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Evidence for the influence of shipping underwater radiated noise on sperm whale coda structure

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ABSTRACT

Shipping underwater radiated noise (S-URN) has been shown to harm whale populations, yet the mechanisms by which anthropogenic sounds interfere with whale vocalization systems are less understood. This paper investigates the impacts of S-URN on the structure of sperm whale coda vocalizations for hundreds of codas collected in the Eastern Caribbean. For the dataset collected, we show that the presence or absence of S-URN can be used to classify coda features, which arguably indicates a systematic effect on sperm whale vocalization. S-URN also results in changes in the spectral properties of the codas. In particular, S-URN decreases the accuracy of coda spectral classification even at short distances (several meters), suggesting that underwater noise impacts the structure of sperm whale coda signals. We further show that in the presence of S-URN, codas are shorter and more coda signals with a specific spectral pattern are vocalized.

1. Introduction

Marine ecosystems are now noisier than at any point in documented history due to increases in both the number and size of vessels. Since 2010, the number of commercial vessels has increased by more than 35% and the total deadweight tonnage has increased by more than 91% (trade and development, 2026). With a broadband shipping underwater radiated noise (S-URN) and environment affected source levels (ASL) above 170 dB (re 1 μPa m)[1] (Shipton et al., 2025), studies have shown evidence of the effects of such noise generation, especially on marine mammals (Erbe et al., 2019).

Sound is a primary sensory cue for marine mammals and many other marine species (Tyack and Clark, 2000; Weilgart, 2007; Mooney et al., 2012; Popper and Hawkins, 2019). Anthropogenic noise has long been established to interfere with cetacean communication systems (Richardson et al., 1995; Nowacek et al., 2007; Tyack, 2008; Weilgart, 2007; Erbe et al., 2019; Rodríguez-Garavito et al., 2025). Sperm whales (*Physeter macrocephalus*) interact using sequences of clicks called codas (Watkins and Schevill, 1977; Weilgart and Whitehead, 1993; Gero et al., 2016; Andreas et al., 2022), which can vary structurally based on rhythm and tempo (Weilgart and Whitehead, 1993; Sharma et al., 2024) as well as spectrally (Beguš et al., 2025, 2026). These parameters have been shown to be contextual and combinatorial (Sharma et al., 2024) and to exhibit phonological behaviors that are hypothesized to be modulated by sperm whales (Beguš et al., 2026).

Several species of cetaceans have been shown to increase the amplitude of their vocalizations (i.e., speak louder; the "Lombard effect") in response to noise. This has been demonstrated in common bottlenose dolphins (*Tursiops truncatus*; Kragh et al., 2019), beluga whales (*Delphinapterus leucas*; Scheifele et al., 2005), orcas (*Orcinus orca*; Holt et al., 2008, 2011), North Atlantic right whales (*Eubalaena glacialis*; Parks et al., 2011; Davis et al., 2023), pilot whales (*Globicephala melas*; Hegeman et al., 2026) and humpback whales (*Megaptera novaeangliae*; Dunlop et al., 2014; Gabriele et al., 2018). Additionally, increases in whistle duration (Foote et al., 2004; Sørensen et al., 2023), modulations of fundamental frequency (Lesage et al., 1999; Brown et al., 2023), changes in inter-pulse intervals and amplitude (Carlucci et al., 2024), bandwidth frequency modulations (Brown et al., 2023; Lesage et al., 1999), and increases in call types (Lesage

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[1] ASL is defined as the mean-square sound pressure level at a distance of 1 m in a natural environment affected by local conditions at the time (Johansson et al., 2024).

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et al., 1999) have been observed. Some studies report an increase in the rates of certain calls in the presence of noise (Lesage et al., 1999; Di Iorio and Clark, 2010; Davis et al., 2023), while others report a decrease in some calls (Melcón et al., 2012; Wisniewska et al., 2018), even within the same species (blue whales/*Balaenoptera musculus*).

Regarding the acoustic responses of sperm whales to noise, various sources of noise have been studied: anthropogenic noise from seismic survey pulses (Mate et al., 1994; Madsen et al., 2002), sonar (Isojunno et al., 2016; Stanistreet et al., 2022; Curé et al., 2025; Wensveen et al., 2025), airguns (Miller et al., 2009), offshore oil and gas activity (Farmer et al., 2018), vessel passage (Azzara et al., 2013), hum transmissions (Bowles et al., 1994), detonators (Madsen and Møhl, 2000), and even non-anthropogenic playbacks of killer whale vocalizations (André et al., 1997; Isojunno et al., 2016) (see also the survey in Whitehead, 2003). Most research focuses on echolocation clicks rather than coda vocalizations. Many studies report impacts of anthropogenic noise on sperm whale behavior (Mate et al., 1994; Bowles et al., 1994; Curé et al., 2025; Wensveen et al., 2025; Azzara et al., 2013; Isojunno et al., 2016, 2020), while some do not observe effects (André et al., 1997; Madsen et al., 2002; Miller et al., 2009). Decreased click activity has been reported (Azzara et al., 2013; Stanistreet et al., 2022). In recent years, there has been growing interest in monitoring and localizing whales using their vocalizations, as whale deaths from vessel strikes have increased in recent decades (Nisi et al., 2024; Winkler et al., 2020). This information can be relayed to ship operators to help prevent whale strikes (Baumgartner et al., 2019), and has led to programs such as Whale Safe (https://whalesafe.com/). However, how whales alter the acoustic properties of their codas in the presence of S-URN has received less scientific attention.

In this study, we examine the effects of shipping underwater radiated noise (S-URN) on the structure of codas. We analyze a dataset of hundreds of coda signals collected over four years in the Eastern Caribbean from acoustic tags deployed on sperm whales and shipping activity indicated by automatic identification system (AIS) recordings. We analyze both traditional coda features and newly described patterns, uncovering acoustic variability that whales use in the presence or absence of S-URN. In our dataset, we observe and describe acoustic changes in sperm whale codas when S-URN is present. We show that the presence of S-URN, and thus a vessel, can be successfully used as a classification metric by observing differences in coda features. Although we do not determine whether this has deleterious impacts on the whale, we offer a systematic tool to evaluate whether S-URN can be considered a disturbance factor for sperm whales. We consider two measures for impact assessment: (1) a spectral and duration analysis that explores differences in coda features; and (2) a classification approach that, given coda features, anticipates if a vessel is nearby. In both cases, changes and classification performance above chance level indicate the presence of the vessel in the whale's coda and, thus, indirectly, the influence of the vessel on the codas themselves. Our contribution is threefold:

1. A dataset combining sperm whale coda signals and S-URN indications from both AIS and acoustic recordings.
2. A method to evaluate the relationship between S-URN and changes in coda structure, including identification of the most dominant coda features.
3. For the analyzed dataset, successful classification of coda temporal and spectral features by the presence of S-URN, with performance improving as SNR increases, reflecting the effect of S-URN on coda structure.

