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Investigating the effects of underwater noise from two vessels on the behaviour of short-finned pilot whales

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A R T I C L E I N F O

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A B S T R A C T

Multiple whale-watching vessels may operate around cetaceans at any one time, and targeted animals may experience underwater noise effects. We hypothesised that the cumulative noise of two vessels with low source levels (SLs) will elicit lower behavioural disturbance in short-finned pilot whales (*Globicephala macrorhynchus*) compared to a single vessel with a higher SL. We measured the behaviour of whales during 26 controls (stationary vessel >300 m) and 44 treatments off Tenerife (Canary Islands, Spain). Treatments consisted of vessel approaches mimicking whale-watch scenarios (distance ~60 m, speed 1.5 kn). Approaches with two simultaneous vessels, with maximum cumulative mid and low-frequency (0.2–110 kHz) weighted source levels ($SLs_{MF\text{-}LF}$) 137–143 dB, did not affect mother-calf pairs' resting, nursing, diving, respiration rate or inter-breath interval. However, a louder single vessel approach with twin petrol engines at $SLs_{MF\text{-}LF}$ 139–151 dB significantly decreased the proportion of time resting for the mother. The results suggest that if a single or two vessels are present, if the cumulative SL is $<$ 143 dB, the behavioural disturbance on the whales will be negligible. By examining noise effects from multiple vessels on the behaviour of pilot whales, the importance of incorporating a noise threshold into whale-watching guidelines was emphasised.

1. Introduction

Whale-watching can cause short- (Christiansen et al., 2010; Constantine et al., 2004) and long-term negative effects on cetaceans (e.g., relative decreases in abundance, population shifts) (Bejder et al., 2006; Lusseau et al., 2006). There are several drivers for behavioural changes, including vessel approach type (e.g., in-path or line-abreast) (Constantine, 2001; Sprogis et al., 2020a,b; Williams et al., 2002a,b), speed (Holt et al., 2021; Sprogis et al., 2023), proximity (Williams et al., 2002a,b), the number of vessels present (Constantine et al., 2004; Villagra et al., 2021; Williams et al., 2009) and underwater vessel noise level (Sprogis et al., 2020a,b). Noise disturbance has received comparatively less research in the literature on whale-watching impacts. However, it has been demonstrated that a louder vessel disturbs cetaceans more than a quieter one (Arranz et al., 2021b; Sprogis et al., 2020a,b). Effects of whale-watch vessel noise may be tested singularly as an individual effect (Arranz et al., 2021b; Sprogis et al., 2020a,b, 2023). In marine tourism destinations, the reality is that cetaceans may be exposed to several whale-watch vessels at the same time. This may include several whale-watching vessels and/or a combination of whale-watch and recreational vessels simultaneously watching an individual or a group of cetaceans. In some locations, there are guidelines on the number of commercial whale-watch vessels permitted around an individual to reduce animal disturbance. For example, in the Canary Islands and Australia, three whale-watching vessels are allowed around a group of cetaceans at any time (Appendix 1). This permitted number of whale-watching vessels excludes recreational vessels; therefore, the number near a group of cetaceans may be greater than this. However, in other locations, there may be no guidelines, or the policies are not enforced on the number of vessels permitted in the proximity to cetaceans. Thus, there could be multiple vessels whale-watching the same group of cetaceans at any one time (e.g., 15 different vessels could be present) (Appendix 1).

Anthropogenic impacts on cetaceans can occur from multiple stressors (*e.g.*, vessel noise, entanglement, pollution) or multiple or single types of stressors (*e.g.*, noise from multiple vessels) (Pirotta et al.,

