Synthetic harbour porpoise (*Phocoena phocoena*) communication signals emitted by acoustic alerting device (Porpoise ALert, PAL) significantly reduce their bycatch in western Baltic gillnet fisheries

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Abstract

Gillnet fisheries are one of the main anthropogenic causes of harbour porpoise (*Phocoena phocoena* L., 1758) mortality in the Baltic Sea. A new kind of acoustic alerting device (Porpoise ALert, PAL) was tested in commercial gillnet fisheries in the western Baltic. PAL emits 133 kHz synthetic harbour porpoise communication signals, unlike conventional acoustic deterrent devices (pingers), which emit artificial noise. Trials were undertaken by three commercial gillnet vessels conducting 778 trips during standard fishing operations from 2014 to 2016. In all, 1120 PAL-equipped net strings were tested against 1529 simultaneously set control strings with no devices. We tested two versions of the PAL (v1 and v2) consecutively. These were spaced <210 m apart on the gillnet floatlines, with all devices pointing in the same direction to ensure complete acoustic coverage of the strings. Two vessels fished in Kiel Bight and around Fehmarn Island in German waters, and the third vessel fished in the Øresund, in inner Danish waters. Overall, 18 harbour porpoises were bycaught in control strings (mean 0.01 ± 0.1/haul), and five harbour porpoises were taken as bycatch in strings equipped with PALs (0.004 ± 0.07/haul). The number of net string bycatches was analysed using a generalised linear mixed model (GLMM). The model applied to all observations revealed that the expected bycatch was significantly influenced by PAL deployment ($p < 0.05$), decreasing the expected bycatch by 64.9% (95% confidence interval (CI): 8.7–88.7%). PAL effectiveness was also increased by reducing device spacing to <210 m (16 bycatches in control, 3 in PAL strings; mean bycatch reduction 79.7%). Additional model cases were applied to the data and are discussed. We conclude that, with this specific communication signal, PAL can significantly reduce harbour porpoise bycatch in gillnets deployed in the western Baltic Sea, thus reconciling anthropogenic activities with protection of the marine environment.

Keywords

Harbour porpoise, bycatch mitigation, marine mammals, gillnet fisheries, pinger, acoustics

1. Introduction

Gillnets are a fuel-efficient fishing gear with high target species size selectivity, low greenhouse gas emissions (Suuronen et al., 2012), and little bottom impact compared with active gear (Grabowski et al., 2014). They are widely employed in small-scale Baltic fisheries. Gillnet fisheries, however, present a pressing conservation threat to air-breathing species taken as bycatch, such as marine mammals or diving birds (e.g. Brownell Jr et al., 2019; Gilman, 2015; Northridge et al., 2016; Reeves et al., 2013; Žydelis et al., 2013). Many of these species are endangered and protected under diverse national and international laws and regulations, e.g. the European Union (EU) Habitats and Species Directive (CEC, 1992).

For more than 30 years, scientists have addressed marine mammal bycatch and its mitigation (see e.g. Dawson, 1991 and references therein; Kraus et al., 1997). Proposed mitigation measures include placing acoustic deterrent devices (ADD), so-called pingers, on the strings (e.g. Gearin et al., 2000; Gönener and Bilgin, 2009; Larsen and Eigaard, 2014), structurally modifying the gillnet twine to increase acoustic reflectivity (Koschinski et al., 2006; Kratzer et al., 2020; Larsen et al., 2007; e.g. Trippel et al., 2003), adjusting fishery operational factors such as net height or twine diameter (see Northridge et al., 2016 and references therein), and enacting spatial and/or temporal fisheries closures (e.g. Gormley et al., 2012; Murray et al., 2000).

Pingers can reduce the bycatch of many small cetacean species (see Dawson et al., 2013, for a review). Concerns have been raised that pingers might initially deter cetaceans from the gillnet, but then lose their effectivity through habituation to the deterring sound, at least in harbour porpoises (Carlström et al., 2009; Dawson et al., 2013; Gearin et al., 2000; Kyhn et al., 2015). Another concern is that the deterring pinger effect might exclude marine mammals from a potentially large and important ensonified habitat (Carlström, 2002; Culik et al., 2001; van Beest et al., 2017; Kyhn et al., 2015). It is also possible that pingers reduce harbour porpoise echolocation rate (Carlström et al., 2009; Cox et al., 2001; Hardy et al., 2012; Teilmann et al., 2006), thus reducing their ability to detect acoustically unmarked gillnets nearby.

To address these concerns, Culik and Winkler (2011) propose equipping gillnets with a device that synthetically reproduces natural aversive communication signals of harbour porpoises. In a field test in the Little Belt in Danish waters, Culik et al. (2015) demonstrated that harbour porpoises there reacted to one of three tested signals (F3) described for Belt Sea animals by Clausen et al. (2011), by increasing their distance to the signal source by 32 m, while increasing their echolocation rate by 10%. Based on these results, B. Culik and M. Conrad (2013; DPMA Patent No. 10 2011 109 955) developed a rugged, individually programmable sound emitting device for deployment in fisheries, the Porpoise ALert (PAL).

To determine if the chosen PAL signal “F3” effectively reduces harbour porpoise bycatch, we tested the device with commercial gillnet vessels during their standard operations in the western Baltic. Thus, fishers did not invest additional fishing effort in these trials, which might have increased bycatch, so avoiding ethical conflicts.

We compared simultaneously deployed net strings equipped with the mitigation devices (PAL strings) and strings without them (control strings) with the expectation that PALs would lower bycatch rates (*null hypothesis:* no difference in bycatch rates between PAL and control strings).

2. Materials and methods

2.1. Criteria to select fisheries for the tests

Fisheries to conduct the tests were chosen based on these criteria:

a) Tests should be conducted in the area occupied by the Belt Sea porpoise population (cf. Culik et al., 2015).
b) In the test area, harbour porpoise densities should be sufficiently high to expect statistically sound results (i.e. sufficiently high bycatch numbers) with a reasonable experimental effort.
c) Only fishing vessels that ensured a sufficiently intensive fishing effort, based on string lengths set per trip and number of trips conducted per month, were selected for the project.

2.2. Study area, fishing vessels, and weather

From 2014 to 2016, three gillnet vessels, under the condition of anonymity, participated in this study in the western Baltic gillnet fishery. One Danish commercial gillnet vessel (Vessel A, approximately 11 m long) fished in the Øresund (International Council for the Exploration of the Sea (ICES) Area 3.b.23; Fig. 1). Two German commercial gillnet vessels fished in ICES Area 3.c.22 (Vessel B, approximately 8 m long, around Fehmarn Island, and Vessel C, approximately 11 m long, in the western part of Kiel Bight). The main target species was cod (*Gadus morhua* L., 1758), targeted with gillnets and trammelnets with 110–160 mm stretched mesh sizes (hereafter mesh size). Secondary target species were flatfish: mainly flounder (*Platichthys flesus* L., 1758), plaice (*Pleuronectes platessa* L., 1758), and turbot *Scophthalmus maximus* L., 1758). In addition, Vessel A fished in spring with 240 mm mesh size for lumpfish (*Cyclopterus lumpus* L., 1758).