2. Methodology

Although significant efforts have been made to examine the effect of S-URN on whales to stimulate policy changes and monitoring actions, more systematic evaluation could help demonstrate effects in larger populations and over longer time periods. One option is to analyze large datasets of marine mammal vocalizations, as proposed in Parsons et al. (2022). However, existing large datasets (e.g., Gero et al., 2014) are from far-field data, raising the problem of sampling noise in the vicinity of the animal. For example, analysis of far-field measurements does not take into account the directionality of whale vocalizations (Ou et al., 2025) or enable detailed, fine-grained acoustic analyses. Modeling approaches (e.g. Putland et al., 2018) are also challenging due to the large variation in shipping noise levels (Chion et al., 2019) and the complexity of underwater acoustic propagation modeling, which requires accurate modeling of vessel noise as well as reliable environmental information such as bathymetry, sea level, seabed composition, and sound speed profile. Considering these limitations, in this study we systematically analyze a dataset recorded from acoustic tags deployed on sperm whales over three years of measurements and follow the methodology described in Diamant et al. (2024). The pipeline for our methodology is illustrated in Fig. 1 and is discussed in details in the following.

2.1. Data collection

2.1.1. Acoustic data collection

We used coda recordings collected through The Dominica Sperm Whale Project (DSWP) (Gero et al., 2014; Tønnesen et al., 2018; Bøttcher et al., 2018). Specifically, these recordings were obtained from animal-borne sound and movement DTAGs (v3) (Johnson and Tyack, 2003; Johnson et al., 2000) deployed on known individuals in an area of approximately 2000 km^2 off the island of Dominica between 2014 and 2016. Recordings were sampled at 120 k sps at 2 B per sample, with a flat frequency response (±2 dB) from 0.5–50 kHz with deployments lasting up to 11 h. Although the DTAGs do not sample GPS location directly, our dataset includes the deployment position as well as locations where visual observations were made of the tagged whale while it was carrying the tag. Raw acoustic data were collected from tags deployed on 15 individuals. Table 1 provides the distribution of codas found within the data.

2.1.2. Coda detection

To detect coda clicks, we used our automatic coda detector, followed by manual labeling for error correction. The automatic method described in Gubnitsky et al. (2024) performs maximum likelihood clustering based on temporal and spectral analysis of a suspected buffer. Specifically, we use the observation that individual clicks within a coda are more similar to each other than to any other non-coda click sequence, combining measures of the clicks' correlation, power, and IPI match into a single similarity metric, along with a likelihood estimation of the coda pattern based on an existing dataset of codas. The result is formalized as an optimization problem that also separates coda sources. Our results, based on more than 2000 manually annotated coda symbols and nine months of continuous acoustic data with no whale coda, show detection rates above 80% for a false alarm rate of 10^{-4} per analyzed 10-second time frame. The method allows coda type estimation by the number of clicks and ICI within, and works well for both tagging and remote sensing data. False alarm rates deteriorate by two orders of magnitude in the presence of echolocation clicks from multiple whales forming coda-like patterns. Another sensitivity observed is in the identification of coda type, where clicks within the coda are sometimes not identified well, especially in the presence of echolocation clicks. To verify the automatic detections, we manually reviewed the detected clicks and corrected any missing clicks within an identified coda. Manual correction was performed using a designated user interface we developed, which provides both the temporal and spectral plots of the identified coda along with the detected click locations. The user can also listen to the data. The result of the annotation is either approval or rejection of the identification, as well as correction of missing clicks that affect coda type identification. This hybrid approach

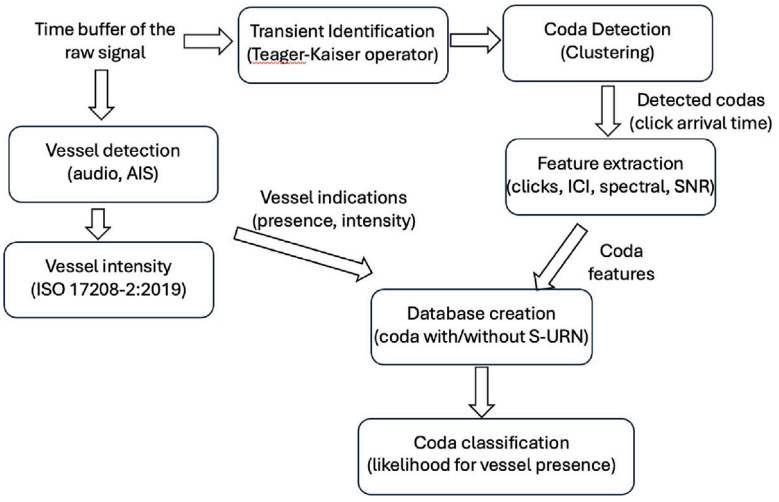

Fig. 1. Pipeline of our methodology for S-URN presence/absence prediction from coda features.

Table 1
Number of coda observations with and without URN (defined by audio-only or AIS-only for $r = 5$ km).

Whale name	Total coda	Coda with URN (Audio)	Coda without URN (Audio)	Coda with URN (AIS)	Coda without URN (AIS)
ATWOOD	407	111	296	256	30
FORK	310	41	269	27	228
NALGENE	14	0	14	0	14
TWEAK	22	3	19	0	0
PINCHY	142	29	113	21	75
TBB	125	52	73	0	73
SAM	54	38	16	0	0
LAIUS	42	13	29	17	12
SOPHOCLES	56	29	27	0	0
UNIDENTIFIED	47	25	22	8	0
FRUIT SALAD	50	25	25	0	0
SOURSOP	35	35	0	0	0
JOCASTA	28	28	0	0	0
SALLY	59	40	19	0	19
LADY ORACLE	7	7	0	0	0
Total	**1398**	**476**	**922**	**329**	**451**

enables the analysis of large files while validating positive detections. In our analysis, we focused on codas generated by the focal whale (the whale to which the tag was attached), as we needed to determine the S-URN level experienced by that whale. To achieve this, we augmented the detector in Gubnitsky et al. (2024) with an additional layer to detect focal codas. This was done by thresholding the acoustic intensity, assuming the focal signal is strong, and by automatically searching for a stable angle of arrival across clicks within the coda (each coda consists of several identified clicks). Manual verification of 100 codas from both focal and non-focal whales confirmed the success of this approach.

Once a coda and its corresponding clicks are identified, we perform feature extraction and signal-to-noise ratio (SNR) evaluation. The coda features considered are the number of clicks, their inter-click interval (ICI), the coda duration, and the spectral properties of the clicks within the coda. The number of clicks is readily available from the detection process and is identified from the output of the Teager-Kaiser Energy Operator (TKEO), which is a common method for identifying transients in the signal (Kandia and Stylianou, 2006). The ICI of the clicks is measured as the delay between the received times of consecutive clicks, where we identify the first arrival from multi-pulse and surface reflections as the first detected peak. The duration of the coda is measured by the delay between the first and last click arrivals, and the spectral feature refers to one or two maxima in the spectral response of each click. We identify six main features in the coda: (1) the number of clicks in the coda (*nClicks*), which ranges from 5 to 15 in our database; (2) the duration of the coda (*Duration*), which ranges from 0.1 s to 2 s in our dataset; (3) the ICI between the first and second clicks (*ICI1*); (4) the ICI between the second and third clicks (*ICI2*); (5) the ICI between the third and fourth clicks (*ICI3*); and (6) the ICI between the fourth and fifth clicks (*ICI4*). In our dataset, these ICI values range from 10 ms to 0.5 s.