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2022). Here, we focus on the latter, on the noise effects from multiple vessels (definitions in Orr et al., 2020). The effects of multiple stressors may be additive or interactive (synergistic or antagonistic) (Crain et al., 2008; Orr et al., 2020). An additive effect is an accumulation in an additive way (*i.e.*, no interaction). A synergistic effect is an interaction between stressors that results in a more significant cumulative effect than expected by the combination of stressors. An antagonistic effect is an interchange resulting in a lesser cumulative effect than expected by the combination of stressors. It is generally understood that cumulative effects are complex and rarely simple (*i.e.*, additive) (Pirotta et al., 2022). If the effects are antagonistic, then it can be helpful to managers to prioritise conservation decisions on a single stressor (*e.g.*, stressor intensity) rather than focusing on multiple stressors (Teichert et al., 2016). The general consensus is that the effects of underwater noise could have negative consequences on cetaceans (Erbe et al., 2019). However, studying noise effects from multiple vessels has been challenging and is a knowledge gap. Assessing the noise effects from multiple vessels is important in assessing noise pollution of today's oceans (European Commission's Marine Strategy Framework Directive, Descriptor 11 - Energy and Noise; North-East Atlantic Environment Strategy, 2030, Strategic Objective 8 - Reduce anthropogenic underwater noise to levels that do not adversely affect the marine environment).

In this study, we test the hypothesis that the cumulative noise of two vessels with low source levels (SLs) will elicit less of a behavioural disturbance in short-finned pilot whales (*Globicephala macrorhynchus*) compared to a single vessel with a higher SL. To do this, experiments using a single vessel and two vessel approaches were conducted, and data were collected in a control scenario (vessel >300 m stationary in neutral). Subsequently data from different whale-watching scenarios were compared to control data (e.g., natural behaviour) to test for potential behavioural changes in pilot whales to vessel approaches. We selected pilot whales as a model species to test this hypothesis. Their predictable distribution and relatively long resting periods 'logging' at the surface facilitate their observation, and they consequently represent one of the most targeted species by the whale-watching industry globally (Hoyt, 2018). A population of around 250 pilot whales are resident on the calm, leeward side off Tenerife, Canary Islands (Spain) where deep oceanic waters are close to shore (Servidio et al., 2019; Aguilar de Soto and Alves, 2023). This species is targeted by local whale-watching operators year-round (around 48 operators with 68 vessels; from 2018 data) (IWC, 2021). Whale-watching pressure in Tenerife is high, being the fourth most common whale-watching destination world-wide (Hoyt, 2018; O'Connor et al., 2009).

2. Methods

2.1. Study site and model species

Experiments on pilot whales were conducted off the western coast of Tenerife, Spain (Natura 2000 Network ES7020017; 28.193200° N, 16.891800° W; Fig. 1). Data of pilot whale responses to the simultaneous approach of two vessels were collected in 2022–23 (this study) and to the approach of a single vessel in 2020-21 as presented in Arranz et al. (2021b).

2.2. Data collection-controlled exposure experiments

Experiments were designed to drive two vessels, with known doses of an acoustic stimulus, past focal animals in a whale-watching scenario to examine any behavioural responses of pilot whales. These experiments with two vessels approaches were compared to the results of one vessel approaches on pilot whales, which were previously collected and presented in Arranz et al. (Arranz et al., 2021b) (Table 1, Fig. 2). The acoustic stimulus was generated by the vessels itself, of which the source level (SL) was recorded prior to experiments (detailed below). The distance the vessels drove past pilot whales was measured with a range-finder and was roughly 60 m during each experiment, following the Canary Islands whale-watching guidelines (Decree 178/2000, 6th Sept, Canary Island Government). The distance aimed to be 60 m; however, during whale-watching, this distance varies depending on the animals and weather conditions. Different approach types and vessels were used (Tables 1 and 2). During whale watching approaches, skippers typically switch between using twin engines or a single engine depending on the animals' behavioural state or environmental conditions. Thus, both approaches with a single engine and twin engines were tested.