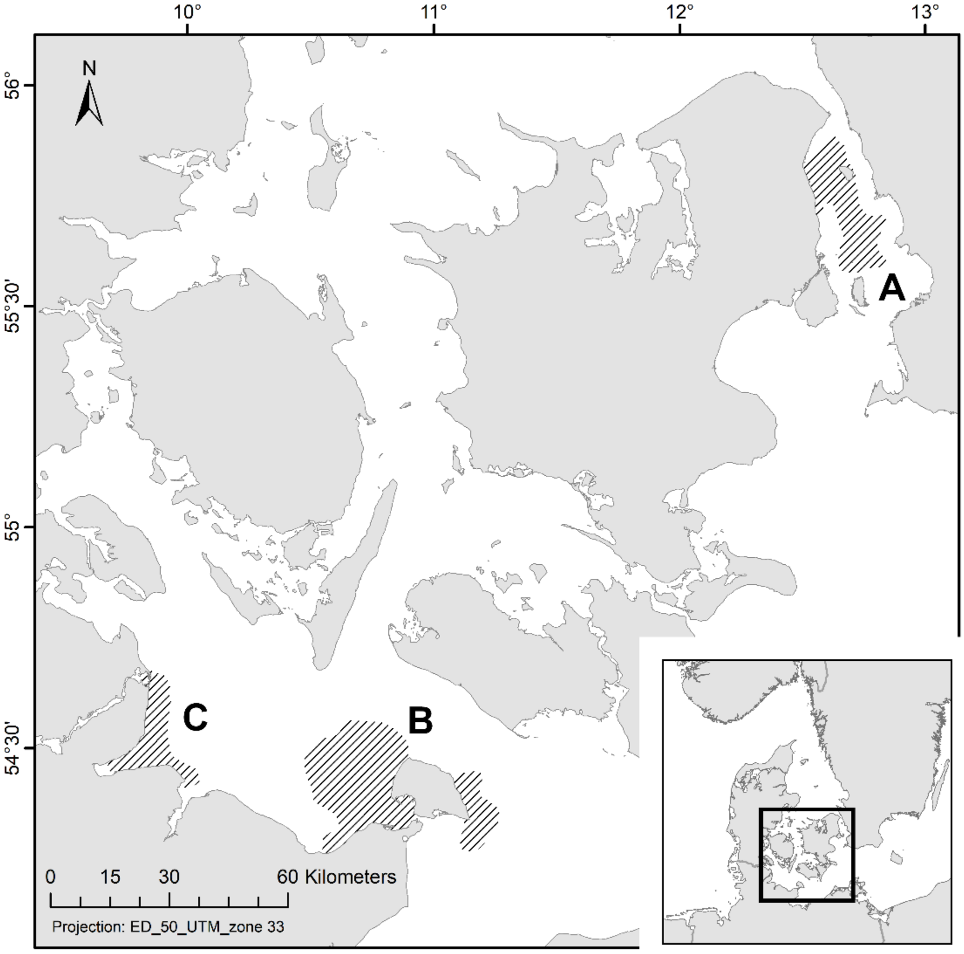

Figure 1: Map of study area where three commercial gillnet vessels fished during this study (hatched areas). Letters indicate vessels operating in the Öresund (A), around Fehmarn Island (B) and western part of Kiel Bight (C). Note that the fishing areas shown are approximate, because a buffer was added to the setting positions to ensure confidentiality.

Vessels participating in this project were to pursue their usual fishing activities and operating conditions using their own nets. When setting and recording the deployment of both PAL and control strings, they were paid a small compensation. The catch-optimised fishery continued to be their main source of income and thus, PAL trials followed realistic operational conditions.

A research design coupling control and PAL strings was followed: Fishers were instructed to set half of their strings with PALs (PAL strings) and the other half without PALs (control strings) on the same trip. A trip was defined as the period from a vessel's departure from port to conduct fishing until its return to port. Both strings had to have identical net characteristics (mesh size, net panel length, and panel height) and string lengths. Fishers, however, had a limited number of PALs at their disposal. Sometimes there were not enough PAL to equip 50% of the strings they chose to set for commercial purposes. As a result, fishers often set more control than PAL strings. Therefore, we decided later to include these additional control strings as well, to expand the number of observations available for analysis (see the Results section). PAL and control strings set by the same fisher during the same period were considered as "coupled." Fishers were instructed to space PAL and control strings at least 500 m apart, to ensure that porpoises would not detect the PAL signal near the control strings.

Maximum porpoise detection range was conservatively estimated at 460 m by Culik et al. (2015) for a source level of 158 dB peak–peak re 1 µPa, 1m, which is 6 dB higher than the PALs used here. Using the method of Culik et al. (2015), PAL received levels were simulated, demonstrating that harbour porpoises should detect the signal at wind conditions 0 Beaufort wind force scale (Bft) within a range of approximately 230–320 m, depending on porpoise orientation and position with respect to the PAL. This is reduced to 90–150 m at 7 Bft.

To determine if PAL efficacy is diminished by bad weather conditions through increased environmental noise (Urick, 1983), we acquired windspeed (m/s) and swell height (m) from the sea state model of the German Meteorological Office (Deutscher Wetterdienst, Marine Meteorological Service) for the three fishing areas during the project time frames. This model contains archived 12-hour forecasts based on recorded meteorological data in a 0.05° grid over Baltic Sea areas with greater than 10 m average water depth. Forecast values are modelled for every 3 hours. The forecast datapoints are non-homogenised forecast values and most accurate in areas of average depths greater than 15–20 m. The German Meteorological Office informed us that they assume an error of 0.1% for the data (M. Gerber, German Meteorological Office, pers. Comm.). In a GIS software (ArcGIS version10.3.1; ESRI 2014), each recorded gillnet string was assigned to the forecast grid point nearest to its setting point. Using the statistical software R (version r74432; R Core Team, 2018), each string was subsequently assigned the maximum windspeed and swell height during its setting period (distances between starting position of net setting and nearest forecast grid point: mean 2497 m, min. 1 m, max. 7428 m).

2.3. PAL hardware and attachment

PAL is a spindle-shaped acoustic transducer optimised for use in fisheries. In water, the device has a positive buoyancy of approximately 80 g. Two PAL versions were used in the experiment: PALv.1 was equipped with a 1.5V carbon-zinc battery and a saltwater switch allowing for approximately six weeks or 35 days of operation. PALv.2 is equipped with a 3.6V lithium-ion battery and a saltwater switch delivering autonomy for approximately two years under standard operating conditions, where the nets are in the water and the PAL is active for approximately 50% of the time. PALs were acoustically checked on board after each haul by crew and observers, and defective devices were replaced immediately. Because device failures could occur under any normal fishing operations, strings with defective devices were included in the analysis.

