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Artificial clicks (Porpoise ALert) affect acoustic monitoring of harbour porpoises and their echolocation behaviour

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Introduction: In 2021, a continuous acoustic monitoring programme was initiated in the Baltic Sea of Schleswig-Holstein to determine the occurrence and seasonal distribution of harbour porpoises. At the same time, fishers in this area applied acoustic devices (Porpoise ALert, PAL) generating artificial porpoise clicks to reduce bycatches in set-net fisheries. The underlying hypothesis was that signals from porpoise acoustic warning devices (PALs) might be misinterpreted by the click loggers (C-POD) as genuine porpoise clicks, potentially leading to an increase in detections. The study aimed to determine whether PALs were being recorded at the monitoring stations, and to identify effective methods for filtering out artificial signals.

Methods: Therefore, we deployed an array of 11 C-PODs at distances between 50 and 350 m to a duty-cycled PAL in the middle over a period of 3 months. A sophisticated machine learning approach was employed that was able to discriminate natural porpoise signals from artificial PAL signals using the full click sequence parameters.

Results: The trained algorithm showed remarkable efficiency in discriminating between artificial PAL signals and natural harbour porpoise clicks, demonstrating good sensitivity (99.74%) and accuracy (97.12%) in the test dataset.

Discussion: The consequences for compromised monitoring are significant, particularly in regions with low harbour porpoise densities, where artificial signals may influence the interpretation of diurnal and seasonal aspects of natural harbour porpoise behaviour, leading to misinterpretations. The effectiveness of management measures depends on the availability of reliable monitoring data, which is essential given the urgent need to improve the conservation of harbour porpoises, which are declining in the western Baltic Sea within the waters of Schleswig-Holstein. Finally, the study design was maximised to provide further information on PAL functionality and effectiveness as warning devices. The results revealed a reduction in the number of porpoise clicks during PAL operation, and changes in echolocation

patterns characterised by increased minimum Inter-click-intervals (ICI), suggesting a shift from foraging or communication to orientation activity, and decreased maximum ICI, indicating enhanced long-range orientation. The function of these devices on echolocation behaviour remains therefore unclear, as it is not known whether they act solely as an alarm or rather as a deterrent.

KEYWORDS

acoustic warning device, Schleswig-Holstein Baltic Sea, C-POD, passive acoustic monitoring, harbour porpoise (*Phocoena phocoena*)

Introduction

In the coastal waters of the German Baltic Sea, the ‘western Belt Sea porpoise population’ (*Phocoena phocoena*) is estimated to 14,403 animals (assumed range: 9,555–21,769) (Owen et al., 2024). Legislation such as the Agreement on the Conservation of Small Cetaceans of the Baltic and North Sea (ASCOBANS) and the Helsinki Commission (HELCOM) have been implemented in an effort to protect harbour porpoises within the European region. The EU directives NATURA 2000 and the Marine Strategy Framework Directive (MSFD) have also been put in place with the aim of ensuring the good status, management, and conservation of harbour porpoise populations in European waters. The Habitats Directive (92/43/EEC) is a key legislative instrument in this regard, with its Annexes II and IV listing harbour porpoises as species to be protected. The Directive requires EU Member States to implement monitoring programmes to assess the conservation status of these species, and in this context, C-PODs (Cetacean Porpoise Detectors) were deployed at four sites (Holnis, Bredgrund, Schleisand and Damp) in March 2021 as part of a long-term monitoring programme to detect the presence of harbour porpoises.

In the Baltic Sea, harbour porpoises are particularly vulnerable to fishing, with gillnets being extensively utilised in small-scale fisheries. This poses a substantial conservation threat to marine mammals that are incidentally captured (Brownell et al., 2019; Gilman, 2015; Northridge et al., 2016; Reeves et al., 2013; Kindt-Larsen et al., 2023). Proposed mitigation measures include the use of acoustic deterrent devices (ADDs), attached to set-nets (Gearin et al., 2000; Gönener and Bilgin, 2009; Larsen and Eigaard, 2014). The efficacy of ADDs in reducing bycatch of small cetacean species has been demonstrated (reviewed in Dawson et al., 2013). However, concerns have been raised that ADDs may lose effectiveness due to habituation to the deterrent sound (Carlström et al., 2009; Dawson et al., 2013; Gearin et al., 2000; Kyhn et al., 2015; Kindt-Larsen et al., 2019), their deterrent effect might exclude marine mammals from potentially large and important ensonified habitats (Carlström, 2002; Culik et al., 2001; Beest et al., 2017; Kyhn et al., 2015), and devices like pingers may reduce porpoise echolocation rates, thereby impairing their ability to detect acoustically unmarked gillnets in

the vicinity (Carlström et al., 2009; Chladek et al., 2020; Culik et al., 2015). In order to address the aforementioned concerns, F3: Forschung in Germany developed the Porpoise ALert (PAL), a robust, individually programmable sound emitting device for deployment in fisheries that synthesises the natural aversive communication signals of harbour porpoises (Chladek et al., 2020; Culik et al., 2015; DPMA Patent No. 10 2011 109 955). By mimicking biologically significant sounds, this device is expected to minimize the risk of habituation (Culik et al., 2015). Furthermore, unlike conventional ADDs, PAL is designed to raise porpoise awareness by increasing their echolocation activity rather than deterring them, thereby reducing the risk of collision or entanglement without displacing them from fishing grounds (Chladek et al., 2020; Culik et al., 2015).

The initial results from Porpoise Alerts (PALs), which emit porpoise clicks, demonstrated that porpoises increased their echolocation activity by 10%, thereby enabling early detection of gillnets, resulting in a 70% reduction in bycatch (Chladek et al., 2020; Culik et al., 2015). As a result, the Baltic Sea Information Centre in Eckernförde has provided 1,680 PAL devices to fishers in Schleswig-Holstein since spring 2017 without systematic monitoring of application effort (ICES, 2019). However, concerns have been raised that the outcomes of a C-POD monitoring programme may be inaccurate due to the C-POD software misidentifying signals from the PAL as authentic porpoise clicks (Culik et al., 2015), thereby overestimating the porpoise presence and activity.

To assess how PAL-generated signals may affect C-POD porpoise detection accuracy, and thus bias acoustic monitoring results, a specialized detector capable of distinguishing PAL emissions from biological clicks is needed. This detector would filter out PAL signals, enabling reliable estimates of true harbour porpoise presence. In the present study, an array of 11 C-PODs at distances between 50 and 350 m to a duty-cycled PAL in the middle over a period of 3 months was deployed to record PAL signals from varying distances and meteorological conditions in an area with natural harbour porpoise occurrence. These recordings aimed at two objectives: 1) to ascertain whether PAL signals were being recorded at the monitoring stations and misinterpreted as porpoise

clicks, and 2) to establish a database for the subsequent development of a filter to determine the proportion of real porpoise detections. Furthermore, the investigation sought to provide effective methods for filtering out the artificial PAL signals. Finally, the study sheds light on the functionality of the PAL on harbour porpoise behaviour, as the efficacy of PALs is yet to be fully elucidated, as demonstrated by trials in the North Sea and Iceland, which have shown an increase in porpoise by-catch (ICES, 2019; Read, 2021).

