Low-frequency noise influences fin whale songs

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Abstract

Shipping noise can negatively affect baleen whales behaviour, including their reproductive singing. Currently limited research studies have focused on the fin whale (*Balaenoptera physalus*). The aim of this paper is to describe how shipping noise may affect fin whale songs. Background noise levels for 42 songs were measured and analysed in relation to parameters that describe song structure. Here we show that increasing noise levels were associated with significant changes in the Inter-pulse-interval – for all deployments investigated - as well as peak and center frequency of classic notes. Effects were not the same for all deployments, suggesting that responses to shipping noise might depend on seasons, locations and/or inter-individual variability. Such modifications may increase energetic costs and reduce communication efficacy, potentially lowering the reproductive success.

Introduction

Shipping noise is ubiquitous and is strikingly increasing. Analyses demonstrate that global ship traffic increased fourfold between 1992–2012 and there are predictions that underwater noise in the Mediterranean Sea will double in the coming 10 years [1,2]. Underwater radiated noise from commercial ships is a dominant component of the low frequency band in the marine environment, with peaks between 20 and 100 Hz [3]. The same frequency range is occupied by cetaceans to communicate, in particular baleen whales which rely on low-frequencies [4]. Chronic exposure to noise has been linked to a) physiological stress, b) behavioural changes (e.g. altered migration routes, habitat avoidance and foraging interruption), c) communication masking, and d) alteration in the vocal activity [5–13].

Among baleen whales, the fin whale (*Balaenoptera physalus*) produces the so called “20-Hz pulse”, a downsweep from about 23 Hz to 18 Hz, with a duration of about 1 s [14,15]. These pulses (or notes), occurring in two types in the Mediterranean Sea, namely classic and backbeat, can be repeated in stereotyped patterns to form songs [14–16]. Since songs play a key role in reproduction and occupy the same frequency band as shipping noise, there is concern that fin whale communication is susceptible to acoustic disturbance [17,18]. Auditory masking as well as alterations in the structure of songs can influence their efficacy, interfering with reproductive success and reducing the individual fitness [13,19].

Despite this concern, research on the effects of shipping noise on fin whale acoustic behaviour remains limited. Most previous work focused on the humpack whale (*Megaptera novaeangliae*), e.g. [20–29]. Only a few studies exist for the fin whale, investigating auditory masking [4,10,30,31] or modifications in the structure of songs [13]. The study by Castellote et al. (2012) provided the first evidence of changes related to shipping noise in fin whale songs [13]. It was conducted in the Mediterranean Sea and revealed that note duration shortened, bandwidth decreased, centre frequency decreased, and peak frequency decreased with increasing noise levels. Beyond this study, the relationship between shipping noise and fin whale song structure remains poorly understood.

Understanding such relationships is not only crucial for the conservation of this endangered species but also for policy development. The Marine Strategy Framework Directive (2008/56/EC) requires assessment of continuous underwater noise under Descriptor 11 – Criterion 2 – (D11C2) in order to achieve Good Environmental Status (GES) of the European marine waters [32]. To do that, the percentage of habitat where the Level of Onset of Biologically adverse Effects (LOBE) can be exceeded within a specific assessment period was set as the threshold to evaluate GES [33–35]. However, defining LOBE for one or more indicator species is quite challenging and currently there is no full agreement[36]. This is mainly due to our understanding on the effects of noise on marine life, which is evidently incomplete.

Here, we investigate how shipping noise may affect fin whale song structure in the Ligurian Sea. Through correlation analysis, we test the hypothesis that increasing sound pressure levels (root-mean-square) of underwater radiated noise from ships can lead to changes in songs with respect to: a) Inter-pulse interval (IPI), b) minimum as well as maximum frequencies, c) peak and center frequencies, d) song duration, e) rest duration and f) the number of notes per song.

Findings, including a significant change in the IPI for all deployments investigated, suggest that shipping noise induces alterations in the songs of fin whales. This might lead to a reduction of communication efficacy well as alteration of energy budgets due to modified singing activity, with final implications for the reproductive success. Our findings aim to fill a critical knowledge gap and provide scientific basis for improving D11 in the Mediterranean Sea.

Results

Data were collected in the Ligurian Sea, the northernmost sector of the western Mediterranean, during 1999–2001 by means of autonomous recorders called “Pop-Ups” (PUs). Pop-Ups were deployed in three different sites, namely a) Ile Rousse, b) Arma di Taggia and c) Cape Corse (Fig. 1). Eight different campaigns were made, using 5 different Pop-Ups (Table 1). The Pop-Ups identified with the number 19, 6 and 18 were deployed twice.

Table 1
Summary of PU data (Number of deployment, position, depth, recording period, location, sampling rate (SR), count of recording days and file duration).

