been largely outside of the reliable measuring distance of the acoustic transducer, corresponding to the far field.

The area backscattering strength S_a estimated for a frequency range is much stronger than for a single frequency, due to the possibility that echoes of some frequencies add coherently (Baus and Radlinski, 1994). Since porpoises emit narrow-band clicks and do not use a fixed frequency, it is possible that the effect may be comparable to the 120 – 140 kHz frequency range measurements in this study, meaning that the animal could perceive the higher S_a value.

The TS values are derived from the S_v values in EchoView and subsequentially added coherently and incoherently, where the latter is a more conservative method to account for possible extinctions and runtime differences from the echoes. Other studies ensonified the gillnets with porpoise clicks, thus the incoherent TS value of the frequency range 120 – 140 kHz is used as a comparative value. Compared to other studies the cod reference net made from nylon has a similar TS (TABLE 5), albeit fairly low considering the larger ensonified area. The difference might be caused by differences in acoustic energy per ensonification frequency and different gillnet properties. Similarly to other studies, the TS drops with inclination, as the incident signal on the net is refracted in another direction than the receiver (Goodson, 1997). This effect does not apply to the gillnets with spheres, as their TS increases with inclination. When target strength is considered as a proxy for detection distance, the 50% detection distance of the Cod-20cm net is likely comparable to the detection distance of a 5 cm water filled stainless-steel-sphere, i.e. approximately 16 m (Kastelein et al., 1999).

TABLE 5: Comparison of TS values between different studies with diameter/size of transducer beam and ensonified area at the gillnet. Values vary when more than one type of gillnet was used in the measurements. This study uses the incoherent TS from the cod nylon reference net in the frequency range 120 – 140 kHz to be comparable to an ensonification with porpoise clicks as used in the other studies.

	Mooney et al. (2004)	Kastelein et al. (2000)	Larsen et al. (2007)	Au & Jones (1991)	this study
Diameter/ size [m]	0.68	0.52		0.34 by 0.55	1.6
Ensonified area [m²]	0.36	0.87		0.19	2.01
TS [dB] perpendicular	–52	–53 to –61	–53	–42.2 to –60.2	–64.28
TS [dB] small inclination	–60 (20°)			–62 (15°)	–67.65 (20°)
TS [dB] large inclination	–62 (40°)	–54 to –66 (45°)		–60 (45°)	–70.36 (45°)

For some frequency ranges, the echo measurements should be treated with caution, especially in the edge regions of the frequency range of each transducer. In these regions, the measurements are likely to be imprecise, which is reflected in a similar pattern of very low S_a values in these edge regions, due to the physical limitations of the transducers. Care should also be taken with the measurements of the turbot nets (Tur-Ref, Tur-35cm) in the region between 35 – 45 kHz, as the net needed to be placed in the nearfield of the 38 kHz transducer, to avoid ensonification of the floatline and leadline due to the reduced height compared to the cod nets.

Whether the nets with spheres will act as a perceived barrier, is largely dependent on the reaction of the animal and whether it relies more on the absolute echo strength or the distribution of echoes through its echolocation beam. As a next step, the behavior of harbor porpoises around modified nets should be investigated. A preliminary study has shown promising results (Gustafsson, 2020), but should be complemented with visual sightings as well as data on swimming tracks of porpoises. Furthermore, it is unclear whether increased underwater noise is associated with higher bycatch as the animals may be subject to range reduction in their signal perception in high noise levels (Hermannsen et al., 2014). An improved detectability due to higher echo strength of modified gillnets could mitigate the issue of signal reception in noisy environments.

While the increase in acoustic reflectivity is based on the assumption that porpoises echolocate frequently (Wisniewska et al., 2016), they are also known to swim silently for periods (Linnenschmidt et al., 2013). This might imply the need for an additional device that sends a low-impact “wake-up” call to alert the porpoise to an obstacle and increase their alertness. Finally, the modified nets need to be subject to further commercial fishery trials. A recent study (Kratzer et al, 2020, in review) has shown promising, but not ultimately conclusive results on the efficacy of the spheres to reduce small cetacean bycatch. Prior to the large-scale implementation, if the modified nets turn out to be successful, an automated process to attach the spheres needs to be developed.

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DATA AVAILABILITY STATEMENT

Data used in the analysis is provided in the supplementary material.

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APPENDIX

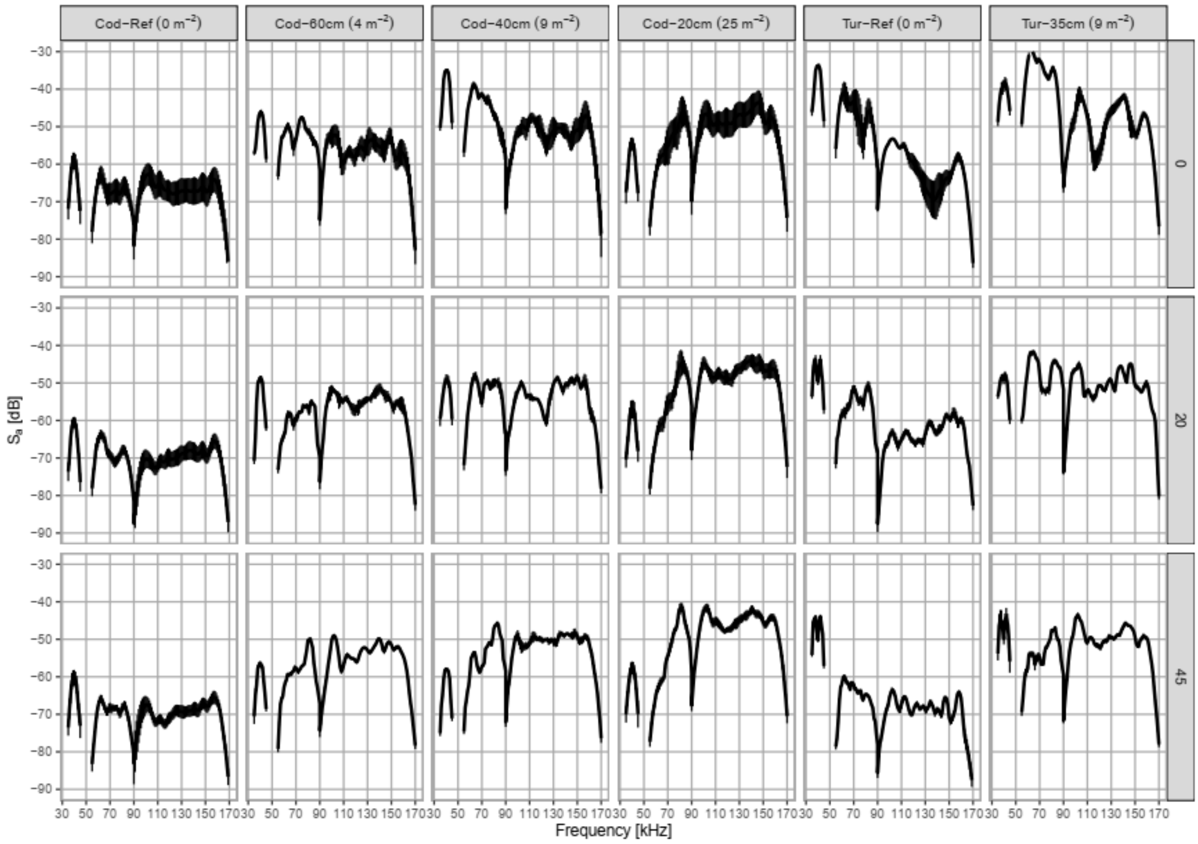

FIGURE A. 1: Mean S_a vs frequency for each combination of net type and inclination, including SD; number of sphere/m² provided in brackets

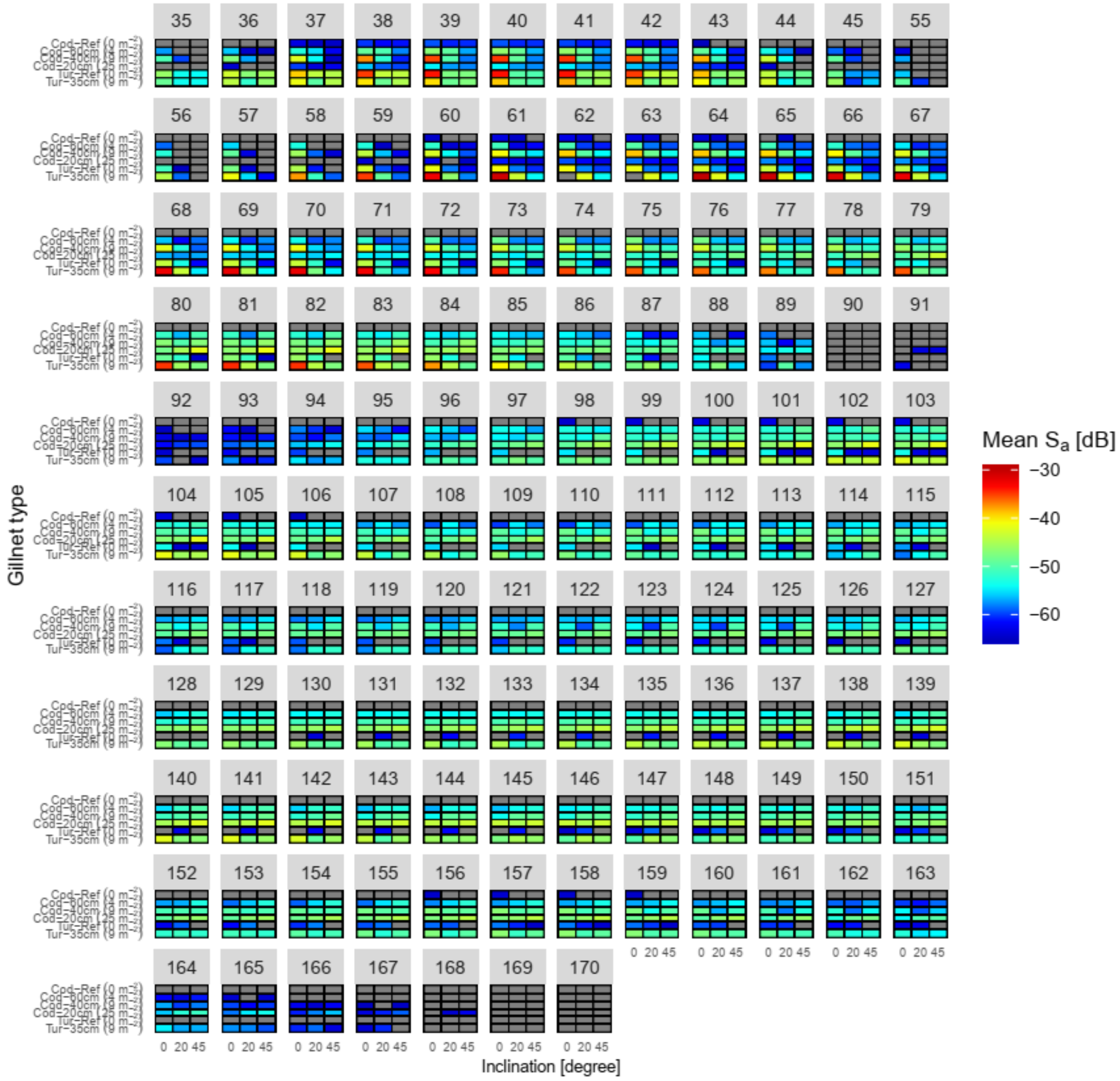

FIGURE A. 2: Mean S_a for all frequencies according to net and inclination; number of sphere/m² provided in brackets