The first PAL version (PALv.1) was programmed to emit acoustic signals while in water and continue to emit for approximately 20 minutes after being hauled on board. It emits a single synthetic signal termed “F3” consisting of two upsweep chirps beginning with a click rate of 173 clicks/s and ending with 959 clicks/s. PAL characteristics were measured by M. Conrad (pers. comm.) in the calibration tank at L3-Elac Nautic, Kiel, using the calibrated reference hydrophone Brüel & Kjær Type 8104, No. 2 393 700, and digital oscilloscope OWON SDS 7102V. PAL has a centroid frequency of 133 ± 8.5 kHz; mean source level 147 dB peak–peak re 1 µPa@1 m (± 5 dB Standard Deviation; n = 36 measurements in 10° around the longitudinal axis, Fig. 2) and a close range audible signal envelope 8 kHz). Signal duration is 1.22 s followed by a pause lasting 20 s (approximately 3 signals/minute). The new PAL version (PALv.2) became available in April 2016 and replaced PALv.1 on all three vessels. PALv2 has a slightly different signal repetition pattern in order to fulfil the requirements for ADDs set in EU Regulation 812/2004 (CEC, 2004), and it emits a series of one to three signals at random followed by a randomised pause of 4–30 seconds (on average 5.5 signals/minute).

To ensure that the PAL signal acoustically covered the whole of the net string, fishers were instructed to attach the device horizontally to the floatline, spacing each a maximum of 200 m from the next. This is in accordance with EU Regulation 812/2004 (CEC, 2004) concerning the use of ADD. Maintaining this spacing limit is crucial because other studies have found that pinger effectiveness may decrease with decreased spacing distance (Kindt-Larsen et al., 2019; Larsen et al., 2013). As in all acoustic devices, the battery compartment causes an acoustic "silent zone." Signal emission is thus slightly directional towards the end where the transducer is located, opposite the battery compartment (Fig. 2). Fishers were instructed to take care to attach all PALs pointing in the same direction of the net string to ensure complete acoustic coverage. The PALs were attached to the connecting bridle between the floatlines of two net panels (distance between subsequent net panels ranged approximately from 0 to 1.0 m). This ensured optimal acoustic coverage, avoided net tangling, and allowed us to gauge the spacing between two subsequent PALs. PAL spacing ranged from a minimum of 120 to 210 m during the trials (cf. Results section, Table 3).

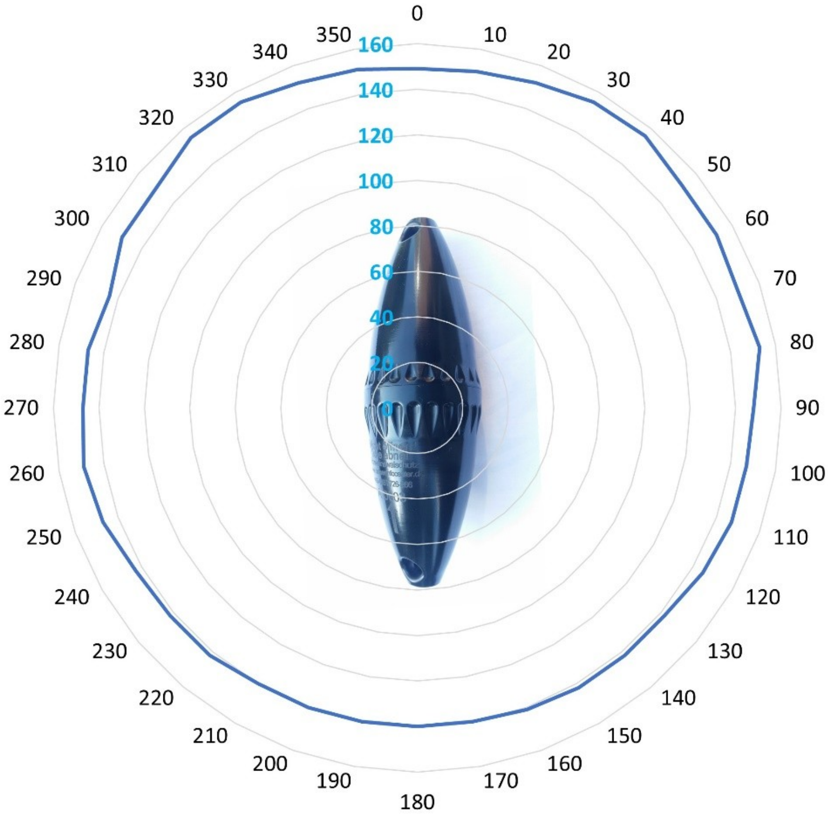

Figure 2: PAL seen from above as attached to the net floatline. Source Level (peak–peak, in dB re. 1µPa 1 m) is not totally omnidirectional around the PAL along the long axis (in degrees). Source level towards the transducer side (top) is approximately 7% higher than towards the battery compartment (bottom).

Figure 3: A PAL.v2 attached to a gillnet bridle. The PAL was marked on the battery compartment (right) to ensure fishers positioned them all pointing in the same direction.

2.4. Trial monitoring

Participating fishers were instructed to self-report the following data about their fishing operations during PAL trials: date and start time of setting and hauling process (yielding soak time), type of gillnet (single or trammelnet), stretched mesh size, panel height and length, total number of panels per string set, geographical (GPS) position of string start and string end, and whether PALs in the string were identified as working or defective after hauling. Each harbour porpoise bycatch observed in a string was to be recorded, including relative position in the string and net type (PAL or control).

Observers regularly accompanied the vessels during operations to inspect PAL attachment, functioning, orientation, and spacing, and to replace depleted PAL batteries, confirm a correct experimental setup, obtain feedback on possible problems concerning PAL usage (e.g. entanglement in nets), maintain a good understanding of the fishery tactics pursued by the fishers, and observe possible bycatches.

The Danish gillnet vessel (Vessel A) was equipped with a remote electronic monitoring (REM) system during the study. The REM system (Anchorlab, Denmark) records time, position, and video footage of all trips (port to port), and allows the recording of setting and hauling positions. By linking both positions, it is possible to deduce string soak time. Fishers, however, were tasked to record the same information in paper logs, as well as net characteristics because these are not recognisable from REM records. Two cameras film the net coming out of the water from different points of view, allowing detection of the entire catch breaking the surface (Kindt-Larsen et al., 2012). In addition, the fishers kept a paper log of their sets and harbour porpoise bycatch. One hundred per cent of all trips fulfilling the experimental conditions and used in the analysis (hereafter valid trips) of Vessel A were observed with REM. The fisher on German gillnet Vessel B only agreed to the installation of a REM system (Archipelago Marine Research, Canada) several months after the trials began (start of project participation 8 May 2015; REM system coverage beginning 9 January 2016). Two cameras filmed the point when the net exited the water. Vessel B is <8 m long, with only an open cab and very restricted berthing space. The single fisher, therefore, was reluctant to admit an observer on board owing to safety concerns. Therefore, only 18.3% of Vessel B's trips were covered by REM or an observer. The crew of German gillnet Vessel C did not agree to have a REM system installed for the PAL project. Therefore, observation was only achieved with observers, and 28.5% of all valid trips had observer coverage. Of the total 778 fishing trips with PAL trials in all three vessels, 49.2% were observed by REM and/or on-board observers. All REM data were analysed by trained staff who recorded all harbour porpoise bycatch events (Vessel A data with Anchorlab software BlackBox Analyser, v. 2.0 and 3.0; Vessel B data with Archipelago Marine Research REM Interpret Pro, v. 2.1.5). Thus, the data collected is a mixture of monitoring data (REM/observer) and self-sampling data (fishers' logs).