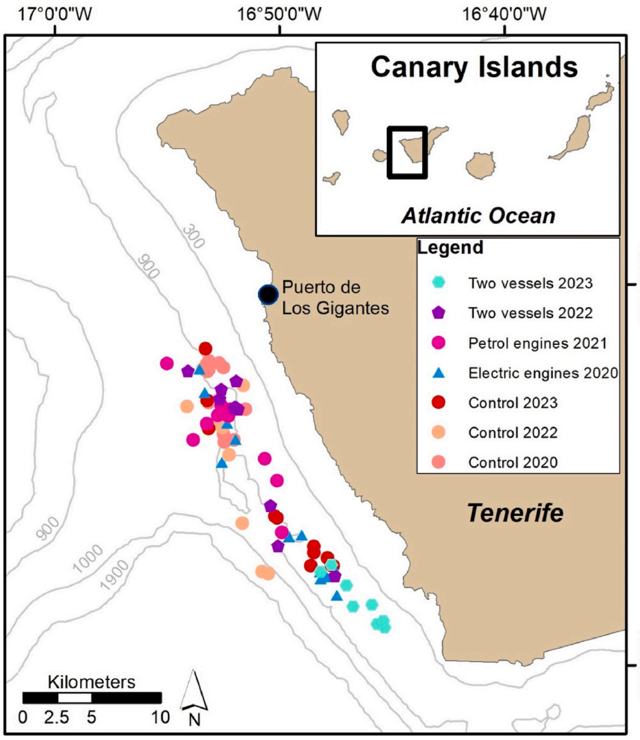

Fig. 1. Study area off Tenerife, Canary Islands (Spain), displaying the locations for data collection in the same location off the southwest of the island from Puerto de Los Gigantes. The different shaped and coloured symbols represent the control data collection on the natural behaviour of pilot whales and the other treatments (two vessels approach, electric engines approach, petrol engines approach). Grey lines represent isobaths (in metres).

2.3. Vessel noise and ambient noise levels

The two vessels used in treatments two vessels_22 and two vessels_23 had petrol-powered motorised engines (Table 1). The underwater noise levels of these whale-watch vessels when transiting at low speed (<4 kn) were recorded in deep waters offshore (>500 m seabed depth), close to pilot whale sighting locations (28.249833° N, 16.864766° W) to mimic the habitat conditions where pilot whales are exposed to vessel noise during whale-watching approaches. Acoustic data for noise level measurements were collected using a SoundTrap ST300 HF acoustic recorder (Ocean Instruments, New Zealand) (144 and 192 kHz sampling rate in 2022 and 2023, respectively, 16-bit, flat (±2 dB) frequency response from 0.02 to 120 kHz, clip level 175 dB re 1 μPa), recording continuously. The SoundTrap was suspended at 4 m depth from a weighted rope connected to a surface buoy equipped with a 3G global positioning satellite (GPS) (Tractive, Austria) and a very-high frequency (VHF) transmitter antenna (ATS, Minneapolis, MN) for tracking and recovery. The vessels were transiting at ~600 rpm (~1.5 knots) at ~60 m (range closest point approach, CPA 33–58 m) distance to the

Table 1
Details of experiments and how the vessels passed the whales in a whale-watching approach at a slow speed of 1.5 kn and 60 m distance to the pilot whales. For details on the vessel type used, refer to the vessel number in Table 2. Year that the data were collected. The number of vessels corresponds to if a single or two vessels were approaching.

Treatment	Year	Number of vessels	Pass type	Engine	Vessel number
control	2020, 22, 23	0	absence of vessel (>300 m stationary in neutral)	na	na
two vessels_23	2023	2	both sides	twin petrol engines used	1 and 2
two vessels_22	2022	2	both sides	single petrol engine used[a]	3 and 4
petrol_21	2021	1	one side	petrol[b]	5a
electric_20	2020	1	one side	electric[b]	5b

[a] as this can be typical during whale-watching approaches.
[b] data presented in Arranz et al. (2021b).