In our analysis, an important aspect is the level of S-URN relative to the coda's intensity. Because we use a historical database that was not standardized (each tag was attached at different locations on the whales, but all dorsally) and the directionality of the tag was not tested, we avoid using the received noise level directly. Instead, we explore classification results based on the SNR of the coda. We determine the SNR of a coda by accounting for the frequency selectivity of both the noise and the clicks. The signal, defined as the click energy, is evaluated by calculating the power spectral density (PSD) of individual clicks in 1/3 dB octave bands (see ISO 17208-2:2019), then averaging over all clicks that form the coda. The noise is evaluated in the same way for segments that do not include a click. We consider a 10-second time frame, consisting of 5 s acquired 1 s before the first click arrival and 5 s acquired 1 s after the last arrival, ensuring that no other coda is detected during this period. The PSD ratio between the signal and noise is then averaged across the spectral band from 2 kHz to 20 kHz to provide a single SNR value. A histogram of the SNR range measured for all observed codas is shown in Fig. 2. Results show a distribution of SNR values between 0 dB and 20 dB.

2.1.3. Vessel detection

To analyze the coda signals in relation to vessel presence, we developed a scheme to identify when vessels are present. Two data sources

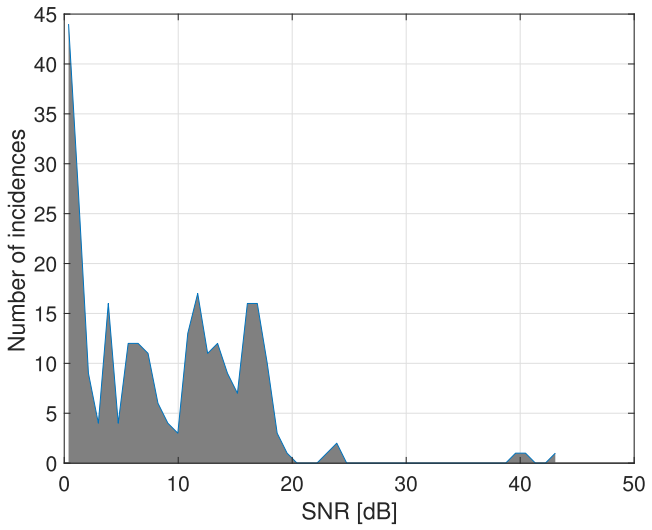

Fig. 2. Histogram of signal to noise ratio (SNR) measured for all coda signals identified to be in the presence of S-URN.

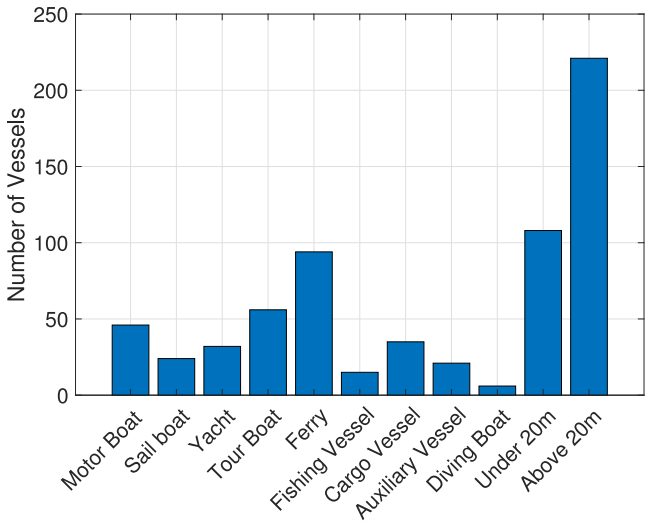

Fig. 3. Vessels considered from the AIS database per type. $r = 5$ km.

were used: *audio*, where S-URN was detected in the acoustic data collected from the tags, and *AIS*, where vessel indications were obtained from an AIS database of vessel reports. The audio database captures both small and large vessels, but its detection range is unpredictable, while the AIS database provides more accurate detections but only for large vessels.

For the audio analysis, as with the initial coda detection, we used automatic vessel detection to ensure objectivity, followed by manual verification to correct errors. The automatic detector, described in Alexandri and Diamant (2024), identifies stable periodicity in the signal by accumulating Detection of Envelope Modulation on Noise (DEMON) processing over short time windows. A coda was classified as having vessel noise if vessel noise was detected within a 5-minute window before and after the coda's arrival time. Manual observation verified the results for each identified coda. Two experts conducted the verification by examining the signal spectrum for periodic signals and listening to the audio when necessary.

The AIS database includes information such as vessel type, location, and speed for commercial, cargo, or passenger vessels that are required to carry AIS while transiting. The AIS log can therefore serve as an indicator of the presence of S-URN. To this end, we obtained from *VesselFinder* a database of AIS reports for the period and locations corresponding to our tag deployments. With no GPS onboard the tag, we made careful assumptions about the whale's movement between the tag deployment location and the surface observations of the tagged whale for which we had GPS positions. For each coda detected within a 60-minute window before and 60 min after a logged position of the tagged whale, we determined an overlap with an S-URN if the AIS database indicated a vessel within r km of the logged position during that time window. We consider $r = \{1, 2, 5, 10\}$ km, for which the number of observed vessels are $\{56, 178, 329, 512\}$, respectively. Fig. 3 shows the empirical distribution of vessel types considered in the analysis for $r = 5$. The dominant vessels were ferries passing between the islands, but we also observe a significant percentage of motor boats and tour boats. Approximately two-thirds of the vessels considered in our analysis were over 20 m in length.Table 2 shows the dominant 1/3 Octave frequency band and the environment-affected source levels (ASL)[2] observed for vessels detected both by audio and AIS. We used the values reported in von Benda-Beckmann et al. (2019) that calibrated the D-tags's sensitivity to −188.5 dB re 1 V/μPa at the frequency band of 10 Hz to 20 kHz. The analysis involved interpolation to a higher frequency resolution of 32,768 FFT points in order to comply with the ANSI Standard S1.11-2014/Part 1 (ANSI/ASA, 2014). We observe that, except for Yacht, the dominant frequency of the vessels is below the frequency band of the coda (mostly above 2 kHz). Yet, higher order harmonics do overlap with the coda band. The differences in the ASL are due to the location of the tagged whale with respect to the vessel and hence the ASL of vessels that might be considered noisy such as larger tour boats is sometimes lower than that of, for example, recreational vessels that are closer to the tagged whale.

The results in Table 1 show the number of coda signals detected for each of the 15 tagged whales. The "Coda with URN (Audio)" and the "Coda without URN (Audio)" refer to the cases of coda identified with and without the presence of a vessel detected by audio analysis, respectively; "Coda with URN (AIS)" and the "Coda without URN (AIS)" refer to the cases of coda identified with and without the presence of a vessel detected by AIS analysis, respectively, considering $r = 5$ km. We allow some level of "uncertainty" such that these are mutually inclusive categories. In particular, we discard cases when the manual annotator was unsure about the existence or non-existence of a vessel by audio analysis, and when vessels appear in the AIS database outside the $r = 5$ km diameter but inside the $r = 10$ km one. Further, some overlap exists between AIS-based and audio-based identification of vessels. The total number of coda is shown in the "Total coda" column. The values in this column are the sum of the "Coda with URN (Audio)" and "Coda without URN (Audio)" columns, which together comprise the coda database used for the analysis. We clarify that the data available for separating coda based on AIS records is more limited than the audio-based data, as it required GPS recording indications from the tags, which were not always available. Accordingly, the numbers in the "Coda with URN (AIS)" and "Coda without URN (AIS)" columns are included within the "Coda with URN (Audio)" and the "Coda without URN (Audio)" categories.