#deployment	PU	Latitude	Longitude	Depth (m)	Recording period	Location	SR (kHz)	#days	File duration (min)
1	19	N 42°43,895	E 8°55,094	500	31/08/1999–19/09/1999	Ile Rousse	2	19	10
2	22	N 43°47,499	E 7°52,773	500	02/09/1999–19/09/1999	Taggia	2	18	10
3	6	N 42°43,942	E 8°55,118	500	23/09/1999–10/10/1999	Ile Rousse	2	18	10
4	16	N 43°47,548	E 7°52,795	500	25/09/1999–12/10/1999	Taggia	2	18	10
5	18	N 43°21,043	E 9°19,725	700	27/11/1999–11/12/1999	Cap Corse	2	15	20
6	19	N 43°46,074	E 7°53,120	650	28/01/2000–12/02/2000	Taggia	2	16	20
7	6	N 43°45,875	E 7°52,821	620	27/02/2001–24/03/2001	Taggia	2	26	20
8	18	N 43°27,056	E 9°23,600	600	16/03/2001–23/04/2001	Cap Corse	2	39	20

The acoustic dataset analysed is composed of 169 days of recordings, corresponding to 4056 hours. A subset with clearly visible notes and clearly measurable IPI was selected. A random selection process was applied to select only 1 song per day to avoid having the same singer in consecutive songs. Considering the a) low encounter rate of sightings as well as of individuals, b) the very low recapture probability in capture-recapture analysis and c) the long-range movements of fin whales in the Ligurian Sea during the study period, we can suppose unlikely that the same individual is detected for consecutive days by the same recorder [37,38]. In this way we could obtain independent data samples. The final subset consisted of 66 files, which correspond to around 17 hours. The total number of high-quality songs selected for the analysis was 42. 15 songs belong to Pop-Up 6, 13 songs to Pop-Up 18 and 12 songs to Pop-Up 19. Due to insufficient data, songs from Pop-Up 22 (n = 2) were excluded from noise analyses. In Pop-Up 16 there were no high-quality songs suitable for the analysis.

We observed both the classic and the backbeat note, while higher frequency components, as described for other ocean basins (e.g. Papale et al., 2023 [39]), were not detected. 1328 notes were analysed, of which 782 were classified as classic note (59%) and 546 as backbeat (41%).

Table 2 reports the statistics for each parameter, namely

a) IPI for all note pair combinations: classic-classic (cc), classic-backbeat (cb), backbeat-classic (bc), backbeat-backbeat (bb);

b) Frequency parameters (minimum, maximum, bandwidth (BW), peak and center frequency of notes). We distinguished classic (c) and backbeat (b) notes;

c) Song duration;
d) The number of notes that make up each song;
e) The pulse rate for each song;
f) Rest duration.

Table 2

Statistics of parameters of fin whale song: a) IPI, b) note frequency parameters, c) song duration, d) the number of notes per song, e) pulse rate and f) rest duration.

		Mean	SD	Min	Median	Max	CI	CV	N. obs.
a) IPI (s)	**General**	17.39	4.39	8.58	15.82	31.81	16.72–18.06	0.25	149
	Cc	15.05	1.64	10.50	14.74	19.79	14.54–15.56	0.06	40
	Cb	17.53	1.66	11.92	17.15	22.54	17.01–18.05	0.09	42
	Bc	14.70	1.43	8.58	14.60	18.00	14.25–15.14	0.10	42
	Bb	25.44	4.09	15.30	25.49	31.81	24.16–26.71	0.16	25
b) Note frequency parameters (Hz)	**Min.**	19.01	0.44	17.97	19.04	20.00	18.92–19.11	0.02	84
	c	19.28	0.33	18.51	19.29	20.00	19.18–19.38	0.02	42
	b	18.74	0.36	17.97	18.80	19.50	18.63–18.86	0.02	42
	Max.	22.36	1.38	20.44	21.94	25.94	22.06–22.66	0.06	84
	c	23.52	0.98	21.95	23.45	25.94	23.21–23.82	0.04	42
	b	21.21	0.38	20.44	21.14	21.93	21.09–21.32	0.02	42
	Note BW	3.36	1.27	1.55	3.09	7.23	3.08–3.63	0.38	84
	c	4.25	1.13	2.64	4.09	7.23	3.90–4.60	0.26	42
	b	2.46	0.59	1.55	2.34	3.85	2.28–2.65	0.24	42
	Peak	20.52	0.56	19.39	20.41	21.65	20.40-20.64	0.03	84
	c	20.99	0.37	20.01	21.04	21.59	20.89–21.10	0.02	42
	b	20.04	0.22	19.39	20.02	20.62	19.97–20.10	0.01	42
	Center	20.54	0.57	19.48	20.46	21.62	20.42–20.67	0.03	84
	c	21.06	0.28	20.51	21.09	21.62	20.97–21.15	0.01	42
	b	20.03	0.20	19.48	20.06	20.41	19.96–20.09	0.01	42
c) Song duration (s)		507.50	256.91	177.22	437.37	1247.97	427.44-587.56	0.51	42

	Mean	**SD**	**Min**	**Median**	**Max**	**CI**	**CV**	**N. obs.**
d) N. of notes/song	31.81	14.52	13.00	27.50	68.00	27.28–36.33	0.46	42
e) Pulse rate	0.06	0.01	0.05	0.06	0.10	0.06–0.07	0.13	42
f) Rest duration (s)	145.02	71.98	71.80	123.80	435.17	122.59-167.45	0.50	37

Correlation analysis

We performed correlation analysis to assess potential relationships between song parameters and noise levels. Correlation coefficients were computed separately for each deployment for two reasons, namely a) noise measurements from different Pop-Ups could not be compared due to calibration differences, b) each Pop-Up is characterized by two deployments, occurring in different locations and/or seasons, as shown in Table 1 (e.g. within Pop-Up 19, deployment 1 was made in Ile Rousse in summer, while deployment 6 in Taggia during winter). We made such a distinction assuming that the fin whale might respond differently to shipping noise depending on the location and/or the season.