Materials and methods

Data collection

The experiments were conducted in the coastal waters of Bredgrund, east of Geltinger Birk (54°47.14' N 09°57.93' E), in the Baltic Sea. The Bredgrund monitoring station is located in the coastal area of the Baltic Sea, in water depths of 10–15 m, and the area has a tidal range of around 0.2 m. This site is part of the continuous static acoustic monitoring of harbour porpoises in

the Baltic Sea of Schleswig-Holstein between Flensburg Fjord and Eckernförde Bay, which was initiated in 2021. This station was selected because it had the highest number of harbour porpoise detections compared to the other monitoring stations (Baltzer et al., 2024). An analysis of the daily rhythm shows that the harbour porpoises at the Bredgrund station are most frequently detected during the night-time hours or in the early morning in the winter and spring months. However, a shift in activity patterns can be observed in the summer months, with porpoise detections remaining constant throughout the day (Baltzer et al., 2024).

The experiment was conducted over a period of 93 days, from 7th July to 8th October 2023. A triangular array with 11 C-PODs was deployed to record harbour porpoise echolocation activity. The click loggers were deployed at a depth of 10–15 metres and each positioned 2 metres above the seabed (Figure 1). A modified PAL pinger, operating in cycles of 24 hours on and 26 hours off, was deployed at the centre of the array in conjunction with a C-POD also 2 m above the seabed in a vertical position attached to a rope. When active, the PAL was programmed to emit the same signals and randomized patterns of one to three signals, each followed by randomly selected pauses ranging from 4 to 30 seconds, as

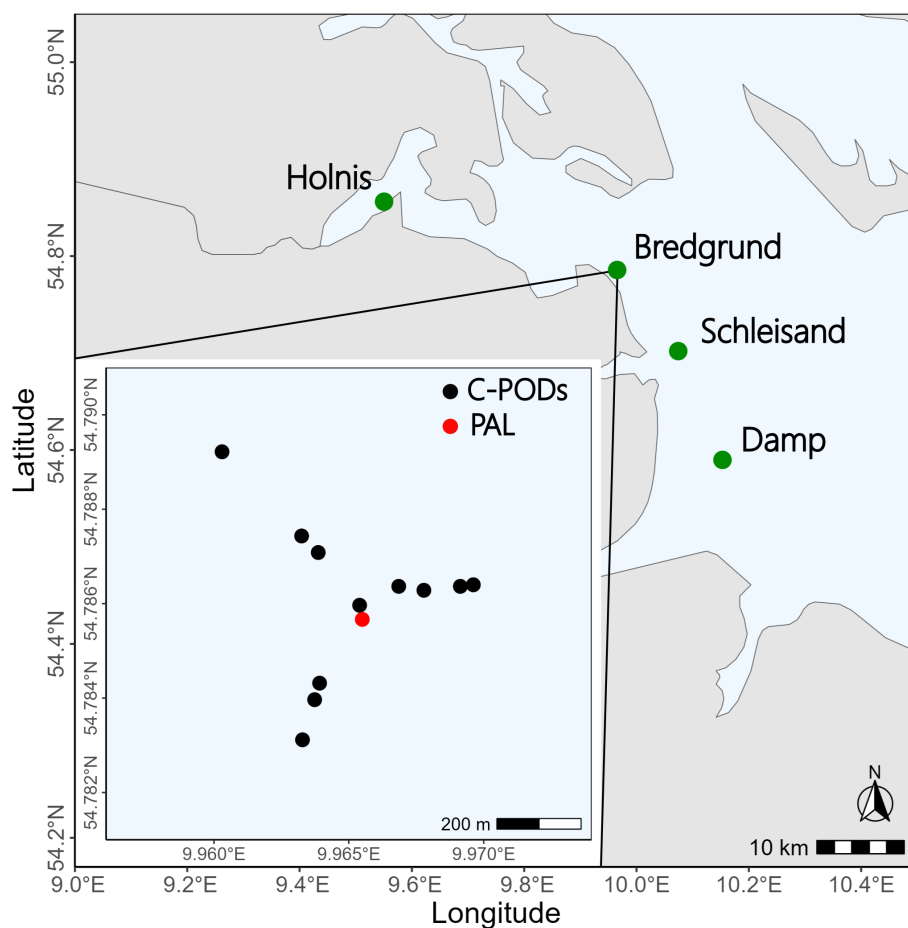


FIGURE 1

Map of the study site. Locations of the C-POD monitoring stations in the coastal area of the Baltic Sea of Schleswig-Holstein are shown as green dots on the map. The bottom-left figure represents a close-up of the Bredgrund experimental array, where stationary C-PODs (black dots) were deployed around a central PAL device (red dot).

described by Chladek et al. (2020). The signals consist of two upswEEP chirps starting with 173 and ending with 959 clicks per second over a duration of 1.22 s. Clicks have a centroid frequency of 133 kHz (± 8.5 kHz) and a mean source level (peak-to-peak) of 147 dB re 1 μ Pa (± 5 dB) (Chladek et al., 2020). The timing of the cycle was set to initiate the PAL at varying times throughout the day, thereby aiming to mitigate the impact of diurnal variations in porpoise echolocation activity (Linnenschmidt et al., 2013). The 11 C-PODs were deployed at distances of 50, 150, 250, and 350 m to the PAL (Figure 1).

Porpoise click classification

The echolocation clicks recorded on the C-PODs were classified as being of porpoise origin by KERNO classifier, which is part of the post-processing software (C-POD.exe V2.048, Chelonia Ltd.). This software automatically detects and classifies porpoise clicks in the raw click data (cp1 file) by use of a proprietary detection algorithm. The clicks in trains were classified into quality classes of high and moderate-probability cetacean trains stored in cp3 files. The indicators of porpoise presence were derived from clicks in trains from these two classes containing more than five clicks and within the frequency spectrum of 125–145 kHz. The automated identification of PAL signals in the C-POD data facilitated the subsequent identification of the PAL cycles. Initially, multiple ‘click trains’ of synthetic PAL signals, characterised by their repetitive pattern, constant frequency, and duration, were manually identified and marked on each cp3 file. These were then exported as text files containing full train details. Concurrently, numerous ‘click trains’ of porpoises were marked and exported, thereby generating a dataset of 4249 characterised trains of both porpoise (15.03%) and PAL (84.97%) clicks. This dataset was then utilised to train machine learning (ML) algorithms that predict and classify the trains between porpoise and PAL origin.