2.2. Coda analysis

2.2.1. Justification for the statistical analysis

In this work, we aim to describe the variation of sperm whale codas, and their features, based on the presences of S-URN. Here, the conditioning variable or observation is vessel noise, while the predicted variables or parameters are the whale's coda features. One possible approach to investigate this posterior is to apply regression methods that

[2] The Environment-affected source levels is calculated by the mean-square sound pressure level in the local environment at the time of recording (Parsons et al., 2021).

Table 2
Dominant 1/3 Octave frequency band of vessel noise observed by both Audio and AIS records (vessel types identified in AIS but not in Audio are not considered).

Vessel type	1/3 Octave band [Hz]	Intensity [dB/1 μPa m]	# vessels (both audio and AIS)
Motor boat	200, 250, 630, 1600	120–140	27
Sail boat	–	–	–
Yacht	1600, 2500	113–135	13
Tour boat	80, 250, 315	126–142	32
Ferry	125, 250, 630	115–147	41
Fishing vessel	–	–	–
Cargo vessel	80, 315, 630, 800	110–138	17
Auxiliary vessel	250, 315	115–121	6
Diving boat	–	–	–

predict coda features from raw acoustic data recorded with and without shipping noise. This is a challenging task due to the complexity of the shipping noise signal, which includes both broadband and narrowband components. A key limitation we face is the relatively small dataset of about 500 codas with and without S-URN. This limited sample size prevents us from performing regression with high confidence. Instead, we evaluate the likelihood, that is, the empirical probability of observing S-URN given the coda feature parameters. This is an easier problem since the S-URN observation can be represented by a binary yes/no parameter. We argue that predicting vessel presence from coda features provides relevant insights into this relationship. In particular, by Bayes' theorem, the above likelihood is related to the posterior through the ratio of priors on coda features and shipping presence. Because the coda feature distributions are spread across similar values for the 'vessel' and 'no vessel' categories (see discussion in Section 3), by balancing the dataset for vessel presence and absence, the estimated likelihood can be considered informative for approximating the target posterior.

2.2.2. Coda spectral analysis

In addition to the traditionally analyzed features of coda structure (timing and number of clicks), Beguš et al. (2025) show that spectral properties are highly structured, repetitive across whales, likely controlled, and not crucially influenced by whale movement (Beguš et al., 2025, 2026). Based on the number of formants,[3] two *coda quality* categories have been described: *a*-codas and *i*-codas. In this paper, we focus on the distinction between the two types based on the number of formants. The *a*-codas have a single spectral peak between 0 and 10,000 Hz, while the *i*-codas have two. These two coda quality features (also called coda vowels; Beguš et al. (2025)) are discretely distributed in codas: a coda is either of one quality or the other, with only a handful of codas containing more than a single click in a coda that does not conform to the majority quality of the coda. The characteristic spectral patterns corresponding to coda quality have been observed on other datasets recorded with different recording devices, such as during a sperm whale birth event using a far-field recorder (Aluma et al., 2026). The importance of spectral patterns was first detected by a GAN-based model (Beguš et al., 2024) and recently confirmed by a transformer-based audio model (Paradise et al., 2025). Recent distributional, durational, and articulatory evidence paralleling coda quality to human phonology further suggests that whale codas are likely actively controlled by sperm whales (Beguš et al., 2026).

To classify each click and each coda into the *a*- and *i*-coda quality categories, we use both automatic and manual coda annotation procedures following Beguš et al. (2025). First, we apply an automated click-based classification method, in which each click in a coda is classified based on the number of spectral peaks. Second, we use a visual coda-level classification, where each coda is classified based on the number of formants observed by two expert annotators. This yields both coda-level classification (each coda is either the *a*-type or the *i*-type) and click-level classification (each *click* in a coda is either the *a*-type or the *i*-type). In our analysis, we consider only codas whose clicks match in their spectral pattern, showing either a single or double maximum in the spectrum. Clicks with the same spectral pattern are considered matched, while a click with a different pattern is considered mismatched. The identification of matched and mismatched clicks was performed manually. Approximately 78% of codas contain no mismatched clicks. This enables analysis of whether noise increases the incidence of mismatched codas.

To automatically classify each click, we used the procedure described in Beguš et al. (2025). We perform a Fourier analysis of each click within a 3.5 ms window (2.0 ms preceding the peak of the click and 1.5 ms following the peak). This window length captures the first pulse of each click. We used the *scipy* (Virtanen et al., 2020) *welch* function to estimate spectral power of this window. The 'nperseg' parameter is set to the number of audio samples in the click, i.e. as a single non-overlapped segment. The 'nfft' parameter was set to 512, resulting in frequency bins of 234.375 Hz, which enables a relatively high spectral resolution for our analysis. We locate peaks with the *find_peaks* function in the calculated spectrum between 1000 and 10 000 Hz (Beguš et al., 2025) based on the observation in Beguš et al. (2025) that the difference between the *a*-type and the *i*-type is reflected within this range. The minimum distance between peaks is set at 1500 Hz, and the minimum height at 25%.

To classify each coda into the two coda quality categories, we use a visual method and compare it to the automatic click-level classification algorithm based on linear predictive coding (LPC). For visual analysis, we use Praat-generated (Boersma and Weenink, 2015) spectrograms in the range 0–15 kHz with a window length of 0.01 s. We then validate the visual coda quality classifications by performing an automated formant analysis of codas. We conduct LPC analysis of all clicks within a coda concatenated using Praat's formant functions with various combinations of hyperparameters. The agreement between the visual and automatic LPC analyses of the two coda quality types ranges from 79.5% to 100% (Beguš et al., 2025), depending on the individual whale. For this experiment, we use only the manual analysis (which shows a high degree of agreement with automated LPC analysis) because it is less prone to noise and has been manually checked several times. We use only codas for which coda quality can be reliably established based on the observers' spectral analysis. The annotation was performed prior to the results of the categorical S-URN analysis and was therefore blinded, meaning that the annotation could not have been biased according to the URN definitions.

2.2.3. Coda classification

To evaluate whether a coda varies in the presence of a vessel, we classify each detected coda into either the 'vessel' or 'no vessel' category. To achieve this, we avoid using the raw acoustic signal to eliminate any traces of S-URN which a classifier could exploit. Instead, we perform classification based on the coda's features. Observing the

[3] A formant is a frequency band that determines the quality of a vowel.

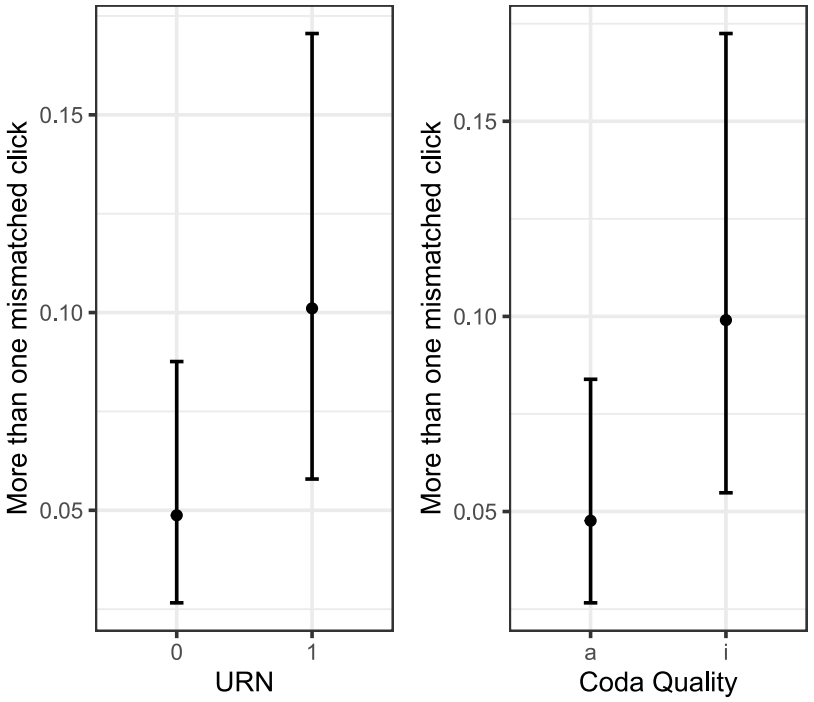

Fig. 4. Estimates of the mixed effects logistic regression model with 95% CIs. The graph on the left shows the increase in the proportion of codas with more than one click mismatched when underwater radiated noise (URN) is present. The graph on the right shows that *i*-coda quality has a higher proportion of more than one mismatched click per coda.