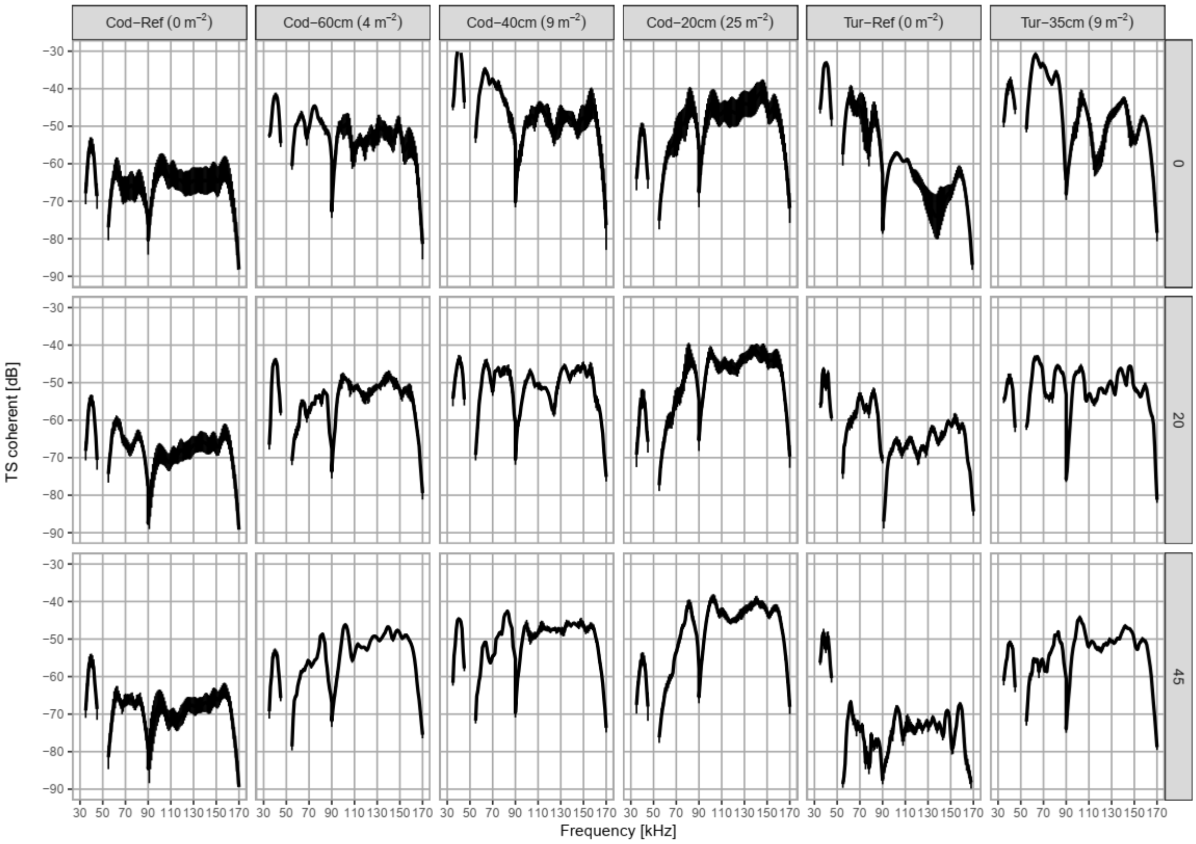

FIGURE A. 3: Mean coherent TS vs frequency for each combination of net type and inclination, including SD; number of sphere/m² provided in brackets

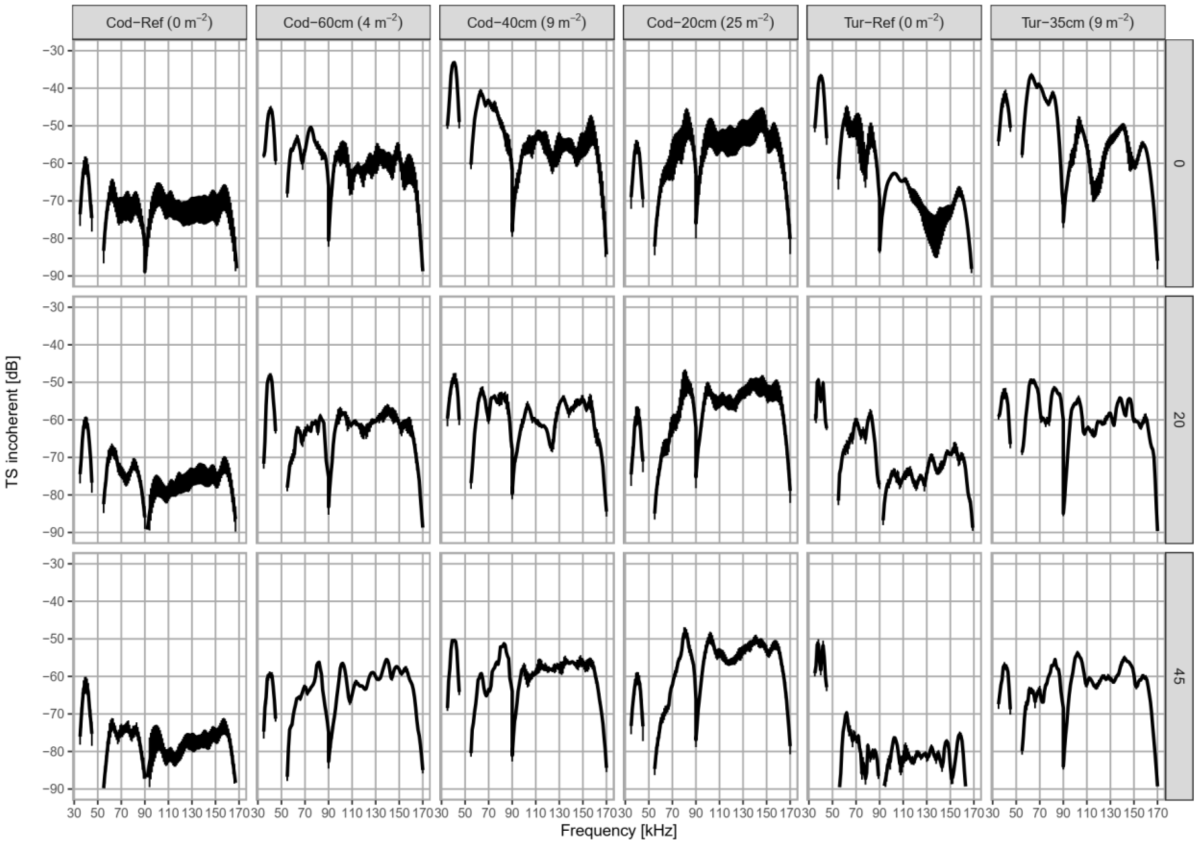

FIGURE A. 4: Mean incoherent TS vs frequency for each combination of net type and inclination, including SD; number of sphere/m² provided in brackets

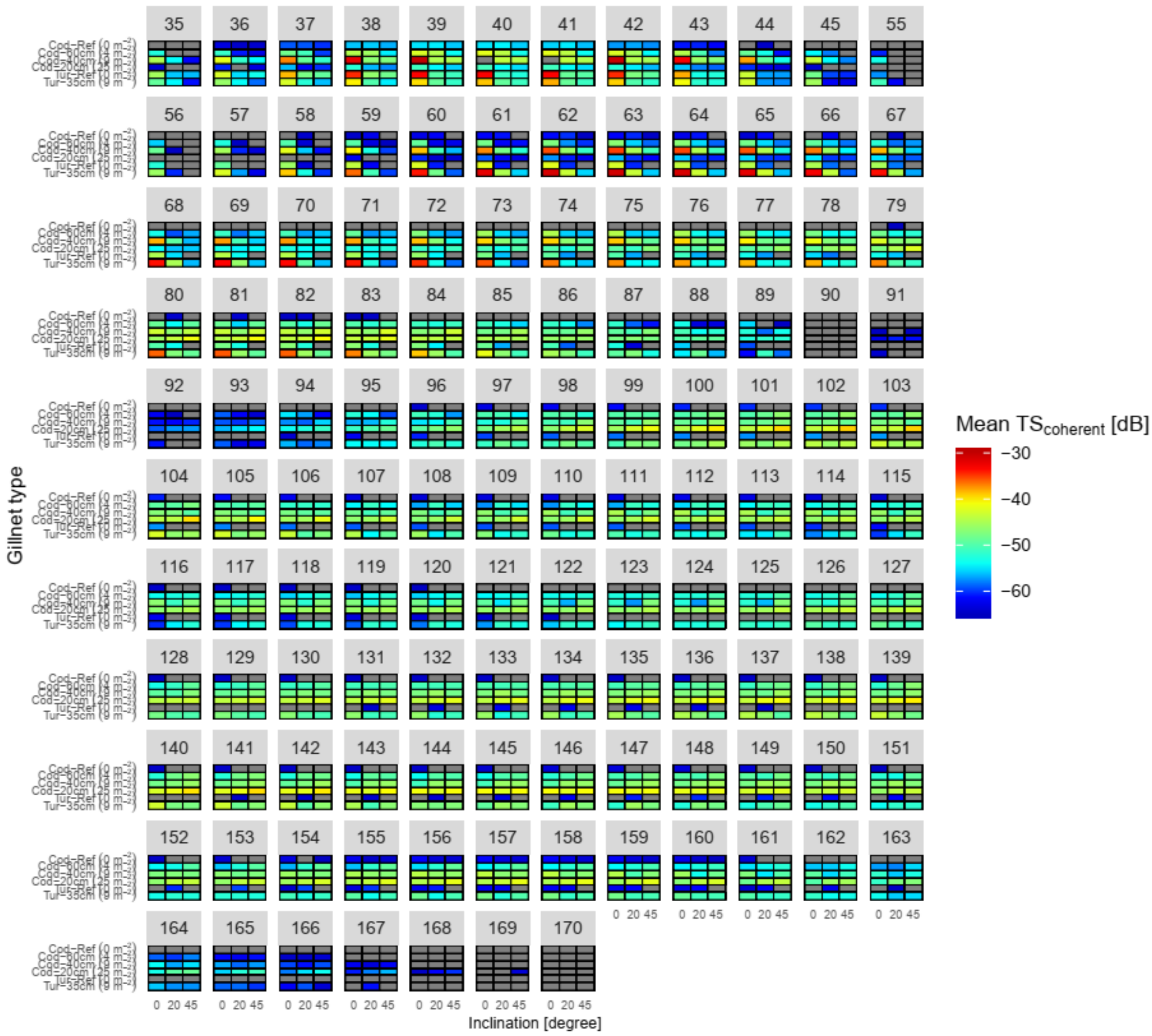

FIGURE A. 5: Mean coherent TS for all frequencies according to net and inclination; number of sphere/m² provided in brackets