Machine learning approaches

A total of 27 variables were selected to be included into the models. The factor variables were transformed to numeric by using on-hot encoding i.e. transforming each level of the variable into its own binary variable. The response variable was coded as “porp” for the natural porpoise trains and “pal” for the PAL signals, with the porpoise being the positive category. We then used this data to train an ensemble of three classifiers: Gradient Boosting machine with trees as base classifier (GBM), Random forest (RF) and Boosted logistic regression (BLR). This simultaneous multi-approach was chosen to increase accuracy through improved specificity and sensitivity, which is essential for the application as a PAL filter. These models were chosen due to their known performance and ease of training and hyperparameter tuning. The hyperparameters of the models were tuned using grid search, in which a set of predetermined combinations of parameters is used to train candidate models from which the best ones are selected.

The three selected models have different hyperparameters that are summarized in the following table alongside the selected optimal values.

Due to the imbalanced nature of our data (with higher presence of “pal” than “porp”), we weighted the observations by the inverse of their frequency, in essence this forces the models to focus on making correct predictions of natural porpoise clicks. We used repeated N-fold cross validation with 10 folds to validate the candidate models. N-fold cross-validation splits the data into N subsets, trains the model N times, each time using N-1 folds for training and 1-fold for validation, rotating the validation fold in each iteration. This allowed us to decrease the chances of overfitting and uses the whole training set. Furthermore, we set the models to return raw probabilities for both “porp” and “pal” and used the ROC curves to determine the best threshold of probability for each model using the Youden method (Table 1).

The final predictions of the models are obtained as an ensemble of majority voting (an observation is only classified as “porp” if at least two of the tree models agree on the prediction). Ensemble models combine multiple individual models to improve overall prediction accuracy by reducing bias and variance, leveraging the strengths of the different algorithms included in the ensemble.

The ensemble performance was finally tested on a test dataset that contained 11,820 observations, with roughly equal proportions of manually defined “pal” (55.39%) and “porp” (44.61%). All the data processing and modelling was carried out in R version 4.4.0 (R Core Team, 2024) using the *caret* package (Kuhn, 2008; Kuhn et al., 2020).

The model and prediction scripts are available at https://github.com/biofelip/PAL_porpoise_classifier_scripts. This tool consists of a set of R scripts and custom functions developed to streamline the automatic classification of data coming from C-PODs as well as additional information on training and testing new models.

Application example

As part of our validation process, we evaluated the filter’s performance using two carefully selected datasets representing

TABLE 1 Hyperparameters selected for the different ML models.

Model	Hyperparameters		Threshold for “porp”
Gradient Boosting Machine	Interaction depth	1	0.429
	number of trees	500	
	shrinkage	0.1	
	Minimal number of observations in a node	50	
Random forest	Number of variables randomly chosen for each tree	9	0.273
Boosted logistic regression	Number of boosting iterations	101	0.158

different environmental conditions. The first dataset consisted of recordings from a static acoustic monitoring station in the North Sea (Zein et al., 2019) where PALs are not applied. This dataset provided a baseline to assess the filter's false positive rate, i.e., how often it might incorrectly retain PAL-like signals in an environment free of such devices. The second dataset was collected at a monitoring station in the Baltic Sea where PALs were not intentionally deployed, but where their sporadic presence was expected due to operational use in nearby set-net fisheries. These more complex acoustic conditions allowed us to assess the filter's ability to distinguish between genuine porpoise clicks and PAL emissions in realistic scenarios where both signal types co-occur, thus demonstrating its practical application in monitoring situations.

Effect of weather and time of day

Sums of porpoise and PAL-generated synthetic porpoise communication signals were computed to investigate the effect of environmental factors such as weather and time of day, hourly. Weather data pertaining to the study location was obtained from the OpenWeather API for a weather recall service during the period of the experiments. This comprised hourly data on temperature, precipitation, wind speed, cloud cover and wind direction. Additionally, data from the E.U. Copernicus Marine Service Information, specifically the BALTICSEA_MULTIYEAR_WAV_003_015 (DOI: <https://doi.org/10.48670/moi-00014>), was extracted. This dataset contained hourly information regarding wave height, wave direction, and wave period. However, the employment of the Poisson-Regression method was precluded due to the presence of overdispersion. Consequently, Negative Binomial Regressions were utilised to analyse the effect of these environmental variables on the hourly sum of recorded PAL-generated synthetic porpoise communication signals when the PAL device was operational, and the hourly sum of recorded porpoise clicks when the PAL device was not in use, respectively.

Kernel density estimates

Spatial distribution of the recorded porpoise and PAL-generated synthetic porpoise communication signals at the 10 recording stations were visualised using kernel density surface estimates of the sum of recorded clicks per minute. These density surfaces were generated using the *spatstat* R package, applying a smoothing bandwidth of 25 without edge corrections and weighting each data point by the number of clicks recorded per minute.

Effect on click behaviour

In order to evaluate the effects of PAL signals on porpoise echolocation behaviour, the dataset was filtered for porpoise clicks that were recorded within a minute with PAL clicks for each station. This enabled the analysis of recorded porpoise click characteristics

by the C-POD in relation to the relative PAL performance, which is summarised here by the number of PAL-generated synthetic porpoise communication signals within the same minute. The finalised dataset comprised 3,106 minutes of data, collected during periods when the PAL device was on and both natural and artificial clicks were recorded. The response variable comprised the number of recorded porpoise clicks per minute, the duration, the modal kHz, the MaxICI and the MinICI. The tensor product of the variable "Number of recorded PAL clicks per minute" was used as a primary explanatory variable. The `gam()` function of the R package *mgcv* (Wood and Wood, 2015) was utilised.