distribution of the six features defined above (see Section 2.1.2), we report significant overlap between the 'vessel' and 'no vessel' categories. That is, we cannot readily separate between the categories of coda features with and without the presence of S-URN. We also report that the empirical distribution of the features is spread across similar values for the two categories, although it appears of different type with a high Kullback–Leibler divergence value greater than 2 for all features but the number of clicks. This observation leads us to adopt non-linear classification approaches in our likelihood analysis. Due to the small number of samples, we avoid implementing a state-of-the-art classifier and instead choose a simple support vector machine (SVM) with a Gaussian Radial Basis Function (RBF) kernel. Our experience with SVM (Abu and Diamant, 2019; Diamant et al., 2017) shows that, if trained without overfitting, it can project a vector of input features to find a separating hyperplane, thereby capturing non-linear dependencies using a small annotated dataset of only tens of samples. The two SVM hyperparameters, the margin error and the scale, are trained using a k-fold training and evaluation process. For each test, we randomly extract 20% of the data for testing and leave the remainder for training. Observing the distribution of the 'vessel' and 'no vessel' classes in Table 1, the training dataset is balanced to a ratio of 1 to 3 in favor of the coda with no vessel presence. We then divide it uniformly at random into $k = 5$ sections and perform training on the first four sections and evaluation on the last section. Training and evaluation are then repeated $\lfloor X/10 \rfloor$ times, where X is the sample size of the training data.

3. Results

3.1. Spectral analysis results

3.1.1. Coda quality type

Previous research on the effects of anthropogenic noise on sperm whales has focused primarily on behavioral responses or changes in the frequency of vocalizations or echolocation (Mate et al., 1994; Bowles et al., 1994; Curé et al., 2025; Wensveen et al., 2025; Azzara et al., 2013; Isojunno et al., 2016, 2020; Stanistreet et al., 2022). Here, we report that whales alter their acoustic behavior with respect to their coda-quality usage rates. To test the effect of coda quality, we fit the data to a mixed-effects logistic regression model. The presence or absence of S-URN (audio-based) is the binary dependent variable, with coda duration and hand-labeled coda quality as independent variables. We analyze 1114 codas from 13 individual whales. The model includes a random intercept for whale identity and a random slope for coda quality. Model estimates illustrating the effects of coda quality type and coda duration are shown in Fig. 5a–c. We observe that whales produce significantly more *a*-codas than *i*-codas when noise is present. Noise is significantly less frequent in the presence of the *i*-coda ($\beta = -2.56, z = -2.179, p = 0.029$). We also observe a decrease in coda duration as the likelihood of S-URN increases. Elsewhere, it has been shown that the *a*-type codas are longer in duration than the *i*-type codas (all else being equal) (Beguš et al., 2026). The shorter duration of codas in the presence of S-URN is thus likely independent of the higher frequency for the *a*-type when S-URN is present. If the two were related, we would expect more *i*-codas (which are shorter) in the presence of S-URN, however, the opposite is true in our data.

We model S-URN as the dependent variable in order to simultaneously estimate the effect of coda quality and coda duration. However, 702 of 1114 (or 63%) codas in our dataset are of the 1+1+3 traditional coda type. Most other coda types have fewer than 40 attestations. The 1+1+3 type is also one of the rare coda types in which the *a*- and the *i*-coda qualities are equally distributed, to show that the preference for *a*-coda types in the presence of S-URN holds in 1+1+3 codas only, we fit a logistic regression mixed effects model on data limited to only the 702 1+1+3 coda types. In this model, the hand-annotated vowel quality is the dependent variable and S-URN and coda duration (centered but not scaled) are the independent variables. The final model includes a random intercept for whale and no interaction between URN and duration (based on AIC and likelihood ratio test). We also fit a full model with a random slope for URN and interaction between URN

and duration: significance levels are the same for both models. The *i*-type is significantly more common when there is no URN present ($\beta = -0.82, z = -3.52, p = 0.0004$; for raw counts and estimates, see Fig. 5d–f). The *i*-codas are also significantly shorter than *a*-codas in duration, which has been reported previously (Beguš et al., 2026).

3.1.2. Mismatched clicks

Spectral properties are highly structured in sperm whale codas. Each coda exhibits one coda quality or the other. In other words, coda qualities are mostly discretely distributed across codas, meaning that the vast majority of clicks in a coda are of the same type: either containing a single peak (the *a*-coda quality) or two peaks (the *i*-coda quality).

The work in Beguš et al. (2025) shows that, using the automated annotation procedure described above, 78.3% of codas have no mismatched clicks, i.e. clicks that do not conform to the majority type (single or double peak) in a coda, while 12.2% of codas have only one mismatched click. In Beguš et al. (2026), codas with a single mismatched click are hypothesized to result from coarticulation, a process also present in human speech production. 9.5% of codas contain more than one mismatched click, and the cause of these mismatched codas remains unknown. Given that the distribution of clicks with one or two peaks is nearly categorical per coda, it is likely that the coda quality is intentionally controlled by the whales rather than an artifact or a random acoustic effect. Under this assumption, an increase in mismatched clicks in the presence of URN would indicate that the originally intended vocalization is distorted by noise. Here, we report that the codas with multiple mismatched clicks are more common in the presence of S-URN. We speculate that S-URN interferes with the classification of coda quality.

To test whether the presence of the URN (audio-based) affects the number of mismatched clicks in a coda, we fit the data to a mixed-effects logistic regression model. The dependent variable is the presence of more than one mismatched click based on the automatic click-level annotation (0 = zero or one mismatched click, 1 = two or more mismatched clicks). Two independent variables are considered: (1) the presence of S-URN (a binary variable) and (2) the hand-annotated quality of the coda. We select more than one mismatched click as the threshold because Beguš et al. (2026) show that a single mismatched click can likely result from co-articulation. Additionally, one mismatched click might fall within the margin of error for the click-level coda quality annotator, although this could include mismatches which are not due to co-articulation. Only models using the threshold of more than one mismatched click in the dependent variable reach statistical significance. We include a random intercept for whale identity, whereas the random slope for URN is not warranted by either Akaike Information Criterion (AIC) or likelihood ratio test and is therefore excluded. When S-URN is present, the number of codas classified as having more than one mismatched click is significantly higher compared to when no noise is present ($\beta = 0.79, z = 3.0, p = 0.003$; see Fig. 4).