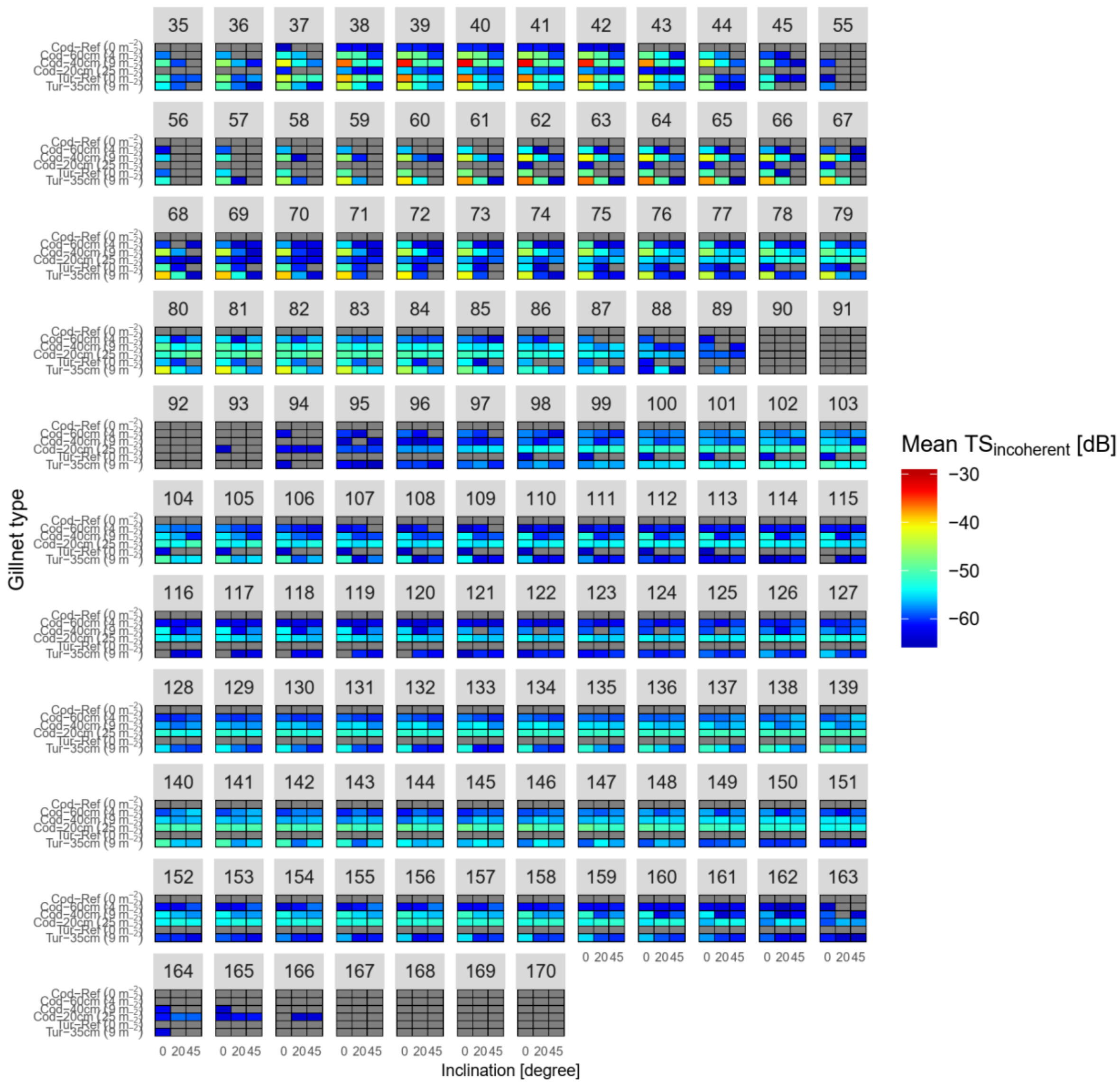

FIGURE A. 6: Mean incoherent TS for all frequencies according to net and inclination; number of sphere/m² provided in brackets

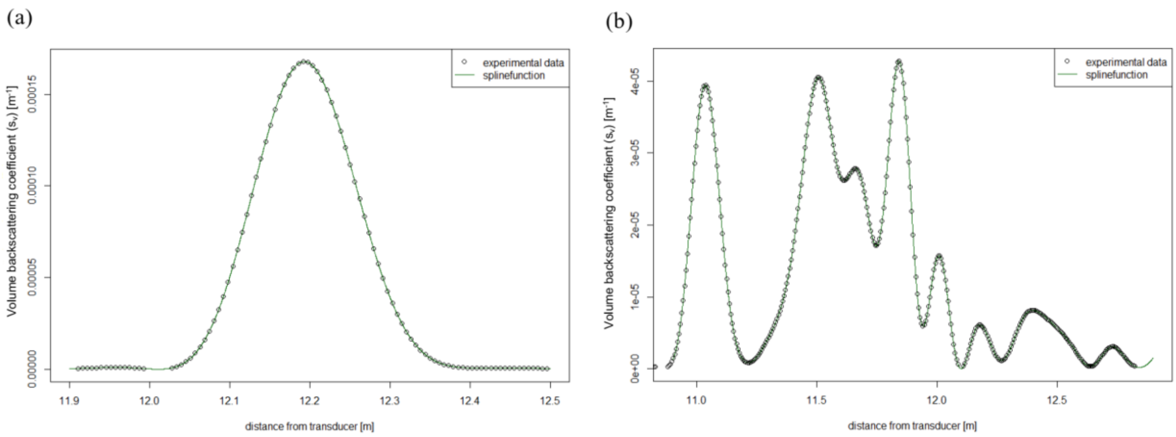

FIGURE A. 7: Measured volume backscattering coefficient s_v across distance from echosounder for one ping exemplarily and corresponding spline function. Data is shown for Cod-20cm net at 0° (a) and 45° (b)

Paper III

Using acoustically visible gillnets to reduce bycatch of a small cetacean: first pilot trials in a commercial fishery

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Under Review at Endangered Species Research

ABSTRACT

Bycatch of protected species, particularly small cetaceans, in gillnets is a worldwide concern. One hypothesis for this is that echolocating cetaceans entangle because they do not perceive conventional gillnets as impenetrable barriers, owing to the gillnet's faint echo. A gillnet modified for improved acoustical visibility was tested in a first pilot trial in a commercial gillnet fishery targeting turbot (*Scophthalmus maeoticus*) on the Turkish Black Sea coast. This study is the first demonstration of the viability of using a gillnet equipped with small acrylic glass spheres to reduce bycatch of harbor porpoises in a commercial fishery and provides the basis for full-scale sea trials of the gear in commercial fisheries. In 10 trips bycatch rates of protected species as well as the catch efficiency on target species were compared between a standard gillnet and a modified gillnet. The total number of endangered cetaceans (*Phocoena phocoena*) taken as bycatch and a vulnerable species (*Raja clavata*) was smaller (2 vs. 5) and larger (114 vs. 81) in the modified gillnet, respectively; however, the differences were not statistically significant. In this pilot study we estimated through a power analysis that a full scale experiment of approximately 130 sets is required for a robust assessment of the sphere effect on harbor porpoise bycatch with the given bycatch rates. More work is required to reach a robust assessment of the underlying circumstances and behavior of *Phocoena phocoena* and *Raja clavata* when bycatch events occur in this fishery.

Keywords: bycatch | gillnet modification | *Phocoena phocoena* | turbot fishery | *Raja clavata*

1. INTRODUCTION

Harbor porpoises (*Phocoena phocoena* L., 1758), small, toothed whales, inhabit temperate and Subarctic coastal waters of the Northern hemisphere (Bjørge & Tolley 2009), including the Black Sea (Notarbartolo di Sciara & Birkun 2010; subspecies *P. phocoena relicta* Abel, 1905) and Mediterranean Sea (Cucknell et al. 2016). Although some populations are stable in size (Hammond et al. 2013), others, such as the Black Sea population, are classified as endangered (Birkun & Frantzis 2008), with the current population at only 10% of its original size (Fontaine et al. 2012). Bycatch mortality in gillnet fisheries (Reeves et al. 2013) is a global threat to cetaceans, including harbor porpoises .

The use of acoustic deterrent devices, i.e., pingers, is one way to reduce bycatch in gillnets. In previous trials, pingers have been used successfully to reduce bycatch of *P. phocoena* (Kraus et al. 1997, Gönener & Bilgin 2009, Dawson et al. 2013, Larsen et al. 2013). Pingers emit loud noise to scare porpoises away from a hazard, but they have several drawbacks, e.g., potential habituation (Cox et al. 2001), potential exclusion from habitats (Carlström et al. 2009), potentially higher bycatch rates than for sets without pingers if a subset of pingers fails (Palka et al. 2008), and a potential "dinner-bell" effect on other species (Bordino et al. 2002).

It has been hypothesized that porpoises are unable to perceive the nets as obstacles and therefore get entangled (Goodson 1997). Although some studies have predicted that harbor porpoises (*P. phocoena*) should be able to detect gillnet netting from a short distance (Kastelein et al. 2000, Mooney et al. 2004), a recent study suggests that porpoises also react to a gillnet from a long distance (Nielsen et al. 2012). Nielsen et al. (2012) used common commercial gillnets, and porpoises may have detected highly visible parts of the gillnet, such as the floatline, which is highly acoustically visible. Previous research has demonstrated that some species of toothed whales (odontocetes) exhibit avoidance behavior to objects that have an echo similar to a floatline. These behaviors include swimming around the object (Perrin & Hunter 1972, Norris & Dohl 1980, Silber et al. 1994, Goodson & Mayo 1995) and diving underneath it (Silber et al. 1994, Kastelein et al. 1995b). This points to the possibility of "filling in" the gap between floatline and leadline, rendering the entire netting area highly visible. Either the porpoise could be "guided" along the net until the end in order to swim around, or it would more easily perceive the net as an obstacle between the floatline and the seabed. In either case, improved acoustic detectability of the netting area could be key to avoiding collision and effectively reduce bycatch mortality without significantly decreasing the gillnet's catch efficiency.

In the past, the gillnet's echo has been increased by adding high-density fillers to the filament of standard gillnets, thus increasing the twine's density. Related field experiments with netting that was supposedly acoustically enhanced have reduced catches of target species (Larsen et al. 2007) or have had no effect on bycatch rates of certain cetacean species (Bordino et al. 2013). Only one study demonstrated both reduced *P. phocoena* bycatch and stable catches of target species (Trippel et al. 2003). Because subsequent comparisons of the echo strength of standard gillnets and modified gillnets revealed no substantial increase in acoustic detectability, it was hypothesized that increased stiffness was partially responsible for a reduction in the catch of target species and bycatch of *P. phocoena* (Larsen et al. 2007, Trippel et al. 2009). A simulation study revealed that increasing the density of filaments cannot lead to a substantial increase in target strength (Kratzer et al. 2020); thus, using fillers will most likely not result in increased acoustic detectability.