We used two correlation coefficients, respectively the Pearson and the Spearman coefficient, based on the distribution of data. Pearson measures the strength and direction of a linear relationship between two variables, i.e. noise levels and song parameters in this case. It is used when both variables are normally distributed. Similarly, the Spearman coefficient examines whether two variables are correlated with each other or not. The difference between Pearson and Spearman is that Spearman is non-parametric, hence it is used when at least one variable is not normally distributed. Both coefficients range from − 1 to 1, with values near 0 indicating no relationship between noise levels and song parameters. Positive coefficients indicate positive correlation, i.e. when noise levels increse the compared song parameters increases too. Negative coefficients indicate negative correlation, i.e. when noise levels increase, song parameter values decrease.

To determine the appropriate correlation coefficient, we checked the normal distribution using the Shapiro-Wilk test. The Shapiro-Wilk test was performed for each variable, separately for each deployment. Outputs of the tests are detailed in the Supplementary information.

Results of correlation analysis are grouped by location: Ile Rousse, Cap Corse and Taggia are respectively shown in Figs. 2–4. The season corresponding to each deployment is reported using the following acronyms: W = winter, SP = spring, SU = summer and A = autumn.

Each figure shows horizontal barplots with bars indicating the strength and the direction of each correlation.The barplots show negative correlations on the left, zero in the middle and positive on the right side of the plot. Song parameters are ordered by the strenght of their correlation: from the strongest positive at the top to the strongest negative at the bottom. Statistically significant correlations ($p < 0.05$) are marked with an asterisk. The colour of each bar indicates the type of correlation used: orange for Pearson (both variables were normally distributed), and blue for Spearman (one variable was not normally distributed).

Ile Rousse

Pop-Up 19 (deployment 1 in summer) and Pop-Up 6 (deployment 3 in autumn) were positioned in Ile Rousse.

With respect to deployment 1 (Fig. 2a), 8 songs were analyzed. For this deployment the majority of variables were normally distributed (Supplementary Table 1).

Correlation coefficients of Fig. 2a indicate the following significant correlations: a) the IPI decreased as noise levels increase; only cb–pairs and noise were significantly correlated; b) pulse rate was positevely correlated with noise.

Figure 2. Correlation coefficients for Pop-Ups deployed in Ile Rousse. a) deployment 1 occurring in summer (SU) and b) deployment 3 in autumn (A). Pearson coefficients (orange) as well as Spearman coefficients (blue) between song parameters and noise levels are shown. The y-axis represents the variables compared with noise levels; the x-axis reports values of the coefficient, with positive values to the right and negative values to the left. Significant correlations are marked with * (p-value < 0.05).

With respect to deployment 3 (Fig. 2b), 9 songs were analyzed. For this deployment the majority of variables were normally distributed (Supplementary Table 2).

Figure 2b suggests that the IPI increased as noise levels increased and only cc–pairs and noise were significantly correlated. As noise levels increased, several frequency parameters decreased, namely a) maximum-, b) bandwidth and c) center frequency of both classic and backbeat notes, and d) peak frequency of classic notes; significant correlations were observed for center and peak frequency of the classic notes.

Cap Corse

Pop-Up 18 (deployment 5 in autumn and deployment 8 in spring) was positioned in Cap Corse. 5 songs were analyzed in deployment 5 (Fig. 3a), while 8 in deployment 8 (Fig. 3b). For both deployments the majority of variables were normally distributed (Supplementary Tables 3 and 4).

Deployments 5 and 8 shared similar trends, respectively:

- The IPI of the cc and bc - pairs was positively correlated with noise; only cc–pairs and noise were significantly correlated;
- The IPI of the cb and bb-pairs was negatively correlated with noise;
- Minimum frequency of backbeat was positevely correlated with noise;
- Several frequency parameters were negatively correlated with noise, namely a) maximum frequency and b) bandwidth of both note types, c) peak- and d) center frequency of backbeat notes;
- Pulse rate as well as rest duration were negatively correlated with noise.

Additional significant results occur in both deployments: for deployment 5 the center frequency of classic notes significantly decreased with increasing noise; for deployment 8 the maximum frequency of backbeat notes significantly decreased with increasing noise.

Taggia

Several deployments were positioned in Taggia, respectively the number 2 (PU 2), 4 (PU 16), 6 (PU 19) and 7 (PU 6). In deployment 4 no high-quality songs suitable for the analysis were found. In deployment 2 and 6 we detected an insufficient number of songs for the correlation analysis, respectively 2 and 3 songs. The low number of high-quality songs seemed, from visual inspection of files, to be related to strong low-frequency noise, which lowered the signal-to-noise-ratio (SNR) (it should be noted that this is purely a qualitative observation, not a quantitative analysis). In deployment 7, 6 songs were analyzed (Fig. 4). For this deployment the majority of variables were normally distributed (Supplementary Table 5).

Figure 4. Correlation coefficients for deployment 7, positioned in Taggia during winter (W). Pearson coefficients (orange) as well as Spearman coefficients (blue) between song parameters and noise levels are shown. The y-axis represents the

variables compared with noise levels; the x-axis reports values of the coefficient, with positive values to the right and negative values to the left. Significant correlations are marked with * (p-value < 0.05).

Simple linear regressions

After having identified song parameters significantly correlated with noise, we used simple linear regression to examine their relationship to noise levels. Table 3 summarizes model outputs and Supplementary Figs. 1–5 represents the scatterplots of each acoustic parameter against noise levels for each deployment.

Table 3
Results from the estimated simple linear regression models.