2.5. Statistical analysis

All recorded data were checked for plausibility; data were excluded from analysis (classified as invalid) if implausible, according to the following criteria.

a) Harbour porpoise density is highly variable over time and space; therefore, control strings set without coupled PAL strings of the same net characteristics were not included in the analysis.
b) Spacing, coverage: Control strings set closer than 500 m from PAL strings. In these cases, an effect of the nearby PAL strings could not be ruled out, and those control strings were also classified as invalid. This could result in PAL strings being coupled only with distance-invalidated control strings. These PAL strings were also classified as invalid. Strings with only partial PAL coverage, or trips with missing data in the records, were not included (cf. the Results section for details).
c) An invalid trip is a trip on which all strings were classified as invalid, e.g. resulting from poor REM image quality.

Strings, where PALs were found to be defective after hauling, were included in the analysis, because device failure cannot be entirely ruled out in commercial fishing operations as well.

Because fishers on Vessel A often did not note the correct string length, distances between GPS points at fleet start and end were entered as a proxy for string length. For all three vessels, the PAL and control strings had the same length; mean lengths of PAL and control string were 1.79 (± 0.92) km and 1.64 (± 0.84) km, respectively. However, the total number and total length of control strings exceeded that of PAL strings (in total, 1529 valid control strings 2506.3 km long vs. 1120 PAL strings 2003.8 km long). Therefore, the length of each string was incorporated into the statistical model.

Between 17 February 2016 and 11 April 2016, spacing of the PALs on the strings set by Vessel A was at least 210 m (plus a short bridle length of approximately 0.3–3.0 m). This violated the experimental design by overstepping the PAL spacing limit by at least 10 m. Two PAL bycatches and two control bycatches occurred in this period. Although it seems unlikely that this short extra spacing would have a profound effect on the PAL bycatch effect, we decided to analyse the PAL effect in two separate models, one *including* the PAL strings with 210 m spacing, and another *excluding* these PAL strings (as well as *including/excluding* the corresponding control strings set on the same days, respectively).

Trials with the slightly modified version PALv.2 were begun eight months before the end of the trials. The few resulting data fulfilling all trial conditions (two bycatches occurred in control strings classified as valid, one bycatch in a control string classified as not valid according to the criteria given above) did not allow for statistical analysis of separate effects of version PALv.2 on expected bycatch. Therefore, we chose to analyse the complete PAL-trial dataset in two models, one *including* and one *excluding* the PALv.2 trial data.

Therefore, each of four datasets (hereafter named cases) was analysed with a generalised linear mixed model (GLMM). Case 1 served as the base dataset and included all 2649 observations with strings classified as valid (Table 1). To avoid overfitting caused by the limited number of bycatches, only a limited set of predictors could be included in the model.

The number of harbour porpoise bycatch per string ($N_i \in \{0, 1, 2, 3, \ldots\}$) was modelled for each of the four cases using a GLMM with Poisson distributed observations and a log link function with the glmmTMB (version 0.2.2.0; Brooks et al., 2017) package of the statistical software R (Core Team, 2018). In addition to the Poisson distribution, negative-binomial and zero-inflated models were investigated. However, no indication of over-dispersion or zero-inflation was found. In the full model, “Fishing vessel” was included to account for different fishing strategies pursued by different vessels, while the “Trip” random effect was included to account for spatial and temporal porpoise density variability, which is expected to vary by year, month (Hammond et al., 2013), and even day.

The model had “Number of porpoise bycatches” as the response variable. As fixed effects, the model included an intercept (the parameter β_0), along with effects of “PAL presence” (β_1), “Log-string length” (β_2), and “Fishing vessel” (β_3 for Vessel B and β_4 for Vessel C). Further, the “Trip” (combination of fishing vessel and day) was included as a random effect ($\tau_{t(i)}$). To correct for different exposures to risk, “Log-soak time” was included as an offset ($\log(s|i)$). No interactions were included to prevent overfitting the data. In the full model, therefore, the logarithm of the expected bycatch for the i^{th} haul was

$$\log E(N_i) = \log(s|i) + \beta_0 + \beta_1 P_i + \beta_2 \log(L_i) + \beta_3 V_i^B + \beta_4 V_i^C + \tau_{t(i)},$$

where $s_i > 0$ is soak time, $P_i \in \{0,1\}$ is a dummy variable reflecting presence (P = 1) or absence (P = 0) of PALs on the string, $L_i > 0$ is string length, $V_i^B \in \{0,1\}$ is one if the haul is from Vessel B, $V_i^C \in \{0,1\}$ is one if the haul is from Vessel C, $\tau_{t(i)} \sim N(0, \sigma_\tau^2)$ is a random effect on trips, and $\beta_0, \ldots, \beta_4 \in R$, $\sigma_\tau > 0$ are the parameters described above. In this model, the intercept corresponds to a one kilometer control string from Vessel A with one hour soak time on an average trip.

Covariates with missing data were assumed to be missing completely at random, and entire observations were excluded if a covariate was missing. All model parameters were estimated using maximum likelihood. Before testing the hypothesis of no effect of PAL presence, the model was reduced as much as possible by likelihood ratio tests (LRT).

3. **Results:**

3.1. Fishing effort and bycatch numbers

Trials with PALv.1 were carried out from 19 March 2014 to April/May 2016 (13 April 2016 for Vessel A, 8 May 2016 for Vessel B, and 15 April 2016 for Vessel C; Fig. 4), followed by trials with PALv.2, which ran until December 2016 (Fig. 4). Vessel A ended gillnet fishing and thus trial participation first, in June 2016. A total of 3357 strings were set during these trials.