An alternative approach to the use of high-density fillers is the use of passive reflectors attached to the gillnet to increase the netting's acoustic detectability. The goal is to alter the acoustic image recognized by the porpoise so that the netting is perceived as an impenetrable object. To develop an acoustically visible, yet catch-efficient gillnet, Kratzer et al. (2020), through simulations and subsequent experimental assessment, systematically identified small, almost neutrally buoyant objects that have a strong echo. The ideal reflector shape is spherical, because it has the same echo properties regardless of the animal's angle of approach. The optimal reflector for harbor porpoises is an 8 mm wide acrylic glass sphere. This reflector, owing to its mechanical properties and size, resonates at 130 kHz, the echolocation frequency of harbor porpoises. Thus, the detectability of gillnets when acrylic glass spheres are attached to the nets is substantially increased regarding both an increase in target strength as well as an alteration of the acoustic image of the gillnet (Kratzer et al. 2020). Specifically, the target strength of a single 8 mm acrylic glass sphere is -43 dB (Kratzer et al. 2020), while filaments typically used in gillnet fisheries, e.g. nylon or cotton as a proxy for natural fibers, have a target strength of less than -50 dB

(Au & Jones 1991, Mooney et al. 2004, Kratzer et al. 2020). This means that the intercepted acoustic energy is fivefold when comparing a standard gillnet to a single acrylic sphere. Acrylic glass is a widely available transparent thermoplastic. As the objects are neutrally buoyant, there should be minimal effects on the hydrodynamic behavior of the gillnet and thus minimal effect on the catch of target species or other bottom-dwelling wanted and unwanted bycatch species.

In this pilot project, the efficacy of the passive reflector in reducing the bycatch of harbor porpoises (*P. phocoena*) was quantitatively assessed and the viability of using such a modified net in a commercial fishery was explored. We conducted the first systematic catch comparison trials using gillnets modified with acrylic glass spheres in a commercial fishery targeting turbot (*Scophthalmus maeoticus* Pallas, 1814) on the Turkish coast of the Black Sea. This area was selected because previous trials have revealed seasonally high bycatch rates of *P. phocoena* in commercial fisheries (Gönener & Bilgin 2009). This study forms the baseline for future investigations of the use of the newly developed gear by providing first insight into the efficacy of the modification to reduce bycatch, the necessary experimental protocol, an assessment of the needed extent of a full-scale trial as well as effects on the practical handling of the gear.

2. MATERIALS & METHODS

2.1 Study area and sampling protocol

The study was conducted in the central Black Sea around the Sinop peninsula, Turkey (Fig 1), using a local gillnet vessel (overall length 14 m). Ten paired hauls were carried out between September and December 2019. During each of the ten trips one set of standard gillnets and one set of gillnets modified by attaching 8 mm acrylic glass spheres to the netting (see details below) was used. All hauls were accompanied by two or more local scientists and the vessel crew. The protocol comprised start and end time of setting and hauling the gillnet, start and end coordinate of the nets, number of all animals caught, length and sex determination of elasmobranchs and harbor porpoises (*Phocoena phocoena relicta*), and disc width of thornback rays (*Raja clavata*, L. 1758). Additionally, an electronic monitoring system, consisting of one camera powered by a solar panel, was provided by *shellcatch, inc.* (Shellcatch

VirtualObserver platform 2020) mounted to overlook the net hauler and the area on deck where the catch is disentangled from the net. The system was programmed to take an image every second when the vessel was at sea together with time (hh:mm:ss) and GPS position. The videos were analyzed using the *shellcatch* online tool (Shellcatch VirtualObserver platform 2020) to evaluate the handling time of the two gillnet types and verify the reported catch data. All hauls were conducted in pairs, i.e., the nets were set and hauled one right after the other at a distance of approximately 500 m to avoid any influence of the modified gear on the standard gear.

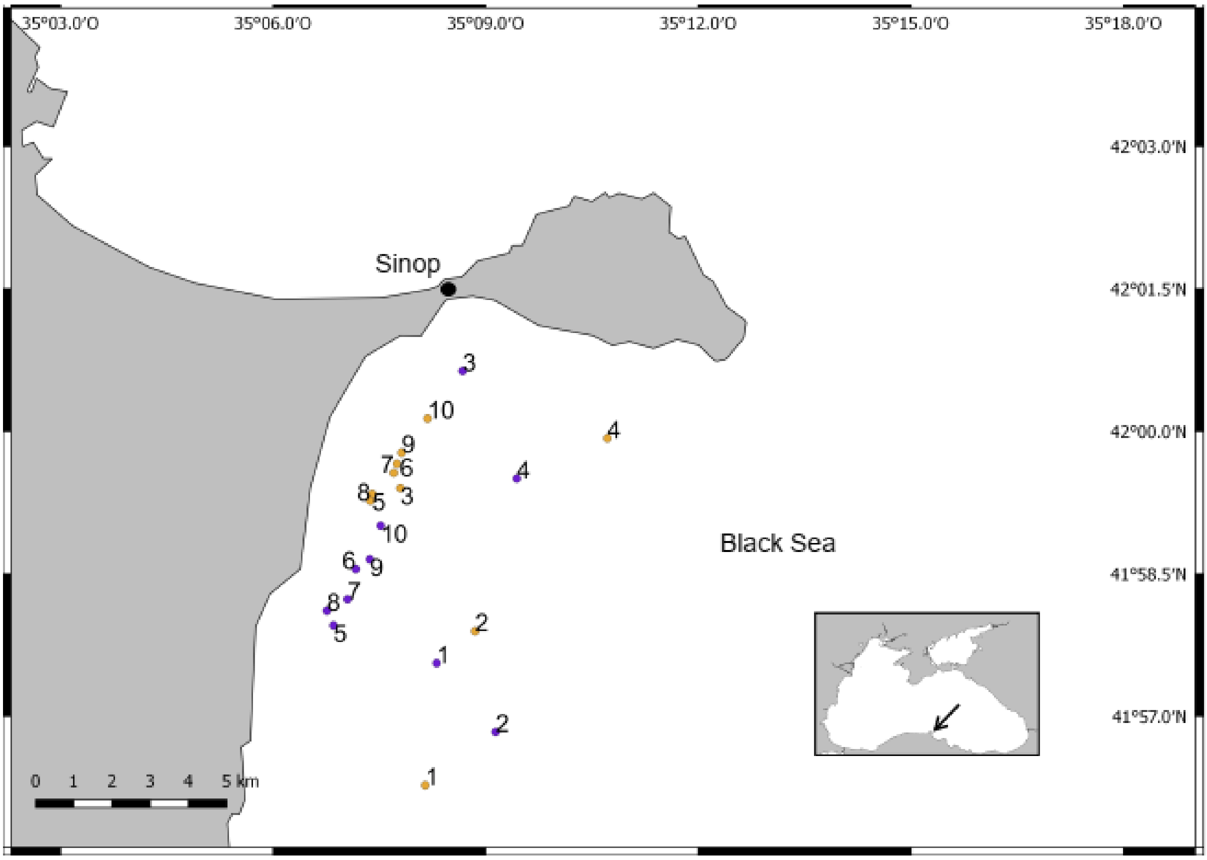


Fig 1. Study area in the Southern Black Sea (indicated by arrow). Colored dots: center points of gillnets (purple = standard gillnet, orange = modified gillnet) set during 10 fishing trips in the sampling area.

2.2 Description of fishing gear

Each gillnet consisted of five individual net panels strung together and resulting in a total rigged length for each gillnet of 2160 m, a stretched mesh size of 400 mm, and a height of approximately 2.5 m (5.5 meshes). The net material was a multifilament (PA) natural orange-colored fiber with R227tex, as required by Turkish fishing regulations. The gillnet was raised by floats in the headline with a positive buoyancy of 70 N and the sinks, attached to the leadline, had a negative buoyancy of

70 N. Floats and sinks were both mounted on a 6 mm PP rope. Fig 2 shows a schematic drawing of the nets. The standard and modified gillnets were constructed identically. To the modified gillnet, 8 mm acrylic glass spheres were attached at a sphere-to-sphere interval of 350 mm horizontally and 370 mm vertically. In a previous trial, Nakamura et al. (1998) determined that their minimum spacing of 0.7 m by 0.5 m between objects would decrease the chance of a porpoise attempting to swim through the objects compared with larger intervals, but not entirely eliminate it. Therefore, we chose to reduce the interval further. As this is the first trial with a gillnet modified using acrylic glass spheres, the spheres were mounted by hand. To attach the spheres, they were cut half way through with a laser and subsequently glued to the netting using acrylic glass adhesive (*ACRIFIX 1R 0192*).

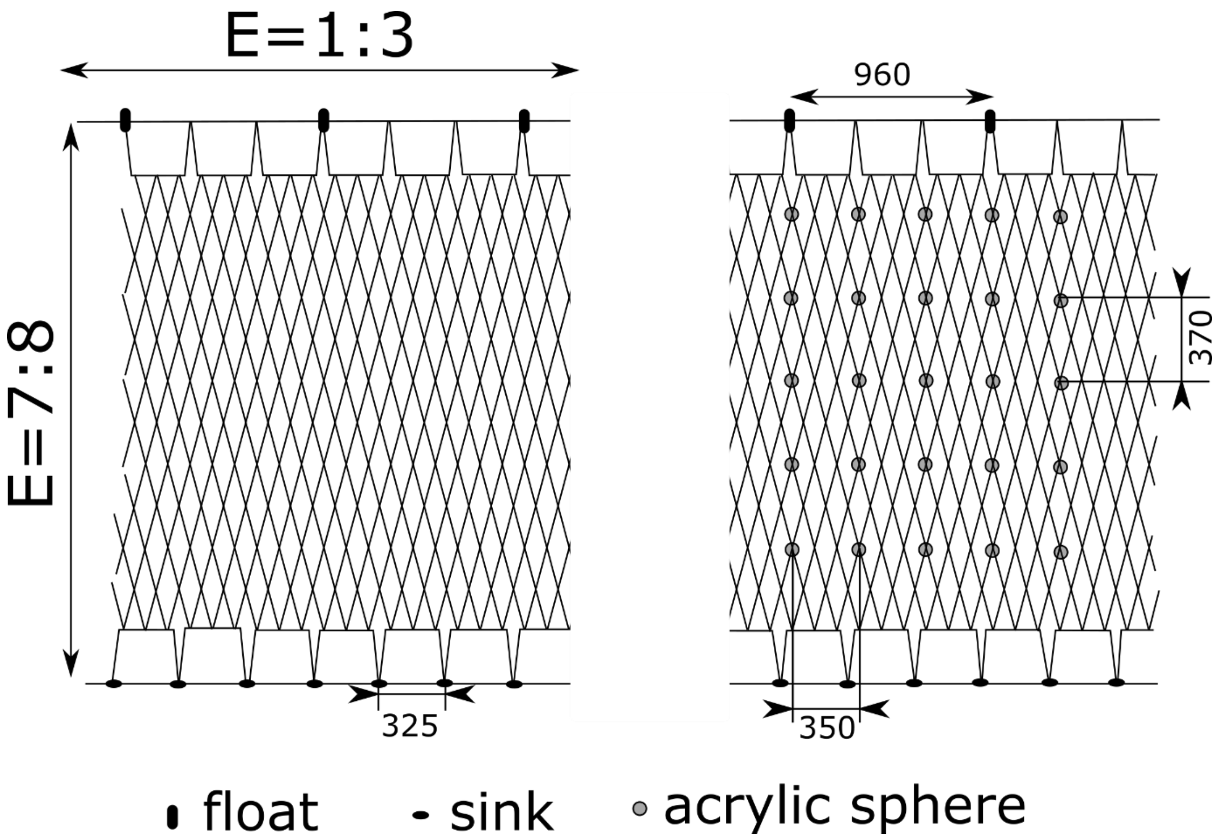


Fig 2. Schematic drawing of a standard gillnet (left) and a modified gillnet (right). Both gillnets have the same characteristics; the only difference is the addition of acrylic spheres to the modified net. All measures are in mm; E is the hanging ratio of the netting; the drawing is not to scale.