Ethics

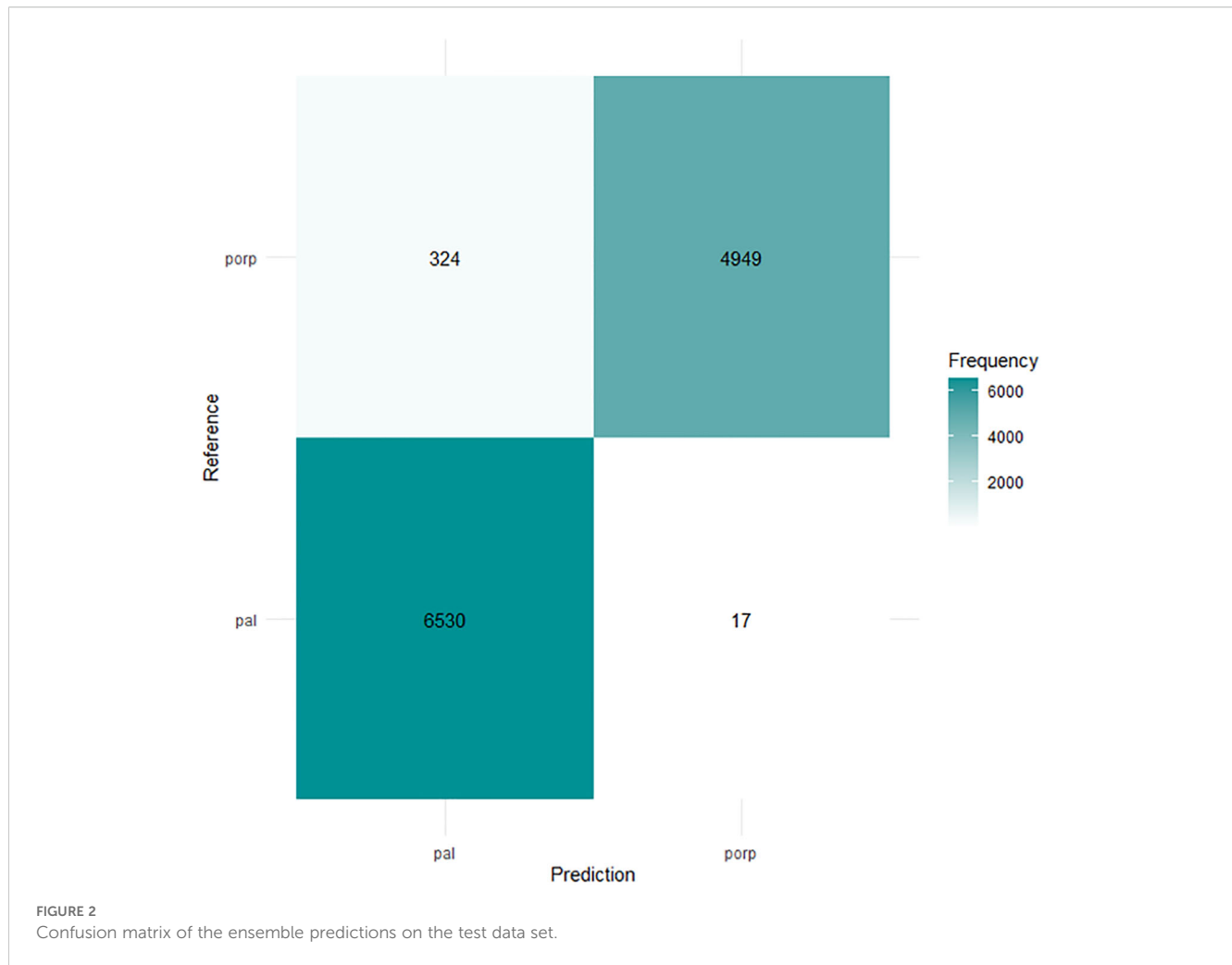
The deployment of the measuring stations was approved and signalled in accordance with the requirements of the Federal Waterways and Shipping Administration (shipping buoy ODAS 69-74, Strom- und schiffahrtspolizeilichen Genehmigung, Nr. OKSB/93), with the purpose of ensuring safe and smooth maritime shipping traffic along the German coast. Given the potential impact of the playback experiments on a variety of species, a project-specific permit was requested from the Ministry for Energy, Climate and Agriculture of the Schleswig-Holstein state of Germany (V 242 - 15552/2021 (25-4/21)). The approval document guarantees that the requirements of § 8 (1) of the German Animal Welfare Act (TierSchG) have been met. In particular, it has been sufficiently demonstrated that the project is essential and ethically justifiable, that compliance with the legal provisions, in particular with the Animal Welfare Act and the Ordinance on Experimental Animals, can be expected and has been ensured by the animal welfare officer.

Results

As one of the measuring devices furthest away from the PAL device failed, the analysis was limited to a total of 10 C-POD stations. The experiment resulted in a total of 93 days of recording, corresponding to 45 on and 45 off cycles of the PAL. The KERN classifier was used to detect a total of 551,192 uncensored click trains. This ensured that no logging time was lost due to minutes reaching their limit.

Performance of the ML approach

As illustrated in Figure 2, the confusion matrix of the test dataset, which comprised 11,820 observations, exhibited approximately equal proportions of manually defined "pal" (55.39%) and "porp" (44.61%) by the ensemble. The ensemble showed an overall accuracy of 97.12% in the test set, with a high capacity of correctly identifying porpoise calls (sensitivity = 99.74%). Likewise a specificity of 93.86% showed a high, albeit lower capacity of the model to identify PALs. The positive and negative predictive value of 95.27% and 99.66%, respectively



indicates that the number of false positives (calls identified as porpoises when they are actually PALs) and false negatives (calls identified as PALs when they are actually porpoises) is very low. In general, the model showed excellent performance in the test dataset.

Recordings of PALs and porpoises

The majority of these trains (327,038) were classified as PALs, with the remaining 224,154 classified as natural porpoise trains. The time-series of the data are illustrated in Figure 3, where data have been aggregated by on/off cycles as a sum of recorded clicks per hour over all recording stations during the experiment for the recorded PAL clicks and porpoise clicks, respectively. The top panel of Figure 3 illustrates that PAL clicks were recorded exclusively during PAL device operation, with a negligible number of PAL clicks occurring during device off periods, except during cycles 16 and 36. It is noteworthy that these particular cycles exhibited a markedly elevated rate of PAL click recordings, despite the device being switched off under normal circumstances. A visual inspection of the data on the C-POD.exe software indicated that a fisher gillnet, operating PALs, was likely in proximity to the recording stations.

The lower panel provides a relative abundance of porpoise clicks throughout the experiment. It is evident that during the initial twenty days, porpoise activity levels were minimal, and that in the second quarter of the experiment, particularly between cycles 25 and 50, a significantly higher ratio of porpoise clicks was recorded. A further notable observation is that a greater number of porpoise clicks (63%) were recorded when the PAL device was deactivated, as opposed to only 37% when the PAL was operational. This difference was confirmed by a paired Wilcoxon signed-rank test, which indicated higher click rates during PAL-OFF than PAL-ON ($V = 684$, $p = 0.030$, one-sided).