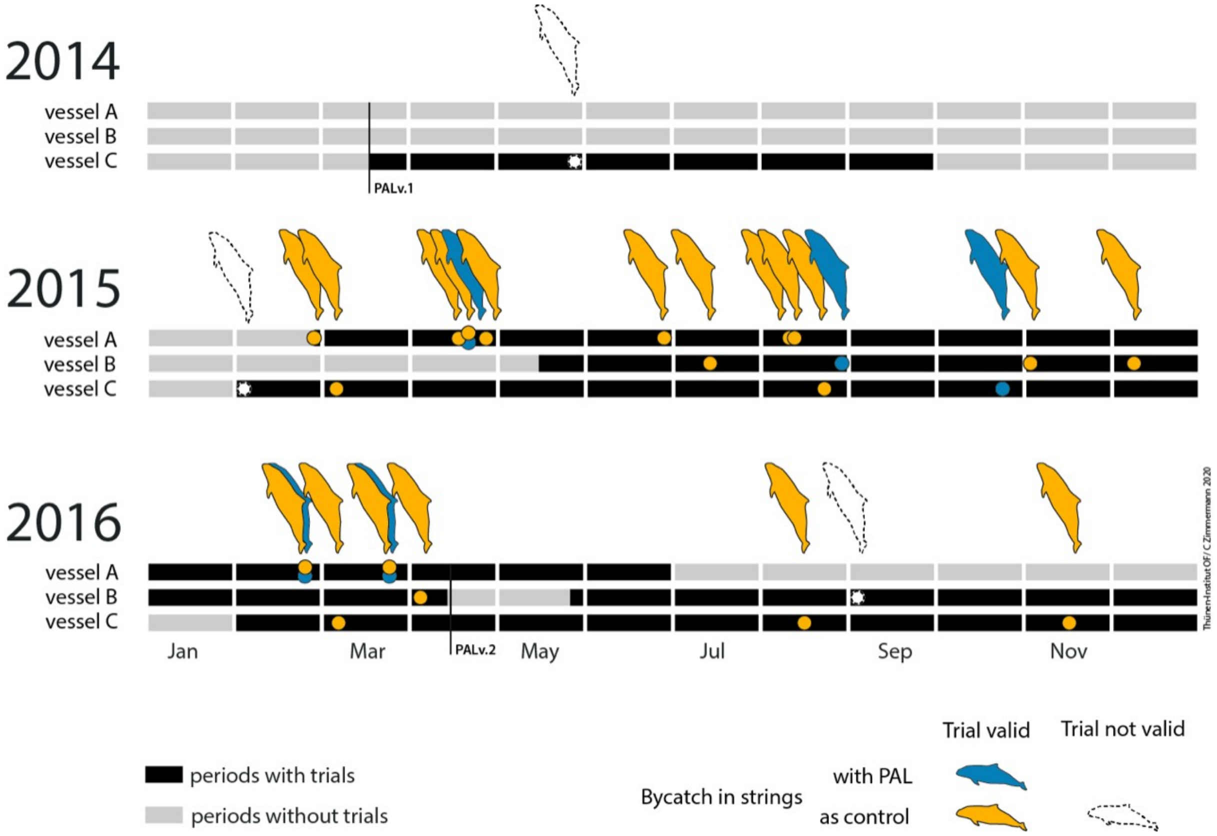

Figure 4: Occurrence of harbour porpoise bycatches over time in PAL and control strings in trials conducted by three vessels (A, B, C) 2014–2016. Different colours of porpoise silhouettes indicate occurrence in PAL and control strings, as well as whether or not the bycatch events were valid for inclusion in the statistical analysis. Invalid bycatch are those where the experimental design was violated. Start of trials with different PAL versions (PALv.1, PALv.2) is indicated by vertical lines.

The following data were not included in the analysis. (a) Vessel A hauled 119 strings where REM image quality was too low to discern whether or not these were equipped with PALs. The quality, however, was always sufficient to detect a porpoise, and none of these strings had any porpoise bycatch. (b) For 13 strings from all three vessels, the length is unknown because the fishers did not note plausible GPS coordinates of either a start- or endpoint, and (c) exact soak time is missing for 129 sets from all three vessels. None of these had porpoise bycatch. (d) In 2014, one control bycatch on Vessel C was observed by an on-board observer, but occurred in a control string tied directly to a string with PALs, thus violating the experimental design. (e) In addition, 446 strings were either control strings set closer than 500 m to the next PAL string or PAL strings coupled only with control strings that were closer than 500 m to their next PAL string. Two of those distance-invalidated control strings, in 2015 and 2016, each had one bycatch. Therefore, 708 strings with three control bycatches were excluded from the data set.

In all, 2649 string observations from 778 trips were included in the statistical analysis (Table 1). Eighteen porpoise bycatch events in the control strings and five bycatch events in the PAL strings classified as valid were included in the analysis (Fig. 4). They occurred over the whole range of mesh sizes used (110–240 mm; Table 3), during all weather conditions, and throughout the year. Each event was a bycatch of a single individual in one string. For the statistical analysis, the number of bycatch events were aggregated per string, and an observation was defined as the number of bycatch (and corresponding covariates) per net string. Thirteen (56.5%) of all bycatches were observed either by REM or an on-board observer. Two of the 18 control bycatches occurred during PALv.2 trials (with no PAL bycatch).

Fishing strategies were unique to each vessel and mostly changed over the year, illustrated by individual variation in gillnet characteristics (Table 2). Usually, soak time lasted approximately 24 h, except for the lumpfish fishery of Vessel A with large-mesh size (240 mm), where soak time could extend up to several days. Catch data were not part of the data collected in this study, but all fishers stated during the study, until the study's end, that they did not perceive any PAL-related effect on their catches.

Table 1: Results of valid PAL trials with model Cases 1-4 and vessels A, B, and C. Strings are split into control and PAL strings. Means are given with standard deviation. Cases 1 to 4 represent inclusion/exclusion of trials with 210 m PAL distance and PALv.2, respectively.

Case	PAL spacing 210 m included	PALv.2 included	Vessel	Trips			No. bycatch events		No. string		String length [km]			
				No.	No. observed	*% observed*	Control	PAL	Control	PAL	Total control	Mean control	Total PAL	Mean PAL
1	yes	yes	A	242	242	*100%*	9	3	732	432	830.0	1.13 ± 0.3	481.7	1.12 ± 0.29
1	yes	yes	B	115	21	*18.3%*	4	1	130	127	361.2	2.78 ± 1.2	358.8	2.83 ± 1.16
1	yes	yes	C	421	120	*28.5%*	5	1	667	561	1315.2	1.97 ± 0.78	1163.3	2.07 ± 0.8
1	**yes**	**yes**	**All**	**778**	**383**	***49.2%***	**18**	**5**	**1529**	**1120**	**2506.3**	**–**	**2003.8**	**-**
2	yes	no	A	194	194	*100%*	9	3	608	349	683.0	1.12 ± 0.32	387.5	1.11 ± 0.31
2	yes	no	B	100	6	*6%*	4	1	106	105	328.7	3.1 ± 1.02	324.4	3.09 ± 1.07
2	yes	no	C	309	88	*28.5%*	3	1	525	444	1086.9	2.07 ± 0.74	965.3	2.17 ± 0.74
2	**yes**	**no**	**All**	**603**	**288**	***47.8%***	**16**	**5**	**1239**	**898**	**2098.7**	**-**	**1677.2**	**-**
3	no	yes	A	216	216	*100%*	7	1	630	392	715.2	1.14 ± 0.31	435.0	1.11 ± 0.29
3	no	yes	B	115	21	*18.3%*	4	1	130	127	361.2	2.78 ± 1.2	358.8	2.83 ± 1.16
3	no	yes	C	421	120	*28.5%*	5	1	667	561	1315.2	1.97 ± 0.78	1163.3	2.07 ± 0.8
3	**no**	**yes**	**All**	**752**	**357**	***47.5%***	**16**	**3**	**1427**	**1080**	**2391.6**	**-**	**1957.1**	**-**
4	no	no	A	168	168	*100%*	7	1	506	309	568.3	1.12 ± 0.33	340.7	1.1 ± 0.31

4	no	no	B	100	6	*6%*	4	1	106	105	328.7	3.1 ± 1.02	324.4	3.09 ± 1.07
4	no	no	C	309	88	*28.5%*	3	1	525	444	1086.9	2.07 ± 0.74	965.3	2.17 ± 0.74
4	**no**	**no**	**All**	**577**	**262**	***45.4%***	**14**	**3**	**1137**	**858**	**1984.0**	**–**	**1630.4**	**–**

Table 2: Aggregated gillnet data (soak time, mesh size (stretched), net height, and string length) of vessels A, B, and C from data selection Case 1, which includes all 778 PAL trials classified as valid. Mesh size, net height, and string length are given with mean and standard deviation, soak time with median and 25/75 quantiles owing to some extremely long soak time outliers.