2.3 Statistical analysis

Because all species were caught in very small numbers, only the endangered species harbor porpoises (*P. phocoena relicta*) and vulnerable thornback rays (*R.*

clavata) were considered for in-depth analysis. The bycatch models are described below.

2.3.1 Bycatch models

We used generalized linear mixed models (GLMMs) to describe the relationship between bycatch rate and gear separately for each species. Number of animals (*N*) per trip was estimated as the response in a GLMM with a fixed effect of gear and a normally distributed random intercept for each trip, as each trip corresponds to one haul with one standard and one modified gillnet. For porpoises, a Poisson distribution was used for hypothesis testing, and *R. clavata* were modeled using a negative binomial distribution; both had log links. No additional terms were included to control for spatial effects or soaktime, because the animal counts did not appear to depend on these factors, based on visual inspection of the graphs. Furthermore, as the data set was so small it is unadvisable to include more terms in the model if they are not expected to explain a pattern. As a rule of thumb, ten informative observations are needed for each parameter to be estimated (Harrell , 2015). GLMMs were fit using the glmmTMB package (Brooks et al. 2017) in the statistical software R Version 3.6.1 (R Core Team 2019). Tests to check for zero-inflation and to determine whether the choice of distribution was adequate were carried out using the DHARMa package (Hartig 2020) by comparing the observed variance and zeros with simulated variance and zeros. The observed values were well within the range of the simulated data. Significance of the gear effect was tested by likelihood ratio tests (LRTs) to compare the full GLMMs with corresponding GLMMs without a gear effect.

2.3.2 Size of effect and power analysis for future trials

The effect size of acrylic glass spheres on bycatch reduction of harbor porpoises was determined from both the raw data and the bycatch models. From the raw data (number *N* of animals caught) the change in bycatch was determined using Equation 1.

$$Bycatch\ change\ [\%] = \frac{N_{modified} - N_{standard}}{N_{standard}} * 100 \qquad \text{Equation 1}$$

We determined the effect size of the gear modification from the bycatch model using the emmeans package (Lenth 2019) to calculate estimated marginal means

(EMMs) from the negative binomial GLMM with the random effect of trip and fixed effect of gear.

Regarding potential future experiments, we conducted a power analysis to determine how many trips with one set of each net type would be necessary to detect a significant difference in the bycatch of porpoises in the two gear types, assuming the same bycatch rate as in these trials. We modeled the potential outcomes if more trips were conducted using a GLMM with the fixed effect of gear and the random effect of trip. We used a negative binomial distribution to account for potential overdispersion, although overdispersion was not indicated by DHARMa residual tests. Johnson et al. (2015) recommends accounting for overdispersion, which will lead to more pessimistic predictions for the necessary number of trips. We used the negative binomial GLMM and the simulate() function in glmmTMB to simulate new datasets, each with the same dimension as the original, with random trip effects simulated from their estimated normal distribution. To create a dataset with 240 trips, we combined 24 simulated datasets, each containing 10 trips, with appropriately relabeled trip identifiers. To create smaller datasets with 10 to 240 trips, we randomly selected (without replacement) a subset of the trips. For each dataset, we fit GLMMs with gear as fixed effect, trip as random effect, and a negative binomial distribution with a log link; then performed an LRT with a GLMM without the gear effect. We repeated this process 3000 times and recorded the proportion of times that an LRT was significant. Any model that failed to converge was considered a non-significant test result.

2.3.3 Handling time and effect on size of entangled thornback rays

The viability of using the acoustically visible nets in a commercial setting was the focus of the study, thus it is essential to investigate handling of the gear. The handling time between the two net types were compared as we determined the time required to disentangle individual *R. clavata* as a proxy. Because handling times were non-normally distributed, the Mann–Whitney U Test was used to compare handling times between net types.

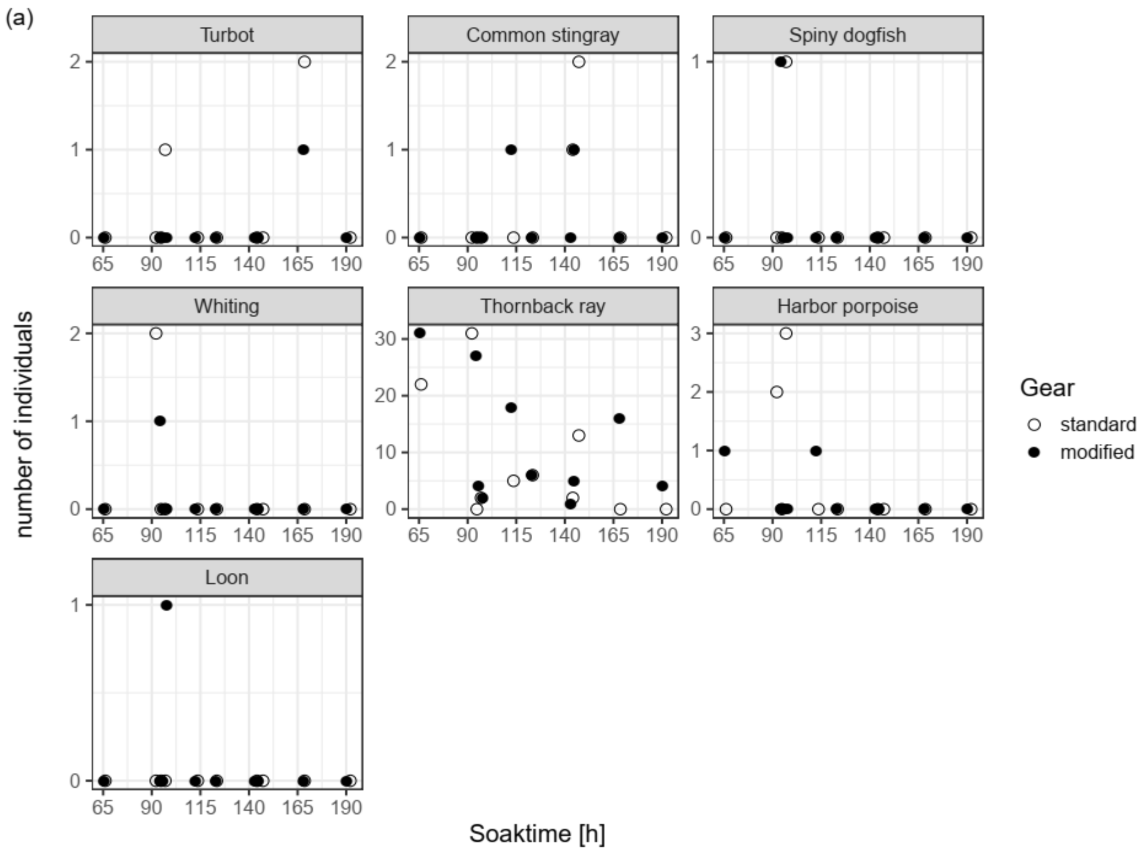
To determine potential influence of the acrylic glass spheres on *R. clavata* bycatch composition, and size, a linear model was used to describe the relationship between total length (TL) and disc width (DW) of *R. clavata* for all individuals as well as for males and females separately (Demirhan et al. 2005, Krstulović Šifner et al.

2009). *R. clavata* also serves as a model species to determine potential influences of the acrylic glass spheres on the hydrodynamic behavior of the net and the mechanical catch process that leads to the degree of entanglement of bottom-dwelling species such as *R. clavata* or target species *S. maeoticus*.

3. RESULTS

3.1 Catch composition

The most abundant fish species in the catch was *Raja clavata* (89 %, 195 individuals); only four specimens of the target species *Scophthalmus maeoticus* were caught. The fish species common stringray (*Dasyatis pastinaca*, L. 1758), spiny dogfish (*Squalus acanthias*, L. 1758), and whiting (*Merlangius merlangus*, L. 1758) occurred only in small numbers. In all, seven harbor porpoises (*Phocoena phocoena relicta*) and one loon (family Gaviidae) were taken as bycatch. The number of animals was independent of the soaktime (Fig 3a), depth (Fig 3b) and location (Fig 3c) regardless of species. Table A 1 in the appendix provides details on soaktime and number of individuals per gear and trip