Deployment	Variable	Estimates	St. error	T value	N	p-value
1	IPI cb	-0.421	0.159	-2.656	8	**0.038**
1	Pulse rate	0.003	0.001	4.658	8	**0.003**
3	IPI cc	0.107	0.033	3.216	7	**0.024**
3	Center freq. c	-0.050	0.020	-2.495	9	**0.041**
3	Peak freq. c	-0.066	0.025	-2.701	9	**0.031**
5	IPI cc	0.340	0.044	7.742	5	**0.005**
5	Center freq. c	-0.044	0.007	-6.264	5	**0.008**
7	IPI cc	-0.107	0.038	-2.849	6	**0.046**
7	Peak freq. c	-0.086	0.030	-2.831	6	**0.047**
8	IPI cc	0.357	0.191	1.864	8	0.112
8	Max freq. b	-0.068	0.017	-4.081	8	**0.006**

Simple linear regression models confirm the results of correlation analysis. The only exception is represented by IPI cc in deployment 8, which is not statistically significant according to the simple linear regression.

Discussion

This study investigated wether shipping noise impacted fin whale songs in the Ligurian Sea. Acoustic data were collected more than 2 decades ago (1999–2001). Our results can be considered as a leap in the past and a benchmark for future studies. Uniquely, our findings provide the earliest evidence that fin whales in the Ligurian Sea reacted to shipping noise already 25 years ago and that the response is not univocal.

A striking result is that the IPI is significantly correlated with noise in all deployments investigated (Figs. 2–4). The cc–pair significantly changes in all deployments, except for deployment 1, where the cb–pair is the one significantly changing. Findings also suggest that fin whale do not always respond in the same way to increasing shipping noise, and that individual variability is likely to occur. The IPI of the cc–pair (hereafter "IPI" to mean the significant correlation) significantly increases with increasing noise in deployment 3, 5, and 8, while it significantly decreases in deployment 7. For the cb–pair in deployment 1, the IPI also significantly decrease. An hypothesis is that different locations and/or seasons might explain such variability.

For Cape Corse (deployment 5 and 8), which is the most pelagic area where Pop-Ups were deployed, the IPI increases. Taggia is the location closest to the coast and most exposed to shipping noise, as shown by the vessel density map from Emodnet (Supplementary Fig. 6). This location is represented by a single deployment (deployment 7) and the IPI decreases. For Ile Rousse a double trend exists: in deployment 1 (summer) the IPI decreases, whereas in deployment 3 (autumn) it increases. In this case, seasonal differences might explain the variation.

According to seasons, the IPI increases in autumn (deployments 3 and 5) and spring (deployment 8), while it decreases in winter (deployment 7) and in summer (deployment 1). Considering that only males sing to attract females to prey aggregations, and that the Ligurian Sea is a key feeding ground for this species during summer, we hypothesize that singers increase their pulse rate (as significantly demonstrated in deployment 1) to signal prey abundance to advertising females[18,40]. Likewise, during the breeding season (i.e. winter), IPI may decrease to enhance the chances of finding a mate and to avoid being masked by shipping noise [41]. Weirathmueller et al.[42] hypothesized that the center frequency of a signal and its repetition rate are linked, suggesting that a decrease in the IPI might lead to sing at higher frequencies. Conversely, an increase in IPI would be associated with lower frequencies, which are energetically more expensive for the fin whale. Our findings align with this hypothesis: (considering only the significant correlations) in deployment 3 increasing noise leads to a concomitant increase in IPI as well as a decrease in center and peak frequency of classic notes; in deployment 5, IPI increases while center frequency of classic notes significantly decreases. An exception is deployment 7, where both the IPI and the peak frequency of the classic note decrease with increasing noise.

If singing at lower frequencies is more energetically expensive for the fin whale, deployment 7 could represent a condition of maximum energy expenditure: peak and center frequency of the classic note decrease with increasing noise, hence according to Weirathmueller the fin whale should call less often to face the excessive effort [42]. Instead, we observe the opposite: the IPI decreases. Given that deployment 7 took place in winter (likely the breeding season), singers might accept higher energetic costs to increase mating success.

The hypothesis of increased effort due to shipping noise was discussed by other authors, such as Parks *et al*. (2007) [43], who documented a reduction in call rate in North Atlantic right whales and South Atlantic right whales in response to increased low-frequency noise. The authors underline that although such response may worsen the detectability of calls in band-limited low-frequency noise, the whales may decrease their call rate due to increased effort. The effort might be an increase in call amplitude when calling in higher noise [43]. Although note amplitude was not investigated in our study, fin whale singers likely experience increased effort; whether this is due to a frequency shift or greater signal amplitude remains unknown. In either case, changes in vocal activity may reduce their energy budget. Moreover, alterations in the structure of songs may compromise song effectiveness. The latter may therefore originate reductions in individual fitness, which as a consequence, will alter population dynamics.

Similar changes were documented for other cetacean species. Carlucci *et al*. [44] described an increase in Inter-Click-Interval and peak amplitude of click trains in the Risso's dolphin (*Grampus griseus*) in the Gulf of Taranto. Hu *et al*. [45] reported a decrease in click emission rate during and after vessel transit for the Taiwanese humpback dolphin (*Sousa chinensis taiwanensis*). Luís *et al*. [46] reported for the bottlenose dolphins (*Tursiops truncatus*) a mean overall call rates decrease in the presence of operating vessels. Also in this latter case, the authors suggest that changes in call emission rates may be a vocal response to the proximity of operating vessels.