	Soak time [h]			**Mesh size (stretched) [mm]**			**Net height [m]**			**String length km]**		
Vessel	**Min.**	**Max.**	**Median, 25 & 75% quantiles**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**
A	1.99	216.83	24.27 (22.9-48.67)	110	240	167.9 ± 38.62	1.50	6	2.29 ± 1.13	0.07	2.67	1.13 ± 0.29
B	4.85	64.53	18.67 (17.33-20.08)	110	160	159.07 ± 6.43	1.45	2	1.46 ± 0.08	0.08	5.17	2.8 ± 1.18
C	2.33	70.50	23.00 (21.58-24.00)	110	150	115.11 ± 12.37	1.00	2	1.43 ± 0.18	0.03	5.29	2.02 ± 0.79

Table 3: Bycatch of harbour porpoise in strings classified as valid: date hauled, observation status, net characteristics, soak time, mean and maximum predicted windspeed, wave height during soak time of strings with observed bycatch in chronological order. Bycatch in PAL strings is in bold.

Vessel	Date hauled	Observed by EM/ observer?	PAL/ control string	PAL spacing [m]	Mesh size (stretched) [mm]	Net height [m]	String length [km]	Soak time [h]	Windspeed [m/sec (Bft)]		Wave height [m]	
									Mean	Max.	Mean	Max.
					PALv1.1							
A	26.02.15	Yes	control	–	240	2.5	1.5	51	5.8 (4)	11.3 (5)	0.5	0.9
C	11.03.15	No	control	–	110	1.5	1.4	47	4.4 (3)	8.2 (4)	0.2	0.5
A	21.04.15	Yes	control	–	240	2.5	1.6	70	4.7 (3)	8.6 (5)	0.5	1.0
A	24.04.15	Yes	control	–	240	2.5	1.2	85	5.9 (4)	11.1 (5)	0.8	1.6
A	24.04.15	**Yes**	**PAL**	**150**	**240**	**2.5**	**1.3**	**84**	**5.5 (3)**	**11.1 (5)**	**0.8**	**1.6**
A	28.04.15	Yes	control	–	150	1.5	1.6	18	3.4 (2)	4.5 (3)	0.1	0.2
A	30.06.15	Yes	control	–	150	1.5	0.4	23	3.9 (3	5.8 (4)	0.2	0.3
B	13.07.15	No	control	–	160	1.45	1.1	20	6.1 (4)	7.4 (4)	0.5	0.6
A	10.08.15	Yes	control	–	150	1.5	1.3	68	2.3 (2)	4.5 (3)	0.1	0.2
A	12.08.15	Yes	control	–	150	1.5	1.1	24	3.5 (2)	5.2 (3)	0.1	0.3
C	22.08.15	No	control	–	110	1.5	1.6	24	3.8 (3)	5.5 (3)	0.3	0.4
B	**01.09.15**	**No**	**PAL**	**195**	**160**	**1.45**	**2.7**	**14**	**4.5 (3)**	**6.3 (4)**	**0.3**	**0.5**
C	**25.10.15**	**No**	**PAL**	**200**	**110**	**1.5**	**2.6**	**25**	**5.6 (3)**	**6.6 (4)**	**0.2**	**0.3**
B	03.11.15	No	control	–	160	1.45	3.9	21	3.4 (2)	4.6 (3)	0.1	0.2
B	10.12.15	No	control	–	160	1.45	1.9	20	9.4 (5)	11.2 (5)	0.6	0.8
A	**01.03.16**	**Yes**	**PAL**	**210**	**240**	**3**	**1.3**	**165**	**7.4 (4)**	**10.9 (5)**	**0.4**	**0.6**
A	01.03.1	Yes	control	–	240	3	1.3	168	5.5	7.4 (4)	0.3	0.4

	6		l						(3)			
C	10.03.16	No	control	–	110	1.5	2.7	46	6.2 (2)	8.1 (4)	0.4	0.8
A	**31.03.16**	**Yes**	**PAL**	**210**	**240**	**3**	**1.4**	**217**	**3.71 (3)**	**6.2 (4)**	**0.2**	**0.2**
A	31.03.16	Yes	control	–	240	3	1.3	192	4.7 (3)	7.4 (4)	0.2	0.4
B	05.04.16	Yes	control	–	160	1.45	1.9	24	2.8 (2)	4.9 (3)	0.2	0.3
						PALv1.2						
C	18.08.16	No	control	–	130	1	1.0	24	2.2 (2)	5.0 (3)	0.1	0.3
C	18.11.16	No	control	–	130	1	1.7	23	7.3 (4)	10.2 (5)	0.4	0.6

3.2. *Modelling of PAL effect on bycatch rate*

The four cases were analysed using a GLMM with string length, fishing vessel (Vessel), and PAL deployment as fixed effects. In a first step, the model was reduced by testing for no effect of string length on the response (null hypothesis: $\beta_2=0$), which could not be rejected at the 5% significance level for any of the cases (Case 1 test size: 0.0160, p-value: 0.8994; Case 2 test size: 0.0050, p-value: 0.9437; Case 3 test size: 0.0113, p-value: 0.9155; Case 4 test size: 0.0288, p-value: 0.8653). Likewise, in the subsequently reduced model, the hypothesis of no fishing vessel effect (null hypothesis: $\beta_3=\beta_4=0$) could not be rejected at the 5% significance level (Case 1 test size: 1.5817, p-value: 0.4535; Case 2 test size: 2.0011, p-value: 0.3677; Case 3 test size: 1.3903, p-value: 0.4990; Case 4 test size: 1.6460, p-value: 0.4391).

Therefore, the model was reduced for all four cases to:

$$\log E(N_i)=\log(s|i)+\beta_0+\beta_1 P_i+\tau_{t(i)}.$$

Finally, in the reduced model, the hypothesis of no PAL effect was tested (null hypothesis: β_1= 0) using LRT and was rejected at the 5% level for cases 1 (all trials), 3 (excluding trials with 210 m PAL spacing), and 4 (excluding trials with 210 m PAL spacing and PALv.2; Table 4). For Case 2 (excluding trials with PALv.2), the PAL effect was not significant (p-value: 0.0741). The estimated mean reduction rates in numbers of bycatch in strings where PALs were deployed varied between 59% and 80% (Table 4).

Table 4: GLMM model results and estimated reduction rate of harbour porpoise bycatch by PAL calculated by profile likelihood for the four modelled cases (representing inclusion/exclusion of trials with 210 m PAL distance and PALv.2, respectively) with number of observations, degrees of freedom (Df), likelihood ratio tests of the hypothesis of no effect of PAL presence in the final reduced model (LRT), p-value, estimated bycatch reduction rate in the final reduced model with 95% confidence intervals calculated from the profile likelihood.