3.2. Classification results

Our second approach to exploring coda variation in the presence of S-URN is to test how well we can classify coda features based solely on vessel presence. We measure this by the percentage of true positives (TP), which accurately classify the presence of a vessel, and the percentage of true negatives (TN), which accurately classify that no vessel is present. We claim that (1) TP and TN values much higher than the chance level (50%) and (2) a correlation of TP and TN with the SNR would indicate that the coda structure changes due to S-URN.

We begin by examining the significance of our vessel labeling methods using audio and AIS information. We consider the TP and TN for three data sources: (1) labeling vessel or no vessel noise using audio data *only*, (2) labeling vessel noise presence *either* by audio or by AIS, while labeling no vessel noise by *both* audio and AIS, and (3) labeling vessel noise by audio *only*, while labeling no vessel noise by *both* audio and AIS. In Fig. 6(a), we present the TP and TN results for these three cases: the first case corresponds to the pair TP (Audio) and TN (Audio); the second case corresponds to the pair TP (Audio or AIS) and TN (Audio and AIS); the third case corresponds to the pair TP (Audio) and TN (Audio and AIS). The AIS-related results (cases two and three) are shown for various r values representing the vessel's distance. The third case is the most conservative, ensuring the presence of noise in the audio file within the ten-minute buffer around the coda, while the second case allows the most detections for vessel presence (i.e., increases 'Codas with URN').

We observe that for all three above cases, the classifications are above the chance level (Fig. 6(a)). This indicates that the classifier was able to distinguish between the features of codas when there are no vessels nearby. The best classifier performance is observed in the second case, suggesting that more distant vessels may have an effect, even when their noise is too low to be detected in the audio. The better results in the first case compared to the third case indicate that the effect of distant shipping is less significant. Comparing the results for different r distances, we observe that the best performance is obtained for $r = 5$ km with 329 vessels. We argue that this is due to the relatively small number of vessels for $r = \{1,2\}$ km, 56 and 178, respectively, which are too small set sizes to generalize. For $r = 10$ km, although the number of vessels is the largest (512), results approach the chance level. We argue that this is because the URN is less dominant at these distances. In the following, we analyze AIS-related data corresponding only to $r = 5$ km.

Next, we examine the differences in the vessel/no vessel classifier for specific whales. Although our dataset includes codas recorded from 15 individual whales, only two of these have more than 300 detected codas, a sample size large enough to attempt classification per whale. According to Table 1, these two whales are *ATWOOD* (Whale #5586 from Unit A) and *FORK* (Whale #5151 from Unit U). The classification performance for these two whales is shown in Fig. 6(b) using all explored features and for case 3. Similar performance is observed for both whales, and the TP and TN rates are significantly higher than chance.

We examine the impact of coda SNR on classification performance. Since codas were collected from tags attached to whales, the classification results by SNR level provide a measure of how intensity affects whale vocalization. For codas with vessel presence and SNR measurement (see sample size in Table 1), we consider a subset of coda signals that exhibit, in their audio, vessel noise within the buffer analyzed for SNR calculation. No limitations are set for codas without vessel presence. We argue that, since vessel noise is orders of magnitude greater than flow noise (Jia et al., 2022), the SNR reflects the strength of S-URN interference. Supporting this, our dataset shows SNR levels greater than 40 dB when no vessel was detected. The TP and TN classification results for this subset are presented in Fig. 6(c) for three SNR levels in the case of vessel presence: below 5 dB, between 5 dB and 10 dB, and above 10 dB. We observe that classification results improve with higher SNR. For low SNR below 5 dB, we observe chance-level classification, which can be interpreted as no effect. Classification improves greatly as SNR reaches 10 dB, achieving 90% accuracy in both TP and TN for high SNR. The results of a similar analysis conducted for the ASL are shown in Fig. 6(d). Based on the ASL measurement results in Table 2, the analysis covers three ASL groups: 110–120 dB, 120–130 dB, and above 130 dB. We observe that prediction performance improves as ASL increases. This may indicate that this effect is more pronounced with noisier vessels.

Finally, to explore the impact of noise on individual coda features, we present in Fig. 7 the TP and TN rates for the third labeling case: labeling vessel noise using audio *only*, while labeling no vessel using *both* audio and AIS data. To determine whether a feature i is significant, we remove it from the feature vector and perform classification without

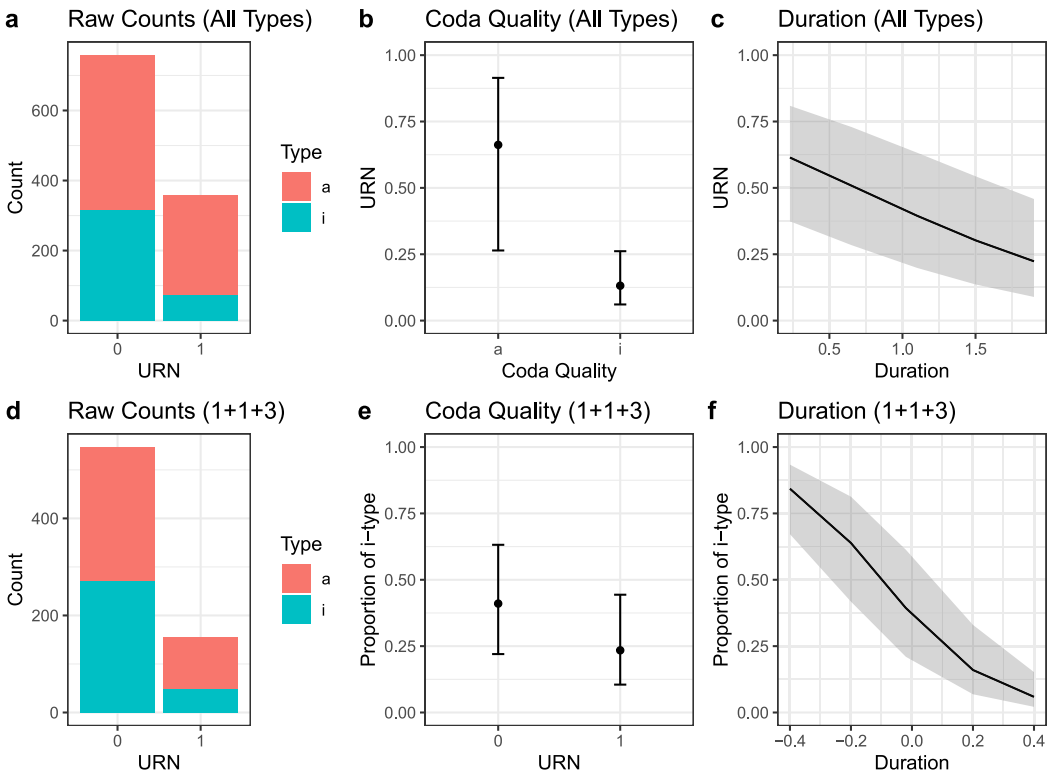

Fig. 5. (a) Raw counts of coda quality types when noise (URN) is present vs. when it is absent for all traditional coda types. Raw counts show a higher proportion of the *i*-type when URN is absent. (b and c) Estimates of the mixed effects logistic regression model. The presence of URN is the dependent variable with the coda quality type (*a* vs. *i*) and duration (in s) as the two independent variables. The estimates of the model show that for *a*-codas, URN is more frequent than for *i*-codas and that shorter coda durations feature more URN. (d) Raw counts of coda quality types when noise (URN) is present vs. when it is absent for 1+1+3 codas. Raw counts show a higher proportion of the *i*-type when URN is absent. (e and f) Estimates of the mixed effects logistic regression models for 1+1+3 codas. The coda quality type (*i* vs. *a*) is the dependent variable with the presence of URN and duration (centered in s) as the two independent variables. The estimates of the model show that *i*-codas are more frequent than *a*-codas when URN is absent and that *i*-codas are shorter.

it. The significance of a feature is evaluated by the extent to which the classification results decrease compared to using all features. From the results in Fig. 7, the 'nClick' feature provides the most significant information regarding the presence of a vessel in the coda structure. We also observe that the 'ICI' features contribute differently, with 'ICI3' being the most dominant.