Concomitant changes in IPI and frequency observed in this study occurred over a temporal scale on the order of days (up to 39 days for deployment 8). For fin whales, similar changes in IPI and frequency may also occur over longer temporal scale, on the order of years. Several studies across ocean basins described a concomitant increase in IPI and a decrease in note frequency over decades, e.g. [42,47,48]. Similar trends were observed also for other baleen whales, including the blue whale (*Balaenoptera musculus*) [49]. The reason of such shift would be always linked to shipping noise and an increased effort [42,49]. Best *et al*.[50] reported an increase in IPI over 10 years for the fin whale in the Pelagos Sanctuary. Nevertheless, they measured a low correlation between IPI and center frequency of notes, suggesting no evidence of an inter-annual center frequency decrease. The authors propose that Mediterranean fin whales might be an exception to this IPI-frequency trend. Similarly, since we did not observe a concomitant decrease in frequency and an increase in IPI for all deployments, an hypothesis is that for the Mediterranean fin whale there are other factors to influence this IPI – frequency correlation. These factors may include the season and/or the location as well as inter-individual variability.

The decrease in center and peak frequency of classic notes we observed for deployment 3, 5 and 7 were also reported by Castellote *et al*. (2012)[8]. With data collected in 2006–2009, they found that in noisy conditions pulse duration shortened, bandwidth decreased, as well as center and peak frequencies of the 20 Hz-pulse (they did not distinguished between classic and backbeat notes). They warned that such frequency shift, suggesting a compensation mechanism to increase signaling in shipping noise environments, may be costly, may not completely compensate for noise and may interfere with reproduction [13,19,51].

Our findings demonstrate that fin whales exhibit responses to noise consistent with those documented by Castellote et al.[13], and notably, such behavioural reactions were observed as early as a decade prior. New studies are urgently needed to assess the response of fin whales, and our findings can can serve as an historical reference for future comparisons [52]. This is particularly important because shipping noise is increasing, and additional sources of underwater radiated noise are expected to grow [2]. To respect Green Deal ambitions of carbon neutrality, installations of offshore wind turbines are planned in the Mediterranean Sea [53,54]. These installations, primarily involving floating technology [53], require vessels during their construction, operational, as well as decommissioning phase [55]. More vessels are required for floating installations compared to the bottom fixed typology [56]. Unlikely fixed-bottom turbines, floating turbines have the advantage of being installed in deep waters, up to 900 m depth [57], potentially overlapping with the pelagic habitat of fin whales [58]. Given that ship radiated noise can propagate over tens to hundreds of kilometers, it is reasonable to think that such developments could have significant effects on the fin whale [59].

We demonstrated that shipping noise alters fin whale song parameters in a non-uniform way. Changes in IPI and frequency parameters may imply increased energetic costs as well as reduced communication efficacy. In either case, we might expect a reduction in individual fitness, hence in population dynamics. Assessing whether the same response to shipping noise determined in this study occurs today is of primary importance. In conclusion, demonstrating that fin whales react to increasing shipping noise, our study represents a step forward in the definition of LOBE whereas the fin whale should be chosen as indicator species for the Mediterranean Sea.

Methods

Data collection

Data were collected in the Ligurian Sea, during 1999-2001 by means of autonomous recorders called “Pop-Ups” (PUs). These were developed by Cornell Laboratory of Ornithology [60]. Data were made available thanks to a collaborative effort between Cornell University Bioacoustics Research Program and Junio Fabrizio Borsani (ISPRA ex ICRAM team).

For all Pop-Ups resolution was 12 bits.

An auxiliary motorsailer was used to deploy and retrieve the instruments. Each time recordings started before Pop-Ups were released at sea. Recordings were continuous. Once begun, they were stopped only when Pop-Ups were retrieved by a physical person, who manually interrupted the recording. Instruments were set to acquire a new acoustic file, without interrupting, every 10 minutes (for deployments 1-4) and 20 minutes (for deployments 5-8).

Statistics and Reproducibility

Dataset and data analysis

The original acoustic dataset here analysed was composed of 169 days of recordings, corresponding in total to 4056 hours and 17424 files. For each day of recording were produced 144 files (for deployment 1-4) or 72 files (for deployment 5-8). A data-subset was used for song analysis. Files with clearly visible notes and clearly measurable IPI were selected. Then, a random selection process was applied to select 1 song per day to ensure data independence. The obtained final subset consists of 66 files, which correspond to around 17 hours.

Acoustic analysis of songs were made manually, through visual and acoustic inspection of spectrograms, using Raven Pro 1.6.5 (http://www.birds.cornell.edu/raven).

Spectrogram parameters set for the entire acoustic work were: FFT 4096 points, window type Hamming, 50% overlap with a 3 dB filter bandwidth of 0.702 Hz.

Noise analysis

Measures of background noise were taken to evaluate possible effects of shipping noise on fin whale songs. Noise was measured using TUNE (v 6.01), a standalone application based on MATLAB developed by our research team (Buogo *et al.*, 2025 [61]). We calculated the root-mean-square (rms) sound pressure level ( ) (dB re 1mPa) over 10-seconds windows within the 7-141 Hz frequency band. A single   measure was taken at the beginning of each analysed song, immediately before the first note. The output value was then used as a representative estimate for the entire song. Frequency ranges were chosen to cover the low frequency band typical of shipping noise. The lower limit is 7 Hz since below this frequency the sound is filtered by the recorders. The upper limit is 141 Hz since this is the upper frequency of the 1/3 octave band centered at 125 Hz, one of the two frequency bands recommended by the Marine Strategy Framework Directive to monitor continuos low frequency sounds [34].