Impact of environmental variables

The number of recorded PAL clicks diminished over the course of the experiment, while porpoise activity exhibited fluctuations. This observation prompted further investigation into the potential for a direct association with environmental variables (Table 2). Subsequent analysis revealed that fewer porpoises were detected during high and short wave periods. Conversely, more porpoises were observed in the evening and overnight. In contrast, no such

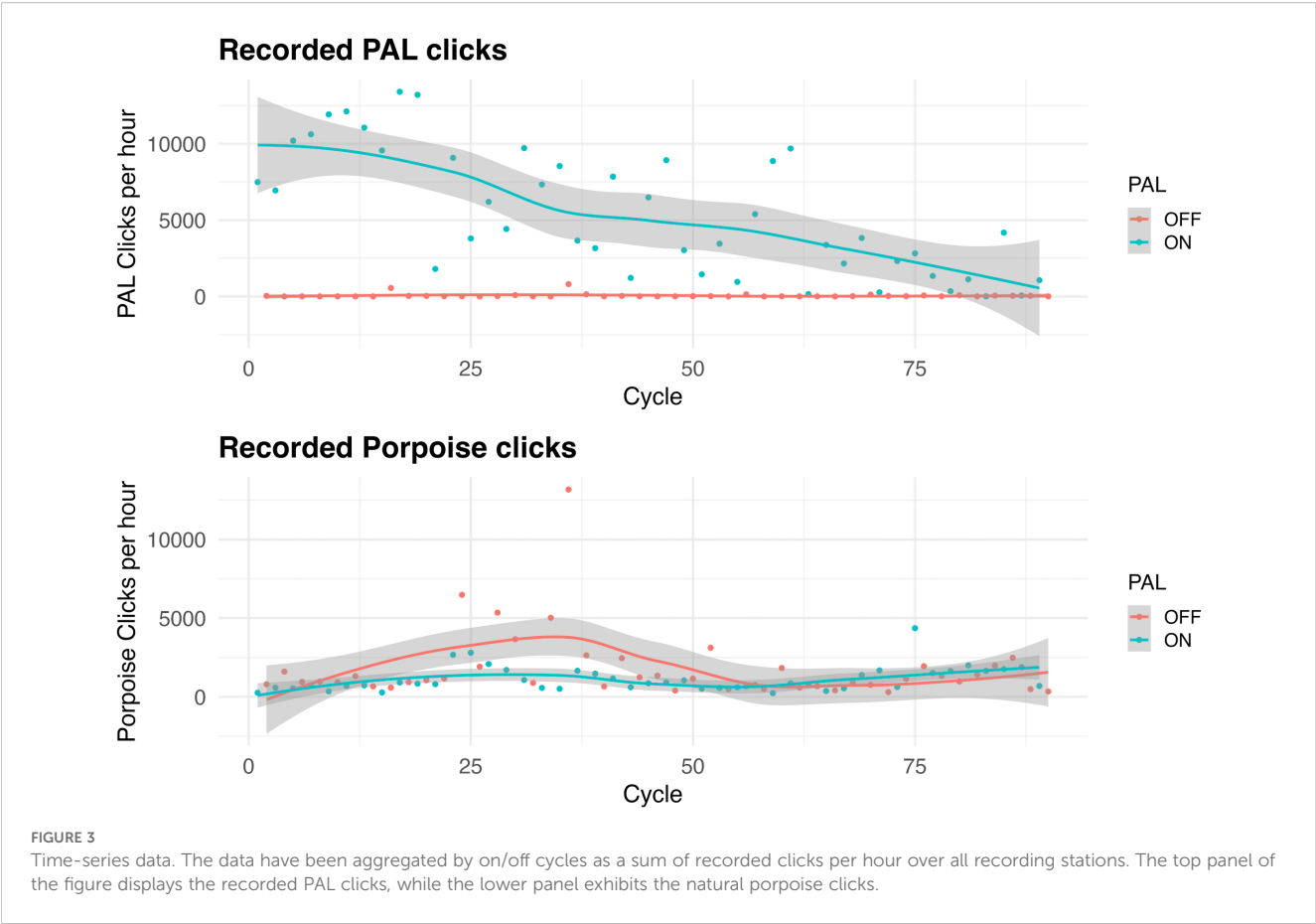


TABLE 2 The results from the Negative Binomial Regression Models reveal an association between click rates per hour and hourly environmental variables.

	PAL Clicks					Porpoise clicks				
	Estimate	Std. Error	z value	Pr(> z)		Estimate	Std. Error	z value	Pr(> z)	
(Intercept)	8,423	0,233	36,2	2,00E-16	***	6,419	0,347	18,5	2,00E-16	***
hourly windspeed	0,030	0,009	3,3	0,001	***	-0,019	0,012	-1,6	0,119	
hourly wind direction	-0,001	0,001	-1,5	0,142		0,001	0,001	1,5	0,133	
hourly precipitation	0,056	0,051	1,1	0,270		0,024	0,129	0,2	0,850	
wave height	-0,466	0,591	-0,8	0,430		-2,647	0,837	-3,2	0,002	**
wave period	0,123	0,211	0,6	0,561		0,912	0,304	3,0	0,003	**
time of day morning	-0,179	0,140	-1,3	0,200		-0,137	0,200	-0,7	0,493	
time of day afternoon	-0,054	0,125	-0,4	0,664		0,086	0,174	0,5	0,622	
time of day evening	-0,030	0,132	-0,2	0,819		0,608	0,180	3,4	0,001	***
time of day night	-0,041	0,115	-0,4	0,725		1,034	0,161	6,4	1,43E-10	***

The dataset under consideration contains a total of 323,045 PAL click trains that occurred during instances when the PAL was switched off, and 137,918 porpoise click trains that occurred during instances when the PAL was switched on.
Significance codes: ** $p < 0.01$; *** $p < 0.001$.
Left block: PAL clicks (negative-binomial GLM); Right block: Porpoise clicks (negative-binomial GLM).
Sub-columns remain: Estimate; Std. Error; z value; $\text{Pr}(>|z|)$.

natural association was observed for the artificial porpoise communication signals generated by the PAL system. The analysis revealed no effect on time of day or wave period, but a modest positive influence on wind speed. This suggests that the observed reduction in PAL click recordings may be attributable to factors other than environmental variables, such as battery discharge or biofouling on the PAL device and/or the C-POD recording devices (Heupel et al., 2008; Delgado et al., 2021; Muhammad et al., 2025; Polagye et al., 2020).

Application to monitoring datasets

Finally, the classifier was applied to a 3-months monitoring dataset from the North Sea, where no PALs have been deployed to date, and to continuous monitoring datasets from the Baltic Sea, where a PAL gillnet is regularly observed in the vicinity. As anticipated, a mere three potential PAL positive hours were detected in the North Sea, with only one to four PAL trains being detected, which can be considered as negligible. The situation was somewhat different for the Baltic stations, with no PAL-positive hours detected on one day at Damp station, PAL-positive hours detected on one day at Schleisand station, PAL-positive hours detected on three days at Holnis station and PAL-positive hours detected on 34 days at Bredgrund station. This finding

indicates that the efficacy of continuous C-POD monitoring in the Baltic Sea can be compromised by the presence of artificial PAL signals, which may be erroneously interpreted as porpoise clicks.

Effect of PAL on porpoises' echolocation signals and behaviour

In order to assess the effect of PAL signals on porpoise behaviour, it was first necessary to ascertain the detection range. The likelihood to record PAL signals could not be explained by distance solely. Consequently, the kernel density approach was employed to visualise the spatial coverage of the PAL signal (Figure 4). The PALs exhibited a certain degree of directionality. The southern stations recorded a higher number of PAL clicks than the northern stations (Figure 4B).