Case	**PAL spacing 210 m**	**PALv.2 included**	**No. observations**	**GLMM model results**			**Estimated bycatch reduction rate**	
				Df	**LRT**	**P-**	**Estimate**	**95% conf. int.**

						value		Min.	Max.
1	yes	yes	2649	1	4.6464	0.0311	0.649	0.087	0.887
2	yes	no	2137	1	3.1891	0.0741	0.593	-0.088	0.871
3	no	yes	2507	1	8.2056	0.0042	0.797	0.373	0.953
4	no	no	1995	1	6.2780	0.0122	0.765	0.255	0.947

The estimates and Hessian-based standard errors for the intercept β_0, the effect of PAL presence β_1, and the logarithm of the standard deviation of the random effect on trips $\log(\sigma_\tau)$ of the final reduced model in all four cases are reported in Table 5.

Table 5: Estimated parameters and Hessian-based standard errors in the final model for the four cases. Parameter β_0 is the intercept, β_1 is the effect of PAL presence, and $\log(\sigma_\tau)$ is the logarithm of the standard deviation of the random effect on trips. Note that confidence intervals for the effect of PAL presence reported elsewhere are based on the profile likelihood.

Case	Parameter	Estimate	Standard error
1	**Intercept (β_0)**	-12.5476	0.9609
	PAL presence (β_1)	-1.0469	0.5213
	Random effect standard deviation ($\log(\sigma_\tau)$)	1.8251	0.2403
2	**Intercept (β_0)**	-12.2934	1.0320
	PAL presence (β_1)	-0.8986	0.5314
	Random effect standard deviation ($\log(\sigma_\tau)$)	1.7612	0.2645
3	**Intercept (β_0)**	-12.9011	1.0325
	PAL presence (β_1)	-1.5939	0.6403
	Random effect standard deviation ($\log(\sigma_\tau)$)	1.9529	0.2459
4	**Intercept (β_0)**	-12.6979	1.1053
	PAL presence (β_1)	-1.4496	0.6501
	Random effect standard deviation ($\log(\sigma_\tau)$)	1.9106	0.2674

4. Discussion

4.1. *PAL mitigates bycatch*

This is the first scientific test of the PAL devices in an operational gillnet fishery and the first scientific test of a technical harbour porpoise bycatch reduction measure in the western Baltic Sea, involving two German and one Danish vessel, each operating in different fishing areas. During the trials, 18 harbour porpoises were taken as bycatch in control strings, i.e. nets without PALs, whereas five were taken as bycatch in strings equipped with PALs in a total of 778 trips. These 23 bycatch observations occurred in a total of 2649 hauled gillnet strings. The GLMM including all observations classified as valid (Case 1) and, with soak time as offset and fishing trips as a random effect, revealed that the deployment of PALs in strings significantly reduces harbour porpoise bycatches by 64.9%.

During some of the trials carried out during a limited period of this study, the pre-set limit of PAL spacing of 200 m was exceeded by 10–13 m, depending on the length of the bridle connecting adjacent net panels. Two bycatch events occurred in PAL strings during these trials. Therefore, we included these results in the models as a separate case to test for any effects. Although some pinger types have been found to work with intervals of more than 400 m between individual pingers (Larsen et al., 2013), a long-term bycatch monitoring study in an operational fishery has found that too few functioning pingers in a string increases bycatch probability compared with a string where all pingers are functional (Palka et al., 2008). A more recent study demonstrated that pinger effect decreases as distance from the pinger increases (Kindt-Larsen et al., 2019). As demonstrated by Culik et al. (2015), received levels of the PAL signal decrease with distance as well as with sea state. Here we estimated PAL range at 5 Bft. as 150–200 m. This compares well with the fishery results: Omitting trips with PAL spacings ≥210 m (cases 3 and 4) from the model increases estimated PAL effectiveness values. In this study, four of the total of five recorded PAL bycatches occurred in strings with PAL spacing ≥195 m and windspeeds of 4–5 Bft. (Table 3). The effect of windspeed and sea state on ambient noise is well known (Richardson et al., 1995). How these environmental conditions possibly influence effectiveness of pingers or PALs, and thus bycatch rates in nets equipped with it, would have to be investigated in more detail. Although it was not possible to verify this statistically, the bycatches observed in this study could indicate that a shorter distance between two PAL devices than the currently prescribed maximum of 200 m could achieve a greater reduction potential. This could infer that a strict adherence to the maximum spacing limit may be important to emphasize to fishers when using PAL or other pinger types in any fishery.

Our test of PAL as a bycatch-mitigation device was undertaken in an operational fishery, where participating fishers were allowed to follow their normal fishing routine as much as possible, provided that the pre-set experimental conditions were not violated. This included the use of different net types with varying mesh sizes and non-standardised setting patterns (e.g. straight, curved, or zigzag). A lower bycatch reduction effect of acoustic mitigation devices has previously been reported (Palka et al., 2008; 50–70% depending on the time, area, and mesh size) for an operational fishery compared with a scientifically controlled test fishery with less variable conditions. It is hardly possible to compare the bycatch reduction rates of trials carried out in other operational fisheries with different gears, fishing grounds, and harbour porpoise populations. However, the mean reduction rates revealed during this study (66–80%) are in the same range as those found in other studies (Larsen and Eigaard, 2014: 67% in flat bottom/stony ground gillnet fishery; wreck fishery, however, 100% reduction; Trippel et al., 1999: 77%; Gearin et al., 2000: 85%–97% varying according to year; Kraus et al., 1997: 92%; Gönener and Bilgin, 2009: 98%).

Because PALv.1 and PALv.2 do not differ in the signal type, but only in their repetition patterns (PALv.1: one signal followed by a 20 seconds pause; PALv.2: 1–3 signals followed by a 4–30 seconds pause), we assume that there is no decrease in bycatch mitigation efficiency from PALv.1 to PALv.2. On the contrary, when modelling with data selection Case 2, excluding PALv.2 trials but including >210 m PAL spacing, the effect of PAL on bycatch rates is no longer significant (p = 0.07). The small number of bycatch events with PALv2, however, did not allow us to test specifically for other differences between the two PAL versions.

4.2. Factors influencing harbour porpoise bycatch during PAL testing

To avoid overfitting caused by the limited dataset, only a limited set of predictors were included in the model. Next to PAL deployment, we included string length and Vessel (representing fishing area and thus spatially different porpoise densities as well as different fishing strategies). An offset was added to normalise the differences in soak time between the strings. String length and the Vessel parameter were not found to significantly influence bycatch probability. We chose the most relevant bycatch parameter for inclusion following the result of the harbour porpoise bycatch study for the western Baltic of Kindt-Larsen et al. (2016). The bycatch probability model of Kindt-Larsen et al. (2016) also includes a measure of harbour porpoise density. These data, however, were derived from high-resolution position data from harbour porpoises tagged with satellite position transmitters and were not available for this study. Therefore, the present result, that fishing area did not influence expected harbour porpoise bycatch, should be treated with caution, because we cannot exclude the possibility that harbour porpoise densities differed considerably, at least between the fishing areas of the Danish and the two German fishers (Benke et al., 2014). However, the low effective sample size could also have masked possible differences in the effect of the different fishing strategies unique to each fishing vessel.