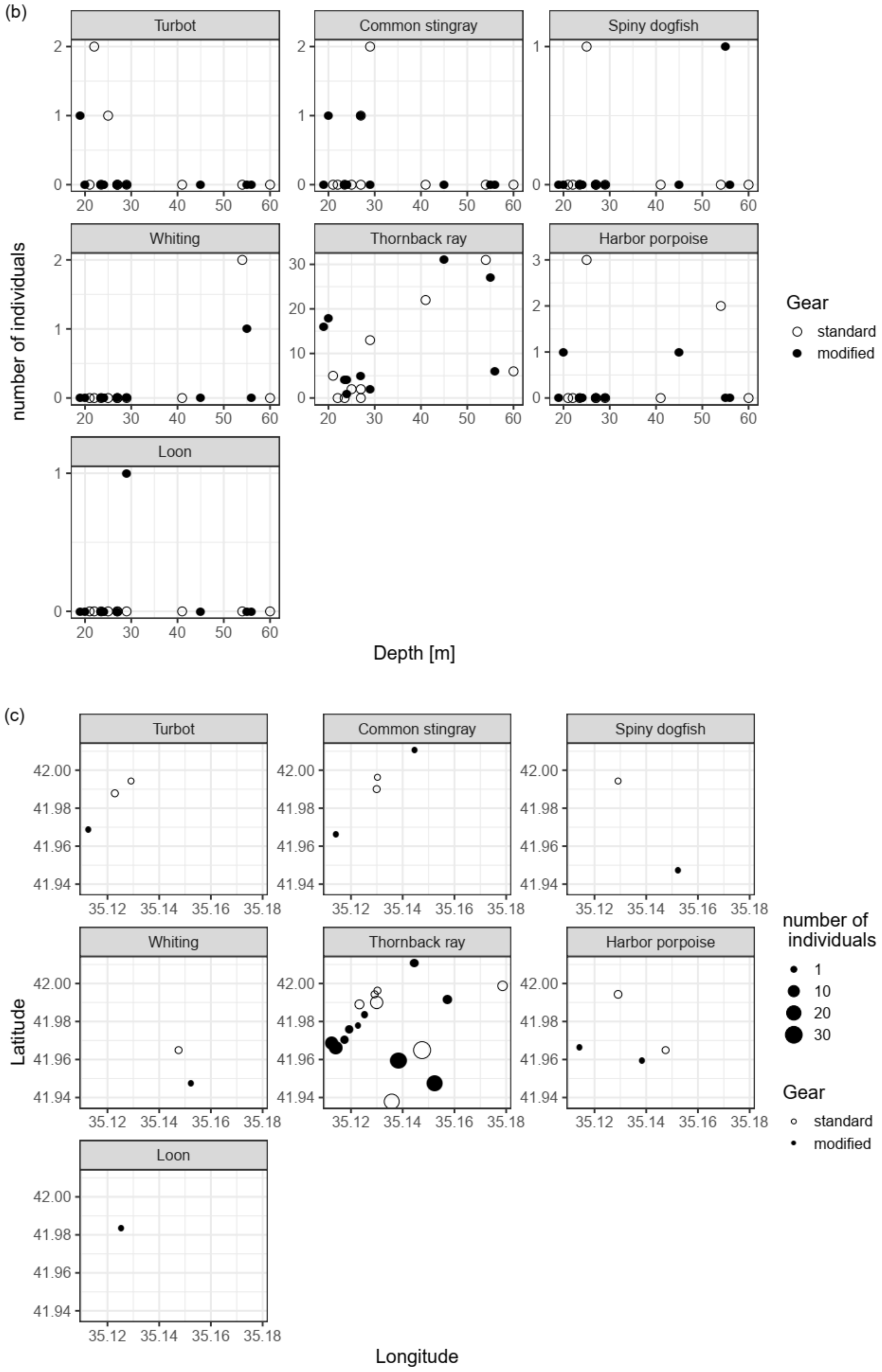


Fig 3. (a) Soaktime, (b) depth vs. number of animals caught per species. (c) Geospatial position per species, size of dot indicates number caught

3.2 Harbor porpoise bycatch

Five harbor porpoises (*P. phocoena relicta*) were taken as bycatch in the standard gillnet and two in the modified gillnet (Fig 4). Five porpoises were male, one was female, and the sex of one was unknown because it dropped out of the net before being hauled on board. The overall observed mean catch per haul of porpoises per gear was 0.5 (standard gear) vs. 0.2 (modified gear). The porpoises were caught in different parts of the gillnet without a clearly discernible pattern.

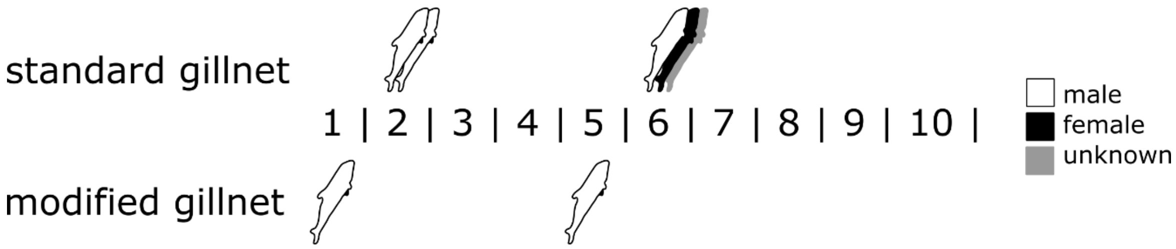


Fig 4. Number of *P. phocoena relicta* taken as bycatch per gillnet type and haul (numbers 1–10) by sex. Each porpoise represents one individual.

The Poisson GLMM revealed no significant difference in *P. phocoena* bycatch between the gears (p-value = 0.25). As this study is conducted as a pilot trial and serves as an initial estimation of expected bycatch rates, the sample size is small, which makes the detection of statistical significance difficult. Based on the raw data, the bycatch is reduced by 60% when using the net modified with acrylic glass spheres. The estimated marginal mean of the bycatch is 0.5 for the standard gear and 0.2 for the modified gear with wide confidence intervals (Fig 5). These values need to be refined by a large-scale field trial.

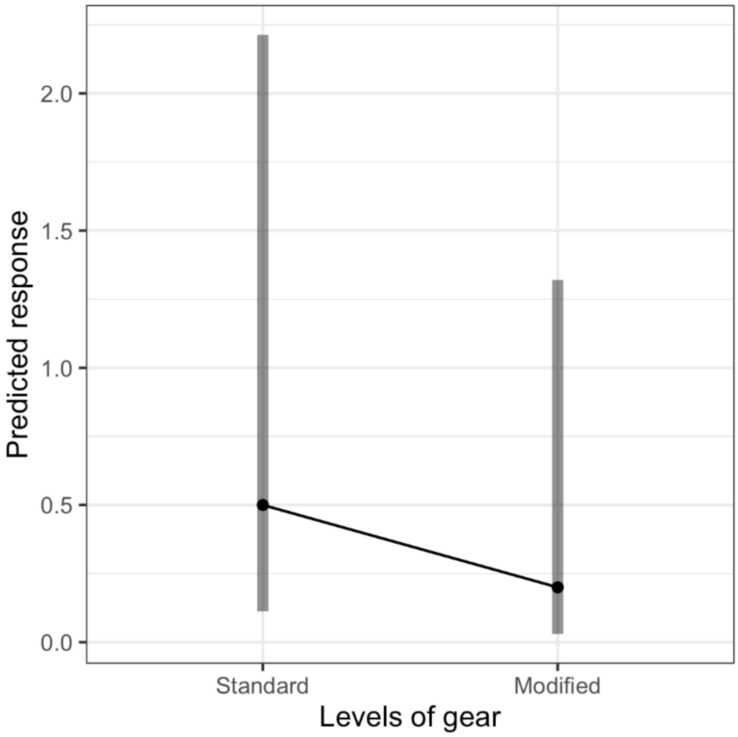


Fig 5. Estimated marginal means and CI of harbor porpoise bycatch by gear

3.3 Thornback ray bycatch and handling time

In all, 81 thornback rays (*R. clavata*) were taken as bycatch in the standard gillnet and 114 thornback rays in the modified gillnet. One juvenile, 80 males, and 114 females were taken (Fig 6 and Fig 7 and Table 1). The GLMM detected no significant difference of *R. clavata* bycatch between the gears (p-value = 0.19). The time used to disentangle animals was determined for 93 *R. clavata*. The handling time required to disentangle individual *R. clavata* from the netting was 28% longer for the modified gillnet (mean 21 s) compared with the standard gillnet (mean 15 s); Mann–Whitney U test: p-value = 0.033.

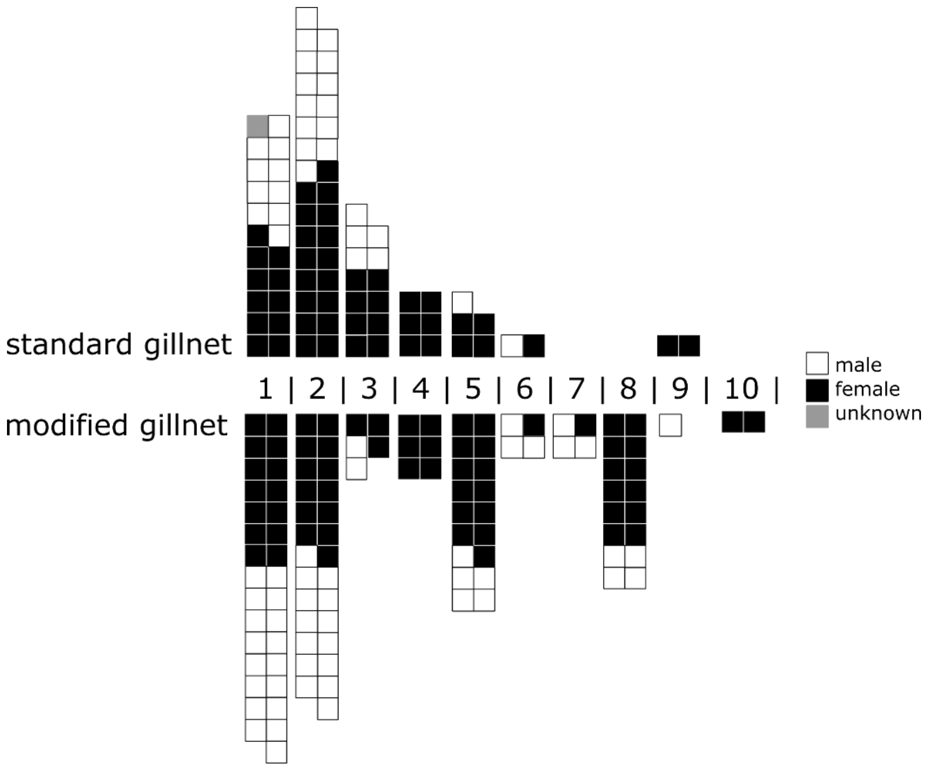


Fig 6. Number of *R. clavata* taken as bycatch per gillnet type and haul (numbers 1–10) by sex. Each box represents one individual.

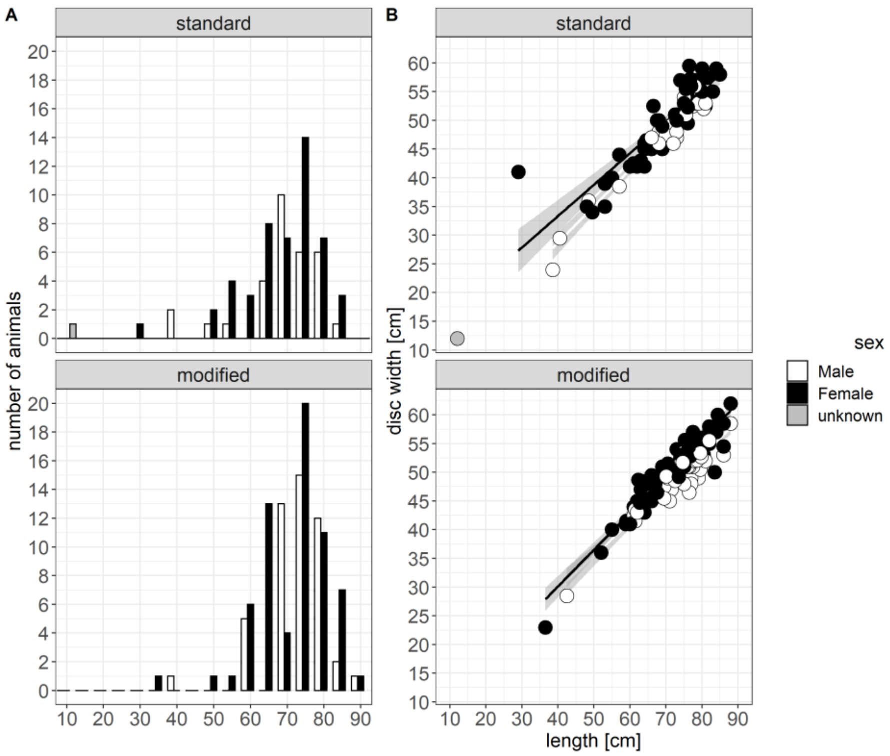


Fig 7. Length distribution of *R. clavata* by sex and gear type (left, column A). Disc width–length relationship by sex and gear type (right, column B)

Table 1. Coefficients of length–disc–relationship of *R. clavata* according to gear type and sex.

	standard	**modified**
Male	DW = 0.637 · TL + 3.2	DW = 0.585 · TL + 6.21
	R^2 = 0.94	R^2 = 0.85
Female	DW = 0.548 · TL + 11.42	DW = 0.639 · TL + 4.57
	R^2 = 0.76	R^2 = 0.899
Total	DW = 0.59 · TL + 7.27	DW = 0.611 · TL + 5.58
	R^2 = 0.86	R^2 = 0.847

3.4 Power analysis

The power analysis revealed that approximately 130 trips (each trip testing one set of each gear type) would be necessary to have 80 % power to detect a statistically significant difference in porpoise bycatch with the modified gear (Fig A 1). This was mainly the result of the large number of zero catches. The code used is available in the supplementary material.