A reduction in porpoise clicks was also evident on the Kernel Density Estimates plots, a finding that was subsequently confirmed by the violin plot (Figure 5A). In order to evaluate the effects of PAL signals on porpoise click behaviour, we analysed only the natural porpoise clicks that were recorded at a station simultaneously with PAL-generated synthetic porpoise communication signals at the same station. This facilitated the analysis of recorded porpoise click characteristics by the C-POD in relation to the number of PAL-generated synthetic porpoise communication signals within the

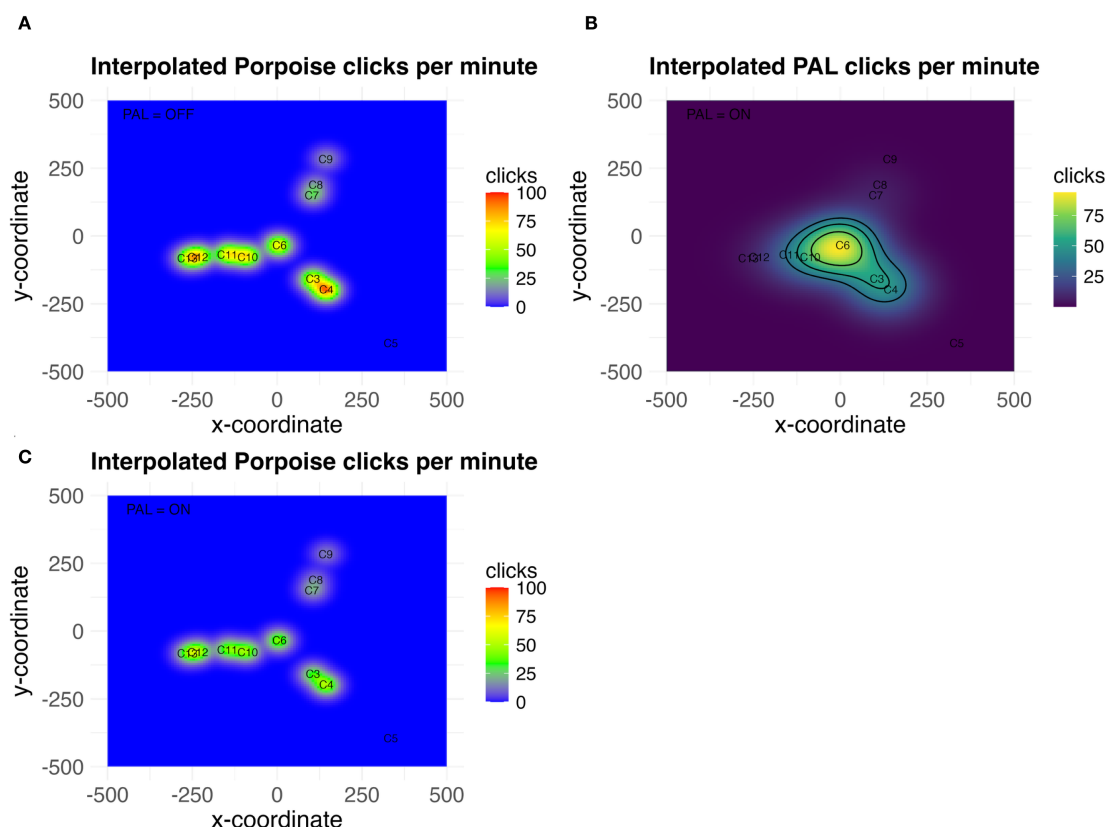


FIGURE 4

2D kernel density plot of clicks per minute recorded at each recording station. (A) shows porpoise clicks recorded when PAL was OFF, (B) shows PAL clicks recorded when PAL was ON, and (C) shows porpoise clicks recorded when PAL was ON.

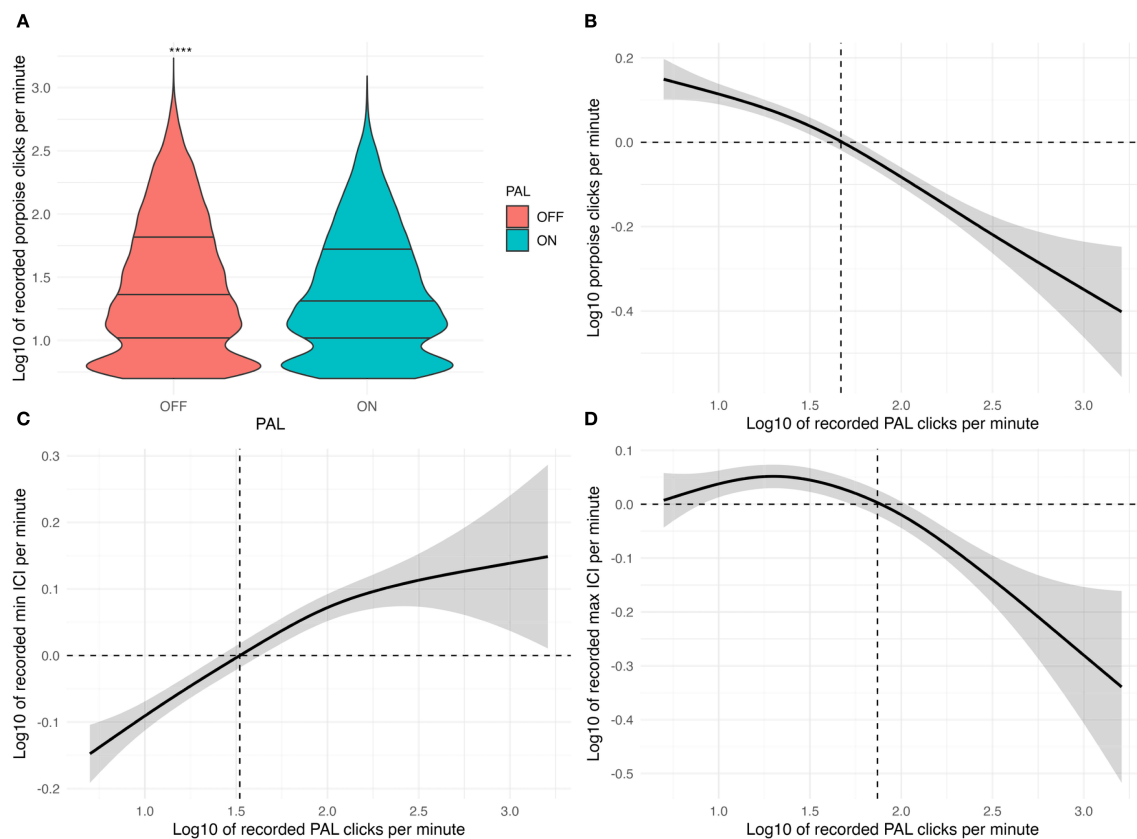


FIGURE 5

The effect of PAL signals on porpoise communication and behaviour: (A) shows a Violin plot of recorded porpoise clicks when PAL was on and off. (B–D) show Generalised Additive Model (GAM) plots showing the partial effects of received PAL clicks on selected variables such as porpoise click rate (B), minimum Inter-click-intervals (ICI) (C) and maximum ICI (D).

same minute. The finalised dataset comprised 3,106 minutes of data, and we tested how the number of recorded PAL clicks per minute affects the response variable, which comprised the number of recorded porpoise clicks per minute, the duration, the modal kHz, the MaxICI and the MinICI.