Pop-Ups were not individually calibrated, since the original goal of the study was to detect fin whale vocalizations rather than to perform environmental noise measurements. We applied the same calibration value for all Pop-Ups (-165.4 dB ref 1V/µPa), based on the hydrophone sensitivity reported by Barclay and Buckingham (2013)[62], who used the same hydrophone model (HTI-94-SSQ Hydrophones) in their research. Since all Pop-Ups shared the same assumed sensitivity, direct comparison between different units was uncertain. For this reason, we could not compare noise measurements acquired by the different Pop-Ups within the Ligurian Sea.

Song analysis

Each note was assigned to one of the two types, namely to “classic” or “backbeat”, based on frequency and amplitude characteristics [15].

The following fundamental parameters were investigated to describe fine whale songs:

a) Inter-pulse interval (IPI): it was defined as the amount of time between peak pressure levels in two consecutive pulses (notes). According to note type, 4 different IPI combinations were measured:

1) cc (between two classic notes),

2) cb (between a classic and a backbeat note),

3) bc (between a backbeat and a classic note),

4) bb (between two backbeats).

b) Frequency range of notes: in detail, minimum and maximum frequency, note bandwidth (BW), peak and centre frequency of notes. We distinguished classic (c) and backbeat (b) notes.

c) Song duration: the amount of time between the first and the last pulse of a consistent sequence of notes, where IPI are no longer than 60 s (1 minute).

d) The number of notes that make up each song.

e) The pulse rate for each song, defined as $\frac{n.of\ notes\ per\ song}{duration\ of\ that\ song}$

f) Rest duration: pause of silence between consecutive songs, usually between 1-20 minutes.

Each parameter was correlated to the respective noise value (i.e. the noise measurement taken at the beginning of each song) to understand potential effects of noise. All of the above-mentioned parameters compose the structure of songs.

Statistics

All statistics were done using the software R (version 4.3.2).

For each song the following parameters were calculated: a) IPI for the combinations cc, cb, bc and bb, b) minimum and maximum frequency, note bandwidth (BW), peak and centre frequency, differentiating for classic note (c) and backbeat (b), c) song duration, d) the number of notes, e) pulse rate, and f) rest duration. Each song yields a single output value of i) song duration, ii) rest duration, iii) the number of notes comprising that song, as well as iv) pulse rate. In contrast, the four IPI combinations and the frequency parameters produce multiple values per song. To avoid pseudo-replication, the mean of each of these parameters was calculated for each song. As a result, for each song there is a single output value respectively for a) cc, cb, bc and bb duration, b) minimum-, maximum-, peak-, centre frequency as well as note bandwidth for both classic and backbeat note.

Correlation analysis was used to detect possible relations between song parameters and noise levels. Depending on the distribution of data, we could use two types of correlation coefficients, namely the Pearson and the Spearman coefficient. The former was used when both variables were normally distributed, while the latter when one variable did not follow the normal distribution. The normal distribution was checked using the Shapiro-Wilk test for each parameter within each deployment. Correlation coefficients were computed separately for each deployment for two reasons. The first one is that noise measurements from different Pop-Ups could not be compared due to calibration differences. The second one is that each Pop-Up is characterized by two deployments, occurring in different locations and/or seasons, as shown in Table 1 (e.g. within Pop-Up 19, deployment 1 was made in Ile Rousse in summer, while deployment 6 in Taggia during winter). We made such a distinction to avoid potential biases, speculating that the fin whale might respond differently to shipping noise depending on the location and/or the season.

Based on the results of correlations, simple regression models were estimated in R. The objective was to investigate relationships, rather than to develop predictive models. Each model followed the general formula

$$Y = \beta_0 + \beta_1 X + \epsilon,$$

Where X is the predictor (i.e. noise levels), Y is the response variable (i.e. those variables showing a statistically significant correlation), β_0 is the intercept, β_1 is the slope coefficient, and ϵ is the standard error. Statistical significance level was set at $p < 0.05$.

Declarations

Data availability

Dataset are stored at ISPRA, Rome (Italy). Access can be requested via email (jf.borsani@gmail.com).

Code availability

Code used to develop the software TUNE is stored at CNR, Rome, Italy. Access can be requested via email (silvano.buogo@cnr.it).

Author contributions

V.C. conceived the analysis, analysed the data, drafted the manuscript; J.F.B. conceived the experiment, collected the data, and drafted the manuscript; P.R.W. conceived the analysis and drafted the manuscript; S.B. designed and implemented the software TUNE; D.S.P., G.P., A.A. and D.V. drafted and reviewed the manuscript. All authors approved the final manuscript before submission.