4. Discussion

4.1. About coda duration and quality

The results of the statistical analysis in Section 3.1.1 show that, statistically, codas are shorter in the presence of S-URN. Shortening in vocalization duration has been observed in dolphins (Marley et al., 2017; Fouda et al., 2018; Gagne et al., 2022; Hu et al., 2022). Some studies hypothesize that shortening enables fitting "calls into quieter intervals" (Fouda et al., 2018). The opposite effect has also been reported where calls are extended in the presence of noise, including in belugas (Lesage et al., 1999), humpback whales (Miller et al., 2000), and orcas (Foote et al., 2004). The observed shortening in sperm whales is likely driven by coda type selection, as different coda types have inherent durational differences. We also report the first distribution pattern of coda qualities with an environmental cause: the presence or absence of S-URN. Whales emit more *a*-coda quality signals in the presence of noise. This result holds for all codas as well as for the most common 1+1+3 coda. Two hypotheses for the observed changes in vocalizations are that sperm whales alter their vocalizations to increase resistance to noise in response to S-URN –or that the whales change the structure of their coda vocalizations to reflect the presence of S-URN. This is further supported by previous work suggesting that other cetacean species alter the fundamental frequency of their calls in the presence of vessel noise (Heiler et al., 2016). In our case, the changes occur in the resonant or spectral frequencies.

4.2. About coda classification

Our results demonstrate success in classifying coda signals as having been emitted with or without the presence of S-URN. There may be two non-exclusive reasons for this classification success: (a) the whales change their vocal behavior as a result of S-URN, or (b) the presence of S-URN alters the ambient sound. We argue for the first reason for the following two points. First, our classifier distinguishing between 'vessel' and 'no vessel' incidences based on coda features is not prone to overfitting due to the large variation in coda signals and a database spanning four years of study. Randomizing the codas used for training and testing also ensures unbiased results. Second, the classification relies on extracted features of the codas, which separate the parameters from any features of the S-URN itself. The classification performed allows exploration of important features by observing their significance for classification accuracy. This may provide a future way to explain the meaning of the results once the functionality of each feature in the coda signal becomes clear. The results in Fig. 6(c) provide further evidence of the effect of S-URN on the whales' coda, showing that higher SNR enables greater distinction between coda with and without the presence of vessels.

4.3. Limitations

The level of S-URN depends on vessel characteristics such as type, length, engine, speed, and load, as well as environmental factors like

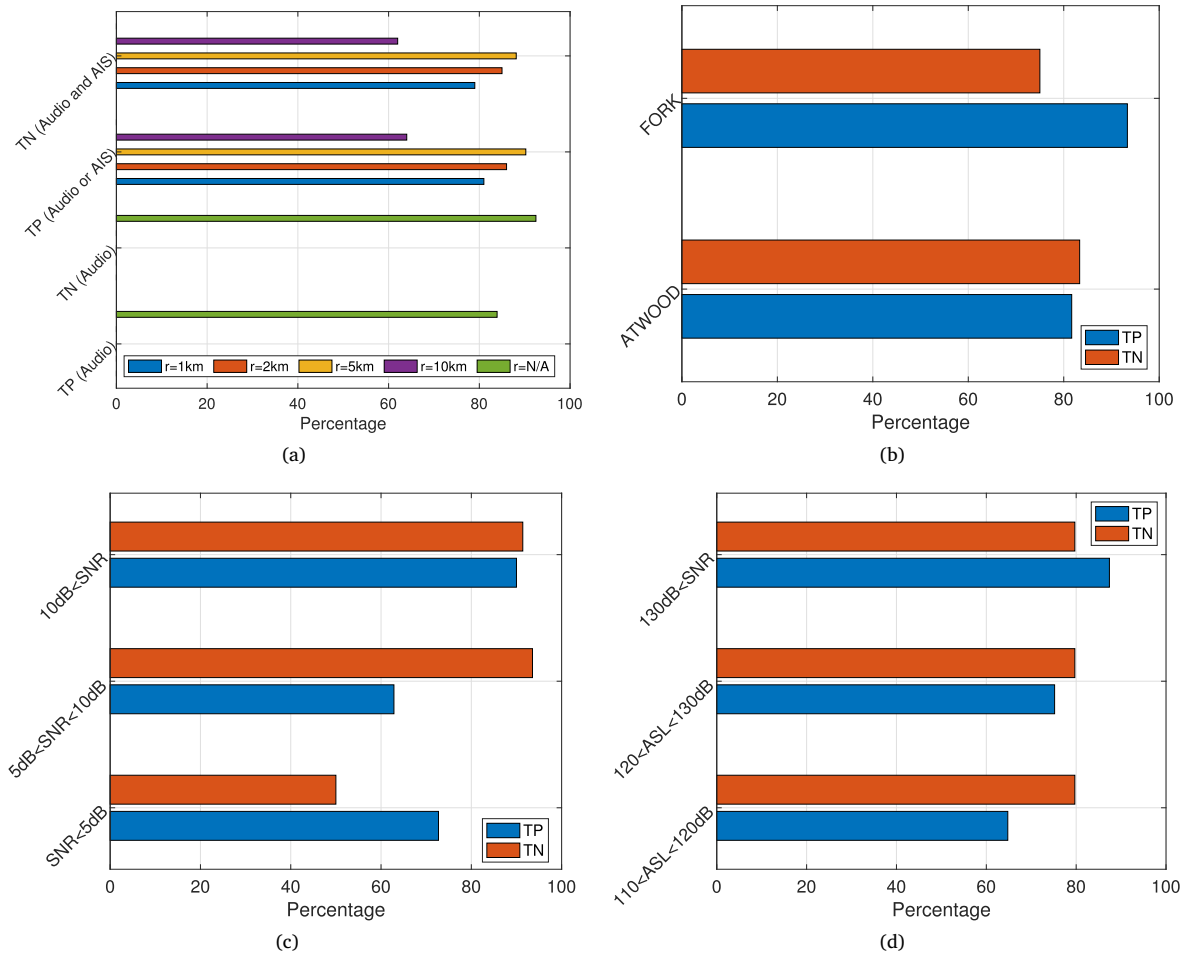

Fig. 6. True positive (TP) and True negative (TN). (a) three tagging attempts (various considered r distances for AIS), (b) two tagged sperm whales: 'ATWOOD' and 'FORK' ($r = 5$ km), (c) as a function of signal to noise ratio (SNR) ($r = 5$ km), (d) as a function of the environment-affected source levels (ASL) ($r = 5$ km).