Although string length did not significantly influence expected bycatch in this study, other studies have found that it affects bycatch rates of harbour porpoises (Orphanides, 2009; Northridge et al., 2016). It should be noted that, in our tests, it was not possible to feed the true string length into the model because, from GPS data, we derived only the distance between start- and endpoint of each string. A relationship of string length with porpoise bycatch, therefore, could have been masked by both the small number of bycatches and constraints in data recording: Some of the strings were, in fact, not set straight and so were longer than the distance derived from GPS positions of setting start- and endpoints. This is indicated by the short minimum string lengths recorded for all three vessels (cf. Table 2) and the large variance. In fact, one of the fishers was sometimes observed setting strings in curves or even in curls and would backtrack and set the string back over itself. Therefore, the validity of the model concerning string length is reduced.

Mesh size could not be included in the model to avoid overfitting and because mesh size varied greatly across the vessels. Some mesh sizes were used only by a specific vessel. Therefore, mesh size was partly also accounted for by the Vessel model parameter, which was dropped from the final model. Bycatches occurred over the whole size spectrum of mesh sizes used: from the smallest (110 mm) to the largest (240 mm; Table 3); therefore, no clear pattern was discernible. Other studies, however, found that bycatch probability increased with larger mesh size, although it covered a larger range of 76–356 mm (Palka et al., 2008; see also Northridge et al., 2016). Ideally, future studies of harbour porpoise bycatch, with more bycatch observations, should also account for this, as well as other net characteristics and string length. Weather data were also not included in the model because of low bycatch rates, to avoid overfitting and because the weather parameters observed during soak times were within a narrow range. It seems plausible, however, that PAL effectivity (and the effectivity of other acoustic bycatch mitigation devices) could be influenced by noise from wind, waves, and other environmental sources (as proposed by Kindt-Larsen et al., 2019). Inclusion of environmental noise information in future acoustic bycatch mitigation studies could assure a more realistic appraisal of the tested device's effectivity.

Gillnet strings with defective pingers have previously been found to result in greater bycatch than strings where all pingers function correctly (Carretta and Barlow, 2011; Palka et al., 2008). Because pinger failure can never be completely avoided in a commercial fishery, we included in the analysis strings where individual PALs had failed during soak time (2.8% of all observations), because we could not disregard the possibility that failures might have led to an increased bycatch rate. After each haul, the fishers or the observer, if present, had to check each PAL to confirm its function or to replace it. Therefore, it was not possible to follow a double-blind test design using, for instance, dummy pingers (Kraus et al., 1997; Larsen and Eigaard, 2014). But because the fishers could not intentionally select areas with higher or lower porpoise densities and bycatch probability, and were required to set the control and PAL strings in the same area, this should not have biased the results (Trippel et al., 1999).

4.3. Observer coverage

Tests of marine mammal bycatch reduction devices are often conducted with 100% observer coverage (e.g. Gönener and Bilgin, 2009; Larsen and Eigaard, 2014). During the extensive pinger experiment of Larsen and Eigaard (2014), a bycatch of 24 North Sea harbour porpoises was recorded in only 168 days at sea, and Gönener and Bilgin (2009) observed 92 harbour porpoises taken as bycatch in their pinger experiment during 107 days at sea. In our validated dataset, 23 bycatch events (Fig. 2) were recorded during a total of 778 trips, demonstrating the much lower bycatch rates observed in our study area and fisheries. From the beginning of this project, we were aware that neither financial nor human resources would be sufficient to ensure 100% observer coverage. From all 23 valid bycatches, 10 were self-reported and 13 were reported by REM or observer (Table 3).

4.4. PAL influence on target catch

None of the fishers reported a decrease in catch in target species when fishing with PALs (pers. comm. to observers and anonymous summary at the end of the trials). This indicates that the PALs do not influence the catchability of the target species during the trials. This is supported by more than 100 fishers deploying more than 2500 PALs in the western Baltic gillnet fishery of Schleswig Holstein since November 2017 (Till Holsten, Ostsee-Infocenter Eckernförde, pers. comm.). Cod do not react to high-intensity ultrasound with 50 kHz peak frequency (Schack et al., 2008), which is lower than the lower spectral bandwidth limit of the PAL with its low-intensity harmonics down to 60 kHz.

4.5. Long-term PAL use and possible habituation

Prior pinger sound exposure studies indicate harbour porpoise habituation (Cox et al., 2001; Culik et al., 2001; Carlström et al., 2009; Kyhn et al., 2015). The long-term bycatch study of Palka et al. (2008), however, did not find any indication of this in commercial fisheries, but their fishing vessels used various pinger types, which were pooled in the analysis. This could have masked habituation for at least some pinger types. A recent study by Kindt-Larsen et al. (2019) found that habituation appears to occur with pingers that emit only one signal type with a fixed repetition rate, not with pingers with randomised signals and repetition rates. The PALv.1 used in this study emits one F3 signal with a set pause between each signal of approximately 20 sec. In comparison, PALv.2 was programmed to a variable signal repetition rate and pause duration. A comparison of PALv.1. and PALv.2 sound exposure studies of wild Belt Sea harbour porpoises using the experimental setup proposed by Kindt-Larsen et al. (2019) would allow the investigation of this with respect to a synthetic communication signal.

4.6. PAL deployment in other regions

Unclear results have been achieved so far during short-term tests of PAL in a commercial fishery in the Danish North Sea (2015 and 2016, own unpublished data) and around Iceland (ICES, 2018). In both cases, no differences in bycatch rates compared with control nets could be observed using the specific synthetic porpoise alerting signal emitted by the PALs, which was derived from the vocalisations of the Belt Sea harbour porpoise population (Clausen et al., 2010). Because different populations have different echolocation properties (Kyhn et al., 2013), it is possible that their communication signals also differ. Dialects in dolphinids, especially orcas (*Orcinus orca*) have been studied over decades (Ford, 1987) and have revealed increasing differences between pods, clans, and ecotypes. For instance, both high- and low-frequency components of North Pacific transient killer whale calls have significantly lower frequencies than those of the North Pacific resident and North Atlantic populations (Filatova, 2015). However, to our knowledge, possible differences in dialects have not been studied in harbour porpoises. If porpoise communication differed between populations as in dolphinids, bycatch reduction rates reported in this study using signal F3 could not be extrapolated to other regions or populations. Therefore, the signal type is the focus of other studies: Purpose-built PAL signals are currently being tested in commercial fisheries in Iceland and Bulgaria (by B. Culik), and research to reduce bycatch in these and other fisheries continues.

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6. Conflict of interest

Boris Culik (BC) developed and markets the PAL and holds a patent on the device (German Patent No. DE 10 2011 109 955, 2013). However, BC is not affiliated with the other institutions authoring this study, nor did he have any influence in conducting the fishery trials, recording the fishery or bycatch data, or analysing it. The other authors are not affiliated with BC or his companies F^3 and F3MT (Ltd) and declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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