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Figures

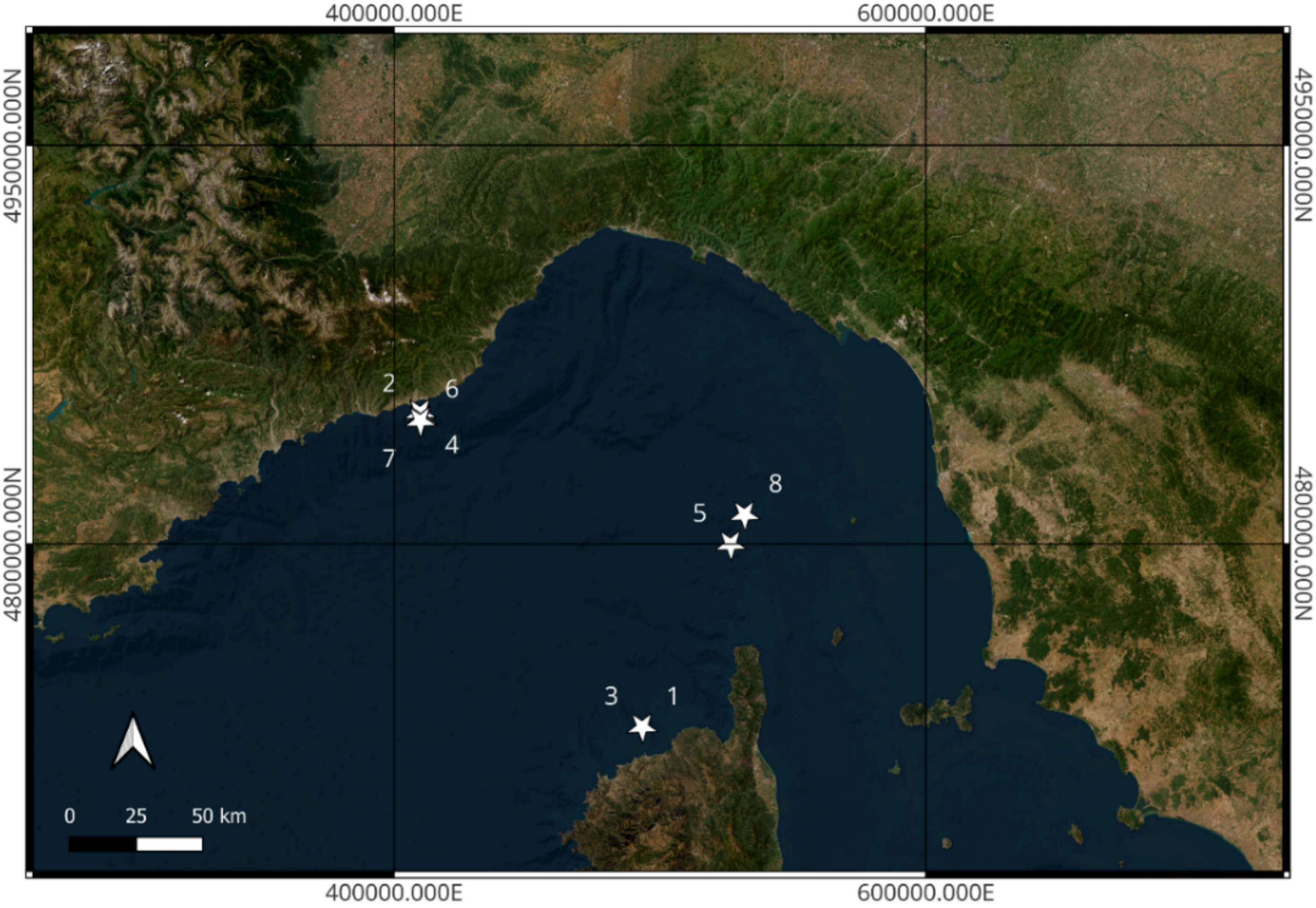

Figure 1

The study area with the positions of the 8 deployments in the Ligurian Sea

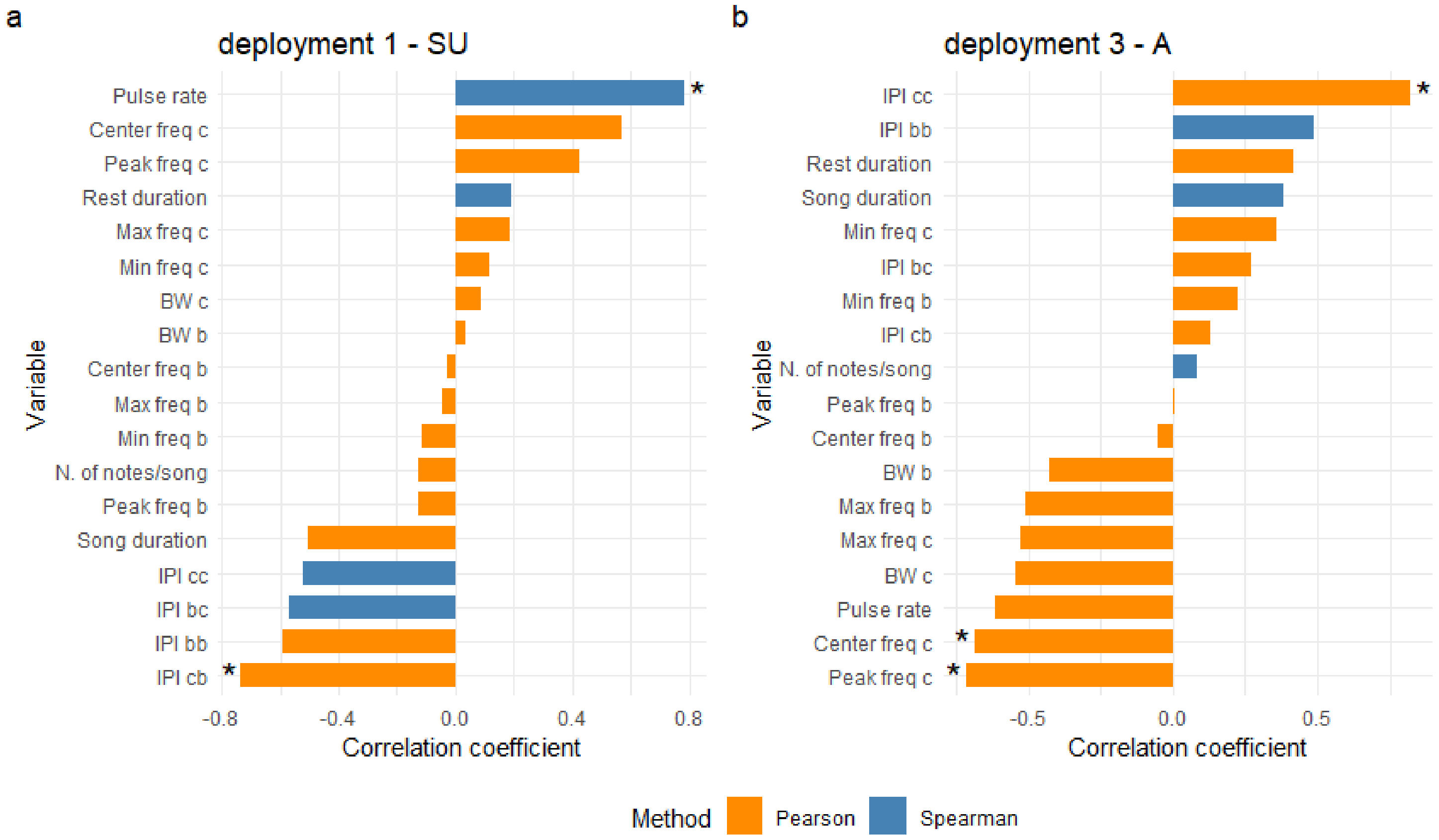

Figure 2

Correlation coefficients for Pop-Ups deployed in Ile Rousse. a) deployment 1 occurring in summer (SU) and b) deployment 3 in autumn (A). Pearson coefficients (orange) as well as Spearman coefficients (blue) between song parameters and noise levels are shown. The y-axis represents the variables compared with noise levels; the x-axis reports values of the coefficient, with positive values to the right and negative values to the left. Significant correlations are marked with * (p-value < 0.05).

Figure 3

Correlation coefficients for Pop-Up 18, deployed in Cap Corse. a) deployment 5 occurring in winter (W), b) deployment 8 in spring (SP). Pearson coefficients (orange) as well as Spearman coefficients (blue) between song parameters and noise levels are shown. The y-axis represents the variables compared with noise levels; the x-axis reports values of the coefficient, with positive values to the right and negative values to the left. Significant correlations are marked with * (p-value < 0.05).

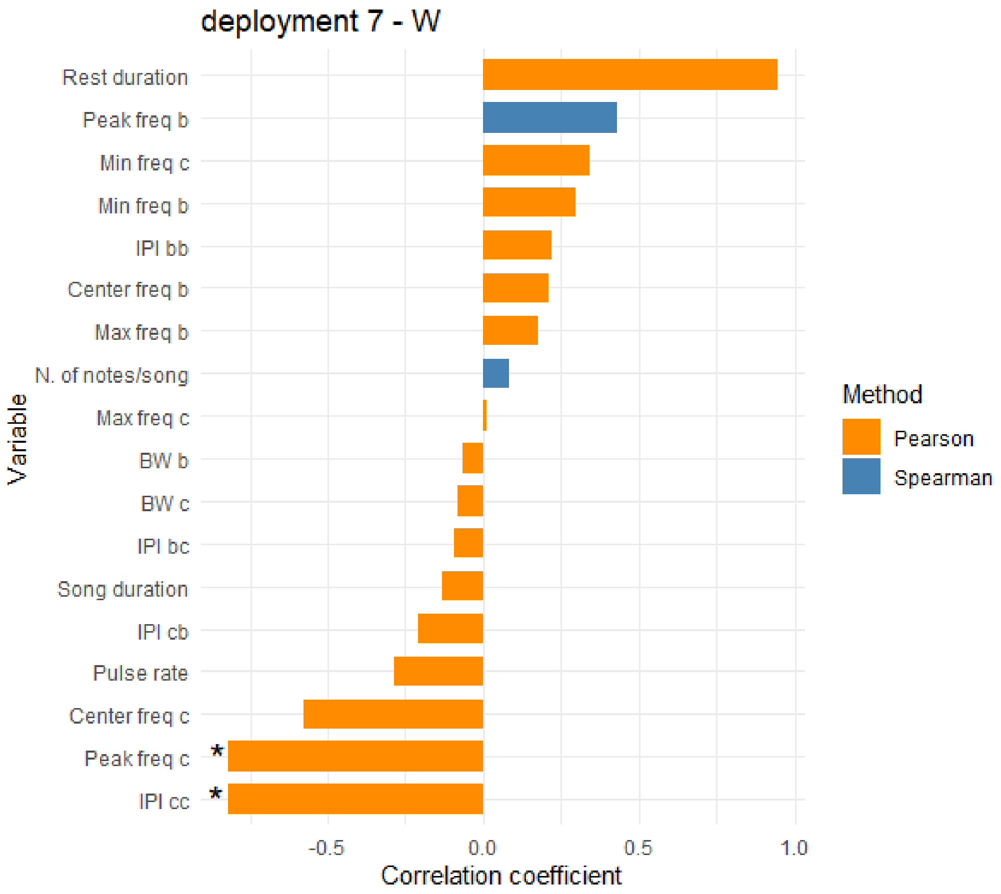

Figure 4

Correlation coefficients for deployment 7, positioned in Taggia during winter (W). Pearson coefficients (orange) as well as Spearman coefficients (blue) between song parameters and noise levels are shown. The y-axis represents the variables compared with noise levels; the x-axis reports values of the coefficient, with positive values to the right and negative values to the left. Significant correlations are marked with * (p-value < 0.05).

Supplementary Files

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