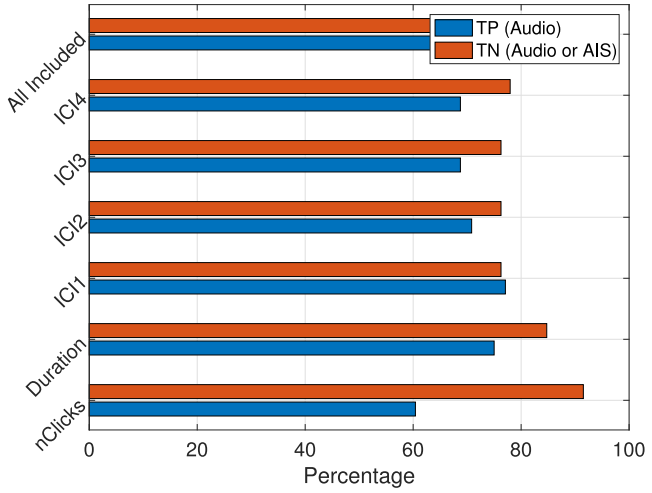

Fig. 7. True positive (TP) and True negative (TN) by removing a single feature from the input to the classifier ($r = 5$ km).

bathymetry and sound speed profile (Shipton et al., 2025). The common metric for evaluating the impacts of S-URN is the sound exposure level (SEL) over a specified time frame. Procedures for measuring vessel URN, particularly those outlined in the ANSI/ASA S12.64-2009 and ISO 17208-2:2019 standards, specify how SEL measurements should be conducted. Other methods associate acoustic data with AIS data to produce noise maps (Alexandri and Diamant, 2025). However, these approaches require precise knowledge of the receiver's location, which is unavailable for the tagged whale except at the sparse times when GPS locations are reported. Additionally, exploring the causality between coda structure and instantaneous S-URN received level is challenging due to the relatively small dataset, which limits the ability to perform regression to predict URN intensity rather than binary classification of presence or absence. For the same reason, we could not perform classification based on vessel type and characterization. Instead, we provide binary classification results for the presence or absence of vessels only and explore the effects in terms of individual whales, the source used to determine S-URN (AIS or audio), coda features, SNR, and received level. The limited database also prevents exploration of other factors in coda vocalization, such as the sequential structure of the coda. Therefore, we treat each coda in isolation rather than in the context of the exchanges in which they are produced between individuals. As a result, we limit our findings to evidence of structured acoustic modulation associated with S-URN, specifically features of the coda pattern, rather than direct disruption of behavioral function.

A main limitation of our study is the relatively small sample of vocalizations, restricted to codas from a single region in the Eastern Caribbean. While the number of codas analyzed is arguably sufficient to avoid overfitting, their sporadic occurrence over approximately four years and the focus on one geographical area make it difficult to generalize our conclusions. Testing such differences in vocalizations

in other clans and larger databases across regions will provide further information on the temporal and spectral effects of anthropogenic noise on the coda structure. For this reason, we leave the interpretation of the spectral effects as well as the identified acoustic changes for future work. While tags deployed on whales are limited in duration, datasets covering longer periods for both marine mammal vocalizations and shipping noise may be obtained from submerged gliders equipped with acoustic monitoring capabilities (Kowarski et al., 2020; Gehrmann et al., 2023). Similarly, investigating responses to anthropogenic non-shipping URN, such as underwater construction or sonar emissions, may allow distinction of responses due to S-URN. Another direction is to augment the vocalization response with changes to the whales' mobility patterns such as diving or speed.

Since our study is observational, we do not confirm the causal effect of S-URN on whales. This is mostly due to the challenge of separating the vocalization response to the existence of S-URN. Here, we have taken an approach which does not require the further ensonification of the waters surrounding the whales through playback of noise stimuli to address a critical question about noise and disturbance. While acoustic properties of codas are well understood, their exact function and potential referential meaning, including the function of the spectral properties (coda quality) remains unknown. Other environmental or behavioral factors can be confounded with the presence of S-URN. However, the data presented in this study suggest that sperm whales alter their codas in the presence of S-URN. For causal proof of the effects of S-URN on the acoustic properties of codas, an interventional and controlled study would be necessary.

5. Summary and conclusions

S-URN has been shown to interfere with the vocal interactions between cetaceans. The effects range from non-vocal behavioral responses to changes in vocalizations, including increased or decreased vocal activity, louder vocalizations, or other acoustic adaptations to noise. The documented impact of S-URN has led to calls for policy change (Duarte et al., 2021), and countries have already incorporated aspects of marine ecosystem protection and pollution prevention into their maritime strategy policies (Tobin, 2019; UK Department for Transport, 2019; France Ministry for Ecological and Solidarity Transition, 2017). These efforts have also been supported by international organizations such as the International Maritime Organization (IMO) (International Marine Organization, 2023), the Convention on the Conservation of Migratory Species (CMS) (Borland et al., 2015), and the Convention on Biological Diversity (CBD) (Harding and Cousins, 2022). However, while some progress has been made through technical recommendations (International Marine Organization, 2023) and international measurement standards (standard, 2025), there has been little advancement in legislation or regulation (Rodríguez-Garavito et al., 2025). Yet, recent studies continue to demonstrate nuanced passive acoustics criteria that can be used to analyze the complexity of whales' vocal responses to anthropogenic pressures (Hegeman et al., 2026).

Relatively few studies have examined the effects of S-URN on sperm whales. Sperm whale vocalizations are unique among cetaceans: the groups of clicks known as codas are found only in sperm whales. This study presents the first observational report suggesting that sperm whale codas are acoustically different in the presence of S-URN. We analyze the acoustic properties of codas in both the presence and absence of S-URN and report that codas are shorter when S-URN is present, and that sperm whales use the *i*-coda quality more frequently when S-URN is absent. We also show that the presence of S-URN can be inferred with high accuracy from vocalizations alone. This leads to our hypothesis that the reception of the spectral properties of coda clicks, which define coda quality categories, may be affected by S-URN, as our automatic classification algorithm produces a higher rate of multiple mismatched clicks per coda in the presence of S-URN. This is especially significant because we detect this effect in whales carrying acoustic tags, where the hydrophones are extremely close to the source of the vocalizations (details of an open-source on-whale biosensor Vogt et al., 2025). These findings suggest that these discrete acoustic properties of sperm whale vocalizations are susceptible to S-URN and possibly other types of anthropogenic noise.

CRediT authorship contribution statement

Roee Diamant: Writing – original draft, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **David F. Gruber:** Writing – review & editing, Supervision, Funding acquisition. **Shane Gero:** Writing – review & editing, Data curation. **Gašper Beguš:** Writing – original draft, Methodology, Formal analysis.

Ethical approval

Data from the Dominica Sperm Whale Project were collected under scientific research permits from the Fisheries Division of the Government of Dominica. The field protocols for approaching, photographing, tagging, and recording sperm whales were approved by the University Committee on Laboratory Animals of Dalhousie University, Canada; the Animal Welfare and Ethics Committee of the University of St Andrews, Scotland, or Aarhus University, Denmark; and sometimes several or all of these. The field protocols for recording sperm whales were approved by The Institutional Animal Care & Use Committee at Harvard University.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Roee Diamant reports financial support was provided by Israel Science Foundation. David Gruber reports financial support was provided by TED Audacious. Roee Diamant reports financial support was provided by EU Framework Programme for Research and Innovation Euratom. If there are other authors, they 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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Data availability

The analyzed data is available in https://github.com/Project-CETI/Database-for-ship-noise. The processing code is available in https://github.com/Project-CETI/Analysis-for-ship-noise.

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