This facilitated the analysis of the effect of PAL power in terms of PAL-generated synthetic porpoise communication signals per minute versus natural porpoise click characteristics. It was observed that PAL signals induce a reduction in porpoise click activity below the average =0 at an onset threshold of 50 PAL-generated synthetic porpoise communication clicks per minute (Figure 5B, $\triangle$ vertical line at $\log_{10}(1.70)$). The PAL signals have been shown to increase the minimum Inter-click-intervals (ICI), which can be interpreted as a cessation of foraging or communication activity and a shift to orientation activity (Bergès et al., 2020; Pirotta et al., 2014a; Pirotta et al., 2014b). It was demonstrated that PAL signals induce an increase in MinICI above the average =0 at an onset threshold of 35 PAL-generated synthetic porpoise communication clicks per minute (Figure 5C, $\triangle$ vertical line at $\log_{10}(1.54)$). Furthermore, it was established that PAL signals increase the maximum ICI, which can be interpreted as long-range orientation activity (Bergès et al., 2020; Pirotta et al., 2014a; Pirotta et al., 2014b; Verfuss et al., 2005). Additionally, it was observed that PAL signals induce a reduction in MaxICI below the average =0 at an onset threshold of 70 PAL-

generated synthetic porpoise communication clicks per minute (Figure 5D, $\triangle$ vertical line at $\log_{10}(1.85)$).

The impact thresholds (corresponding to the thresholds that were previously determined (35, 50 and 70 PAL-generated synthetic porpoise communication clicks per minute)) were delineated as contours in the middle plane of Figure 4B. These contours provide a representation of the impact distances at which the PALs affect harbour porpoise behaviour. It is evident that, given the high directionality exhibited in this experiment, the PAL signals have the capacity to impact porpoises up to distances of several hundred metres.

Discussion

Identification of effective methods for filtering out artificial PAL signals

In 2021, a continuous acoustic monitoring programme of harbour porpoises was initiated in the Schleswig-Holstein Baltic Sea. This initiative was conducted between Flensburg Fjord and Eckernförde Bay, with the primary objective being to ascertain the occurrence and seasonal distribution of harbour porpoises. It was hypothesised that signals from acoustic warning devices (PALs), which were increasingly being used in the study area, might be

erroneously interpreted by the acoustic monitoring device (C-POD) as genuine porpoise clicks, potentially leading to an increase in the number of detections. Consequently, the investigation sought to ascertain whether PAL signals were being recorded at the monitoring stations, with a view to determine the proportion of real porpoise detections they might account for. Furthermore, the investigation sought to provide effective methods for filtering out the artificial signals. Finally, the study design was utilised to the possible extent in order to gain further information on the functionality and effectiveness of the PAL devices.

It is possible to filter out PAL signals by manually checking and removing all data one by one (Culik et al., 2015). However, this approach is both time-consuming and difficult to implement if several stations are analysed over several years. To date, there has been no available filter that can reliably remove only PAL recordings. Conventional filters that are based on different cycle counts and smaller click intervals would also remove ecologically relevant porpoise click sequences, resulting in the loss of interesting click intervals associated with foraging (Verfuß et al., 2007; Nuuttila et al., 2013; Schaffeld et al., 2016). Consequently, a more sophisticated machine learning approach was adopted, capable of distinguishing natural harbour porpoise from artificial PAL clicks through the utilisation of comprehensive harbour porpoise click sequence parameters.

Our extensive, controlled experimental setup enabled the capture of PAL signals from various distances and under diverse environmental conditions, encompassing weather variations and anthropogenic disturbances. The trained algorithm demonstrated remarkable efficiency in differentiating between PAL signals and natural harbour porpoise clicks. The performance of the filter is outstanding, demonstrating good sensitivity and accuracy. The model and prediction scripts are available at https://github.com/biofelip/PAL_porp_classifier_scripts. This tool consists of a set of R scripts and custom functions developed to streamline the automatic classification of data coming from C-PODs as well as additional information on training and testing new models.

The integrity of the C-POD monitoring is compromised

By applying the filter to datasets from other monitoring stations, we confirmed the presence of PAL signals from PAL-equipped fishing nets falsely detected as porpoise clicks by the C-PODs. The extent of this contamination was found to be location-dependent. The analysis of the reference data from the North Sea without PAL application clearly proved the performance of the PAL detector. As expected, hardly any signals were falsely detected in the North Sea. The stations Damp and Schleisand, which are located more to the south of the Baltic Sea, showed only a few PAL signals, while PAL signals were recorded on several days at the Holnis and Bredgrund stations. Besides, we can also notice that the presence of harbour porpoises at these stations is typically high, which is not surprising given that harbour porpoises forage in areas where fishermen deploy their nets, as these areas are known to be abundant in fish (Sveegaard et al., 2012a, b).

The results obtained demonstrate that PAL signals were recorded in variable quantities at the various stations. A comparison of detections with and without PAL signals reveals that they account for only a small proportion of true harbour porpoise click sequences. Even in instances where the proportion of genuine harbour porpoise click sequences is minimal, as observed in this study, the filtering of PAL signals can reveal an overestimation of harbour porpoise clicks in its absence, i.e., without the filtering. This phenomenon assumes particular significance in contexts where PALs are employed in regions characterised by low harbour porpoise density, given their substantial impact on the actual detection of harbour porpoises (Amundin et al., 2022; Teilmann and Carstensen, 2012). Furthermore, these artificial signals have the capacity to influence the interpretation of the diel and seasonal aspects of natural harbour porpoise behaviour (Carlström, 2005; Schaffeld et al., 2016; Zein et al., 2019; Clausen et al., 2021), which can result in misinterpretations. The implementation of effective management measures is contingent upon the availability of reliable monitoring data. These measures are imperative due to the urgent need to enhance the protection of harbour porpoises (Verfuss et al., 2009; Scheidat et al., 2011), which are experiencing a decline in the western Baltic Sea within Schleswig-Holstein's waters (Owen et al., 2024).