4. DISCUSSION

These were the first pilot trials in a commercial fishery worldwide using acrylic glass spheres as passive reflectors with the aim of reducing bycatch of harbor porpoises (*Phocoena phocoena relicta*) while maintaining the target catch. The trials were carried out in the commercial turbot (*Scophthalmus maeoticus*) fishery on the Turkish coast of the Black Sea in 2019. The 10 hauls yielded relatively few animals, and no significant difference in either catch or bycatch was revealed using generalized linear mixed modeling. This study is a pilot project providing a proof of concept of using a gillnet modified with acrylic glass spheres and forming the basis for future trials on a larger scale.

4.1 Target species

Small catches of turbot (*Scophthalmus maeoticus*) are common in the period September–December (WGBS 2017, Bilgin et al. 2018), because most migration to shallow areas where gillnet fishing takes place occurs in spring when fishing for *S. maeoticus* is prohibited to allow for reproduction. The Black Sea *S. maeoticus* stock is generally small (WGBS 2017), but exacting conservation measures (e.g., re-stocking and other measures to reduce fishing mortality, such as the closed season (Ak et al. 2016, FAO 2018)), indicate that the stock is improving. Furthermore, in 2019, regulation EU 2019/1241 specified the minimum mesh size for turbot nets to 400 mm (EU 2019). Since 2016, Turkey has required the same mesh size, possibly resulting in catches that are even smaller than in previous years. The decrease in fishing pressure on *S. maeoticus* by the new 400 mm mesh size was confirmed by the observation that, during the time of the study, the catches of turbot fishers still using the previously legal mesh size of 320 mm were slightly larger than the catches in our trials (pers. comm. with local fishers).

4.2 Harbor porpoise bycatch

The modified gillnets with greater acoustical visibility used in these trials did reduce the total number of harbor porpoises (*Phocoena phocoena*) taken as bycatch, however without statistical significance. The nature of this study is a feasibility trial, thus only 10 trips were carried out, whereas the power analysis suggested that 130 trips each testing one set of standard against one set of modified gillnets would have been required to reliably identify statistical differences (80 % power). Therefore, a full-scale sea trial is needed to confirm the potential bycatch reduction. Assuming that the porpoise bycatch rate is constant over the year, this could be achieved by, e.g., simultaneous fishing trials with several fishing vessels over one year. Carrying out a trial during the “closed season” for *S. maeoticus* (15 April–15 June; TCFR 2016) could, however, decrease the number of required trips, because bycatch rates of porpoise have been higher (0.47 ind day^{-1}*km; Gönener & Bilgin 2009) during this season, and local fishers report that late spring is still the highest bycatch season (pers. communication with fishers). Seasonal studies of *P. phocoena* bycatch in the Black Sea gillnet fishery are scarce (Radu & Anton 2014, Vishnyakova & Gol’din 2015, Bilgin et al. 2018), and sampling effort is not evenly distributed throughout the year. Thus, the low bycatch rate could also be attributed to intra- or interannual variability.

The distribution of *P. phocoena* in the Black Sea has not yet been documented comprehensively, and seasonal movement patterns are studied only locally (Birkun et al. 2014). The porpoises may follow spawning turbot during the closed turbot gillnet season (April–June) or the movements of anchovy (*Engraulis encrasicolus* subspecies *ponticus* Alexandrov, 1927, and *Engraulis encrasicholus maeoticus* Pusanov & Zeeb, 1926) in the Black Sea (Notarbartolo di Sciara & Birkun 2010), with the main fishing season for anchovy between January and April (pers. communication with local fishers). An international survey of cetaceans in the Black Sea was launched recently (ACCOBAMS 2019a) to obtain reliable information on abundance and spatial distribution to better appraise the population's level vulnerability. Moreover, ACCOBAMS continues to emphasize the need for better estimates of bycatch levels and the need for bycatch-reduction measures (ACCOBAMS 2019b).

Although *P. phocoena* are thought to detect at least some parts of the gillnet from a distance (Nielsen et al. 2012), it remains unclear why they still get entangled in the standard and modified gillnets. One hypothesis suggests that, although they can recognize some parts, they do not classify the netting as an obstacle (Goodson 1997), because the echo of gillnet netting is very faint (Pence 1986, Kastelein et al. 2000, Mooney et al. 2004, Kratzer et al. 2020). Increasing the acoustic visibility of gillnets addresses this issue, but a key requirement for the increased detectability to be efficient at reducing bycatch is that the porpoise actively echolocates in the direction of the netting. The echolocation beam of *P. phocoena* is relatively narrow (Koblitz et al. 2012), hence it is crucial that they are echolocating toward the net to detect it. This might not be the case when they exhibit so-called bottom-grubbing (Lockyer et al. 2001), a feeding behavior where the porpoise is facing straight toward the bottom. Furthermore, porpoises have difficulties detecting signals in high background noise (Kastelein & Wensveen 2008, Kastelein et al. 2011) or may be distracted by prey in the water column (Kastelein et al. 1995a). While it is possible that the porpoises are distracted by moving prey, it is unlikely that they mistake the gillnet for food, as fish shoals have a distinctive start and end while the gillnet is an extended structure (Kratzer et al. 2020).

Despite their high demand for food and thus almost continuous echolocation (Wisniewska et al. 2016, Sørensen et al. 2018), porpoises have also been observed to be silent or vocalizing at lower sound levels, potentially in periods associated with sleep (Wright et al. 2017). In these periods, they might not be aware of the gillnets or fail to recognize them. To further improve the potentially positive effect of the acoustically visible nets tested on harbor-porpoise bycatch reduction, it might be worthwhile to combine the improved visibility with an active device sending a "wake-up" call that increases their alertness toward an obstacle, such as the PAL (Porpoise Alert) tested in the western Baltic Sea (Chladek et al., unpubl. data).

4.3 Thornback ray bycatch

The bycatch of thornback rays (*Raja clavata*) in the modified gillnet was greater than in the standard gillnet but not statistically different. Similar bycatch numbers of *R. clavata* have been reported in previous trials in the gillnet fishery (Gönener & Bilgin 2009, Bilgin et al. 2018, Bilgin & Köse 2018). No significant change in thornback ray bycatch was expected as these animals do not echolocate and thus the modified net should not be more conspicuous to them. The almost neutral buoyancy of the spheres could have slightly changed the hydrodynamic behavior and thus opening mesh size of the net resulting in slightly larger individuals caught in the modified net. The DW–TL relationship described here differs slightly from previous observations, where smaller DW:TL ratios for females and larger or similar DW:TL ratios were reported for males (Demirhan et al. 2005, Krstulović Šifner et al. 2009). To quantify changes in hydrodynamic net behavior, both types of gillnets should be tested in a flume tank. Furthermore, the changes in selectivity properties due to a change the geometry of the mesh due to the additional obstacle and potential change of the mesh opening could be assessed using FISHSELECT (Herrmann et al. 2009).

Although no official stock assessment has been made, smaller catches indicate that the population of *R. clavata* is declining (Başusta & Başusta 2014), and they are considered "vulnerable" in Turkey (Fricke et al. 2007). The fate of *R. clavata* discarded from gillnets is largely unknown. Survival rates of up to 72 h post-capture have been estimated for *R. clavata* caught in bottom trawls with a 59% survival rate for 72 h post-capture (Enever et al. 2009) and 80% survival rate for 41 h post-capture (Saygu & Deval 2014). For gillnets, survival rates at capture have been estimated to be high (Ellis et al. 2012); however, long-term survival rates are not yet available. A survival study to quantify survival rates in gillnet fisheries and their potential effect on the population is advisable (ICES 2020).

4.4 Other species taken as bycatch

Other non-commercial species that were unintentionally caught include spiny dogfish (*Squalus acanthias*), common stingray (*Dasyatis pastinaca*), and a seabird from the family of loons (Gaviidae). *S. acanthias* are considered “vulnerable” in the Black Sea (Fordham et al. 2006), whereas *D. pastinaca* are “data deficient” (Serena et al. 2009). No official bycatch assessment exists, but local fishers have reported that small numbers of these species are regularly caught in gillnets.

4.5 Handling of gear

To determine how the addition of spheres would affect the process of clearing the catch from the gear, the time to disentangle catch was estimated for thornback rays *(R. clavata*), as it was the most commonly caught species and serves as a proxy for other species that entangle in the lower part of the gillnet, including the target species *S. maeoticus*. Disentangling thornback rays (*R. clavata*) from the modified gillnets took 28 % longer on average than with the standard net, corresponding to an absolute additional handling time of 6 s per individual ray, which might make the additional time required irrelevant in the overall procedure. The increase in time might be attributable to more “intensive” entanglement of the animals in the net or the netting itself, due to a change in the mechanical entanglement properties caused by the addition of spheres. This increase in handling time should decrease with times as fishers get more experienced with the gear. Similarly, as in other fisheries, newly introduced bycatch reduction methods need time to be adopted, constantly undergo improvement (Catchpole & Revill 2008) and are subject to a learning curve to use the new gear. The learning curve already became evident in this pilot trial when looking at the time needed to set the modified gear compared to the standard gear, which was reduced from an additional 45 minutes to an additional 11 minutes from the first haul to the last one. The addition of spheres did not pose a threat to the fishers, as other modifications of gillnets have done in the past (Peddemors et al. 1991) and they proved to be robust to stay on the gillnet without damage throughout the entire study period.The initial preparation of the nets was quite labor intensive because the spheres had to be glued individually to the gillnet. This is owed to the fact that it was the first trial with gillnets modified with acrylic spheres, hence there is no automation available yet to produce this type of gillnet modification. As the next step before carrying out a full-scale sea trial or introducing the gear on a broad scale, an automated process must be developed to produce this type of modified gillnet.