The impact of human activities on the habitat of harbour porpoises in the Baltic Sea is a significant concern, with the potential to have a negative effect on porpoise populations (Gallus et al., 2012). The activities responsible for this threat include commercial shipping, recreational tourism, seismic surveys, military activities, fishing, offshore construction, ammunition, chemical and pharmaceutical pollution, and marine litter (Verfuss et al., 2009; Scheidat et al., 2011; Philipp et al., 2021). It is hypothesised that harbour porpoises from the Baltic and North Seas are in poor health due to elevated levels of anthropogenic pressure (Siebert et al., 2006, 2020, 2022). Conversely, harbour porpoises inhabiting Arctic waters, which are currently less exposed to anthropogenic factors, exhibit significantly improved health status. Reproductive capacity and age structure studies have shown that the mean age at death of female harbour porpoises in the Baltic Sea is only 3.67 (± 0.3) years (Kesselring et al., 2017), although harbour porpoises can live for 20–25 years. Furthermore, the attainment of sexual maturity is delayed until an average age of 4.95 (± 0.6) years, which reduces the window for successful reproduction across an individual's lifespan (Kesselring et al., 2017). This prolonged maturation period combined with a high rate of early mortality can therefore have serious demographic consequences, highlighting the need for effective management plans to protect this species (Kesselring et al., 2017).

The four monitoring sites, which cover a substantial area of the Baltic Sea in Schleswig-Holstein, have not previously been subject to continuous acoustic monitoring. They provide information on the occurrence of harbour porpoises in the western Baltic Sea. Seasonal trends have been identified, providing a basis for further understanding of local habitat use by harbour porpoises and the ecological importance of different areas (Schaffeld et al., 2016; Zein

et al., 2019). It is imperative that the monitoring is conducted on an annual basis to ascertain the current status and to assess the possible impacts from anthropogenic activities (e.g. blasting or construction of offshore structures) (Amundin et al., 2022; Teilmann and Carstensen, 2012). The implementation of such measures will facilitate the establishment of significant contributions to the objectives of the Marine Strategy Framework Directive (MSFD). Furthermore, planning for the establishment of strictly protected areas on 12.5% of Schleswig-Holstein's Baltic Sea can also be taken forward.

The effect of the PAL on harbour porpoise behaviour

Prior to an analysis of the functionality of the devices, it is important to highlight the factors that differentiate the conventional use of the devices on a fishing net from their use in the present experiment. In the present experiment, the PAL was attached to a 20 mm-thick polyamide rope, which is larger than the gillnet line to which the devices are usually attached. The orientation of the PAL was vertically, downward on the battery compartment. The devices were subjected to continuous activity for a period of three months, both underwater and within constant activity cycles.

Firstly, a continuous decrease in the number of PAL clicks emitted over time was recorded. This phenomenon could not be attributed to external environmental factors, as these demonstrated no effect on the recorded number of PAL clicks. Consequently, the observed decline in efficiency is hypothesised to be attributable to factors such as battery discharge or the proliferation of algae and other biofilm (Heupel et al., 2008; Delgado et al., 2021; Muhammad et al., 2025; Polagye et al., 2020). Furthermore, the experiment demonstrated a strong directionality of the PAL signal. This is surprising given that other studies found an almost omnidirectional emission along the longitudinal axis (Culik et al., 2015). The source level towards the transducer side is approximately 7% higher than towards the battery compartment, but remains relatively constant laterally (Chladek et al., 2020). It is not possible to provide an explanation for the recordings in our experiment.

While the initial studies utilising PALs demonstrated encouraging results in terms of reducing harbour porpoise bycatch in the western Baltic Sea, similar studies conducted in the Danish North Sea and Iceland did not yield comparable outcomes (ICES, 2019; Read, 2021). In the Danish North Sea and Icelandic waters, employing the same PAL signal as in the trials conducted in the Baltic Sea, the bycatch rate of harbour porpoises in standard nets remained largely unchanged in comparison to nets equipped with PAL (Read, 2021). Consequently, the analysis of the experiment was expanded to include an examination of the harbour porpoises' reactions to the PAL signals. The results revealed a decline in the number of harbour porpoise clicks during the period when the PAL device was operational. This outcome is at odds with the intended function of the device, which was to enhance the echolocation activity of harbour porpoises, thereby facilitating an enhanced perception of potential

hazards such as gillnets, and consequently reducing the probability of bycatch (Chladek et al., 2020; Culik et al., 2015).

The results of the present study demonstrate that, upon initial exposure, porpoises respond by increasing their minimum ICI, which can be interpreted as a cessation of foraging activity, perhaps in favour of increased orientation activity (DeRuiter et al., 2009; Villadsgaard et al., 2007). The observed reduction in porpoise clicks with proximity to the device, and the increase in PAL clicks per minute, indicates a certain avoidance of the vicinity. Additionally, a decline in maximum ICI is discernible, which may signify an adaptation in echolocation strategies (Clausen et al., 2018). However, the observed 40% reduction in recorded harbour porpoise clicks when the PAL is active suggests that the devices are causing harbour porpoise deterrence (Kindt-Larsen et al., 2019). Consequently, the function of these devices remains ambiguous, as it is unclear whether they serve solely as an alerting function or also act as a deterrent to animals, similar to the impact of pingers. However, in the absence of simultaneous visual observations, we cannot exclude the possibility that the reduction in acoustic detections reflects a change in echolocation behaviour—rather than a true absence—highlighting a common limitation of passive acoustic monitoring studies. Combined visual and acoustic observations demonstrate spatial avoidance in response to the PAL (Culik et al., 2015), thus supporting the interpretation of the observed reduction as an actual deterrent effect.

The present study highlights the necessity for further investigation into knowledge gaps, including the sound propagation along the nets, the occurrence of deterrence or behavioural changes, and the potential for these devices to be used in other areas with population-specific warning sounds.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://github.com/biofelip/PAL_porp_classifier_scripts.

Ethics statement

The animal study was approved by Ministry for Energy, Climate and Agriculture of the Schleswig-Holstein state of Germany (V 242 - 15552/2021 (25-4/21)). The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

JS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. LM: Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

JE-C: Data curation, Formal Analysis, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. JB: Formal Analysis, Investigation, Methodology, Software, Validation, Writing – review & editing. TS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. LK-L: Conceptualization, Methodology, Writing – review & editing. US: Conceptualization, Funding acquisition, Project administration, Resources, Writing – review & editing.

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Conflict of interest

The authors declare 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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Supplementary material

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SUPPLEMENTARY FIGURE 1

Visual inspection of the data suggesting the presence of a fishing gillnet equipped with operating PAL devices near the recording stations. Red arrows indicate potential PAL signals detected by C-PODs. The ICI parameter was displayed to facilitate visualization of the characteristic PAL pattern, highlighted by the red circle.

SUPPLEMENTARY FIGURE 2

Visual inspection of the data to distinguish natural porpoise click trains from artificial PALs. Red arrows indicate the characteristic pattern of PAL click trains, while green arrows highlight porpoise click trains. (A) The SPL parameter was displayed to facilitate visual discrimination of both click train types, highlighted by the green circle. (B) The ICI parameter was displayed, highlighted by the red circle. The top and bottom panels represent the same sequence for direct comparison of the characteristic PAL pattern identified using SPL or ICI parameters in the C-POD.exe software.

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