Following each trip, the modified gear was entangled in itself to a greater extent than the standard gear, which led to a labor-intensive preparation of the net for the following trip. The issue had not occurred in previous research trials with a prototype net (multi-mono nylon filament, stretched mesh opening 70 mm). However, the netting material and mesh size used in this study were different (multi natural fiber, stretched mesh size 400 mm). The distance between spheres was similar. The smaller mesh size of the prototype gillnet used in the previous study may have prevented spheres from “falling through” meshes to net layers underneath, and the netting material (nylon) may have facilitated “untanglement” from the netting itself. Neither the modified nor the standard gillnet tested in these trials was entangled when it was pulled from the water, but both became entangled after passing the net hauler. The typical net hauler used on Turkish gillnetters lifts the net between two narrow, vertically aligned pulleys pressing the net together. Therefore, an alternative solution to preventing the entanglement could be the use of net haulers often used, e.g., on Danish and German vessels that have broad, horizontally aligned rolls made of rubber. Furthermore, the PP-rope connecting the floats was made from twisted strands, which amplifies entanglement due to twisting of the netting around the floatline. Replacing the rope with braided line could further facilitate handling. Finally, standard gillnets from many small-scale Turkish gillnet vessels are cleaned manually, which can take up to five days, depending on the amount of seaweed and litter. This process could be facilitated and greatly shortened through the use of an automated net stacker, which is a standard tool on board many gillnetters elsewhere, e.g., in the Baltic Sea and North Sea. The prototype nylon net has been successfully cleared with a net stacker. Standard net stackers may require modification to be successfully introduced in the Turkish fishery where natural fibers are mostly used for gillnets.

4.6 Size of effect and scale of future trials

The bycatch reduction of harbor porpoises by -60% based on the raw data using the gillnet with acrylic glass spheres is promising and warrants a large-scale trial. The estimated marginal mean of bycatch calculated from the model using the standard gear was higher than the bycatch in the modified gear, albeit the confidence intervals are wide. While the reduction in full-scale scientific sea trials using pingers was higher (Kraus et al. 1997, Palka et al. 2008, Gönener & Bilgin 2009, Larsen & Eigaard 2014), it has been pointed out that the bycatch reduction rate drops in unaccompanied commercial trials (Palka et al. 2008). This may be due to malfunctioning pingers, lack of compliance or lack of battery life of the pingers. An additional advantage of using a passive reflector over pingers is that battery replacement plays no role and the reflectors cannot malfunction due to electronic issues. In trials using nets with fillers in the filament higher reductions in bycatch were recorded (Trippel et al. 2003, Larsen et al. 2007), likely due to the increased stiffness of the netting material (Trippel et al. 2009) which also led to a decrease in target catch (Larsen et al. 2007). The use of acrylic glass spheres will not influence the stiffness of the netting and since they are transparent, they are likely to be inconspicuous to fish and thus not influence the catchability in a large-scale trial.

To optimize effort in a full-scale trial, it is advisable to carry out a power analysis based on data gained in a pilot study. Previous studies have carried out fishing trials based on only rough estimates without conducting a power analysis (Larsen et al. 2013, Mangel et al. 2013, Larsen & Eigaard 2014, Bielli et al. 2020), resulting in large numbers of hauls (between 195 and 864), which could have potentially been optimized. While these large datasets are certainly valuable, statistically robust and sometimes even necessary – other trials optimized based on a power analysis using observer data (Gearin et al. 2000, Carlström et al. 2002, Barlow & Cameron 2003) have had similar effort needs due to low bycatch rates – a power analysis will facilitate experimental planning. Knowledge on needed effort prior to a large-scale experiment can help reducing observer costs, charter fees and compensation as well as reduce potential scientific fishing effort in addition to the present commercial effort.

For the present study there was no long-term observer data available, thus the pilot experiment was necessary to provide the basis for the future. Conducting a full-scale experiment in the Black Sea could greatly reduce the required effort compared to other fisheries with only 130 hauls needed. As the Black Sea turbot fishery is characterized by long soaktimes, the time required for a full-scale trial could be reduced by equipping several vessels with modified gillnets. If five vessels were equipped, a full-scale trial could be conducted within four months. The code provided in the supplementary material will furthermore facilitate experimental planning for other planned large-scale studies with known bycatch rates.

4.7 Conclusions

We provide first evidence that a gillnet modified with acrylic glass spheres can reduce the absolute number of harbor porpoises (*P. phocoena*) taken as bycatch relative to a standard gillnet under commercial fishing conditions. Consequently, the addition of acrylic glass spheres as passive reflectors could be a promising gillnet modification. However, the small number of *P. phocoena* taken as bycatch hampers drawing a final conclusion regarding the efficacy of the spheres to reduce bycatch. Although in absolute numbers the modified gear caught fewer animals, the difference was not statistically significant. It is necessary to carry out additional sea trials on a larger scale, to investigate further the potential reduction of bycatch using the modified gillnet tested here. Because the estimated number of hauls is 130 with the given bycatch rate, it would be advisable to carry out trials with several vessels simultaneously in future. To equip several vessels with modified gillnets, it is necessary to develop an automated process to build the modified nets. This should be done in cooperation with a netmaker or another polymer industry partner. Within the development of an automated process to build gillnets modified with spheres, alternative – possibly biodegradable – materials to acrylic glass could be taken into consideration as several materials fall within the same range of mechanical properties as acrylic glass (Kratzer et al. 2020). In the current case, acrylic glass was chosen due to the best possible fit, its availability, transparency to be inconspicuous to fish and possibility to be easily attached to the gillnet with the same material (acrylic glass) as a glue.

Additional trials could be carried out in other regions that are affected by *P. phocoena* bycatch, e.g., the North Sea or Baltic Sea. Because bycatch rates in these regions are possibly lower than in the Turkish Black Sea, the development of industrially produced, modified gillnets to equip the necessary number of vessels and thus be able to gather adequate data is even more essential.

Furthermore, the reason why *P. phocoena* become entangled in gillnets in the first place must be better understood, and potential behavioral changes when porpoises encounter a modified gillnet should be investigated. This could be achieved by conducting a behavioral experiment, either in an enclosed environment or in an area where many wild cetaceans are relatively abundant and can be observed both visually to determine changes in surfacing frequency and acoustically to determine underwater swimming paths as well as changes in echolocation behavior upon the encounter of the gillnets. A first, small experiment by Gustafsson (2020) explored the behavior of harbor porpoises around gillnets with acrylic spheres using CPODs and has shown that fewer detections are made around gillnets with acrylic glass spheres. Further behavior experiments should also investigate a combination of a “wake-up call” (e.g., PAL) and the modified net to explore the synergistic effects of passive and active devices on potential bycatch reduction.

Additionally, the underwater properties of gillnets, both modified and conventional, e.g., in terms of hydrodynamic behavior, self-entanglement, hanging ratio, and response to entanglement by fish and other animals, should be investigated in a flume tank and using camera observation during commercial use. The concept of adding small acrylic glass spheres to make gillnets acoustically visible is not limited to reducing *P. phocoena* bycatch (Kratzer et al. 2020). Small, echolocating cetaceans around the world are threatened by gillnets; therefore, additional trials can be conducted in any gillnet fishery with bycatch of small cetaceans.

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APPENDIX

Table A 1. Overview of hauls and number of species caught per haul and gillnet type. All hauls carried out in 2019. (S = standard gear, M = modified gear)

Trip	Start date [DD-MM-YY]	Gear	Soak time [h]	Turbot (*Scophthalmus maeoticus*)	Common stingray (*Dasyatis pastinaca*)	Spiny dogfish (*Squalus acanthias*)	Whiting (*Merlangius merlangus*)	Thornback ray (*Raja clavata*)	Harbor porpoise (*Phocoena phocoena relicta*)	Loon (Gaviidae)
1	09-09-19	S	66	0	0	0	0	22	0	0
		M	66	0	0	0	0	31	1	0
2	18-09-19	S	92	0	0	0	2	31	2	0
		M	94	0	0	1	1	27	0	0
3	02-10-19	S	147	0	2	0	0	13	0	0
		M	145	0	1	0	0	5	0	0
4	15-10-19	S	123	0	0	0	0	6	0	0
		M	123	0	0	0	0	6	0	0
5	25-10-19	S	114	0	0	0	0	5	0	0
		M	112	0	1	0	0	18	1	0
6	04-11-19	S	97	1	0	1	0	2	3	0
		M	96	0	0	0	0	4	0	0
7	10-11-19	S	192	0	0	0	0	0	0	0
		M	190	0	0	0	0	4	0	0
8	20-11-19	S	169	2	0	0	0	0	0	0
		M	168	1	0	0	0	16	0	0
9	05-12-19	S	144	0	1	0	0	2	0	0
		M	143	0	0	0	0	1	0	0
10	13-12-19	S	95	0	0	0	0	0	0	0
		M	98	0	0	0	0	2	0	1
	Total			4	5	2	3	195	7	1

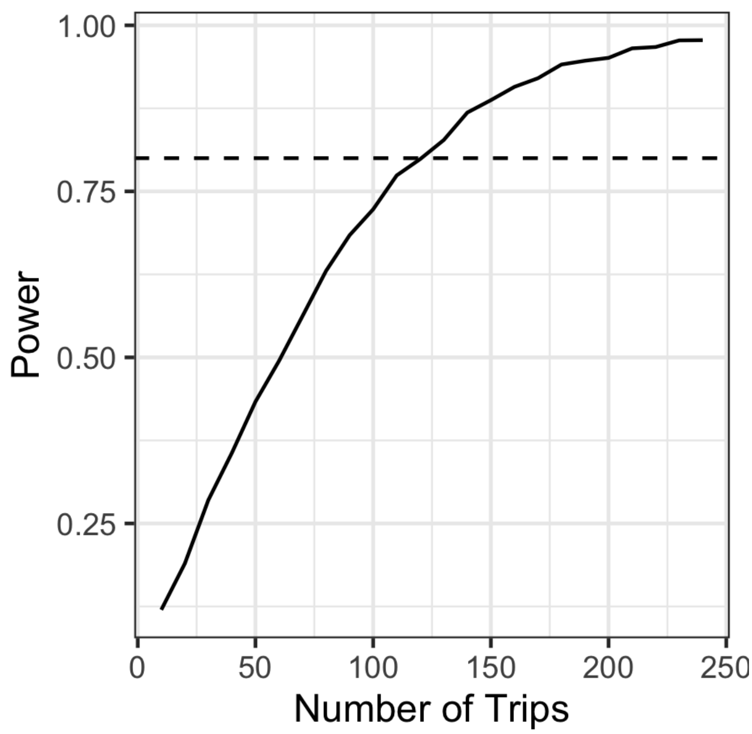

Fig A 1. estimated power vs number of trips, each trip setting one set of standard and one set of modified gillnets. An 80% power can be achieved with approximately 130 sets