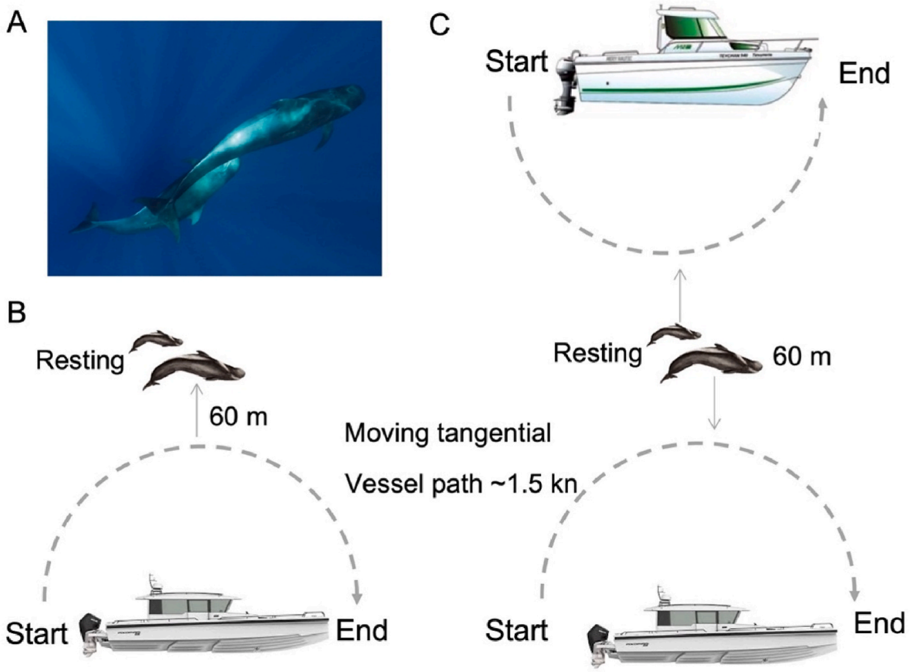

Fig. 2. Schematic diagram of controlled exposure experiments to mother-calf pairs. A) photograph where the calf is nursing from the mother, B) a single vessel passed focal pilot whales as presented in Arranz et al. (2021b), and C) two vessels passed the pilot whales, with the behavioural responses compared to B. Approach distances (60 m), speeds (slow speed ~1.5 kn), and angle of approach (tangential) were the same for all experiments, which mimicked the regulations of whale-watching tours in the Canary Islands.

Table 2
The different types of vessels used.

Vessel number	Length	Inboard/outboard	Engine
1	12 m	inboard	petrol 2x250 hp
2	10 m	inboard	petrol 2x150 hp
3	10 m	outboard	petrol 200 hp
4	6 m	outboard	petrol 80 hp
5a[a]	11.3m	outboard	petrol 2x250 hp
5b[a]	11.3m	outboard	electric 2x11 hp

[a] data presented in Arranz et al. (2021b).

SoundTrap measured with a range finder (Bushnell, MO). Three replicate passes were conducted for each vessel. The SL was quantified as third-octave band levels (TOLs) in dB re 1 μPa RMS (2 s time averaging window, Hann window with 50% overlap) as described in Arranz et al. (2021a). The SL for the two vessels combined was estimated by adding SL intensities (W/m^2) measured from each vessel to minimise potential bias derived from inaccuracies in the range of hydrophone estimation for two moving sound sources.

Pilot whales are mid-frequency (MF) specialists with some sensitivity towards the lower frequencies, with the best hearing in the range from 10 to 50 kHz (Greenhow et al., 2014). Vessel noise was frequency-weighted to match low-frequency (LF) and mid-frequency weighting, ranging 0.2–19 kHz and 8–110 kHz, respectively, to implement representative noise levels within the best hearing range of the pilot whales (Tougaard and Bedholm 2019).

Ambient noise levels (NL) were recorded in the deep-water area where the pilot whales reside. Recordings were made at ~1000 m water depth using two configurations: ~4 m depth from the surface for 5 min periods and (b) ~400 m depth from the surface for a 5 h period on the March 24, 2019 (28.18306° N, 16.8626° W) as in Arranz et al. (2021a). Ambient NL off Tenerife is similar across the year (Jensen et al., 2009), thus, recordings from Arranz et al. (2021a) were suitable for this study. Noise levels experienced by the animals during control treatments were assumed to be equal to the ambient noise statistic, estimated as TOLs (2 s time averaging window, Hann window with 50% overlap). Self-noise spectra were measured from recordings made in the air in an anechoic room at Aarhus University, Aarhus, Denmark, by Malinka et al. (2020).

2.4. *Unmanned aerial vehicle focal follows*

A UAV was used to record the behaviour of pilot whales during the experiments. The target for focal follows were resting mother-calf pairs in small group sizes. Mother-calf pairs are likely the most sensitive to disturbance (Arguelles et al., 2016; Lundquist et al., 2013; Sprogis et al., 2020a,b; Stamation et al., 2010). In contrast, lactating mothers will likely carry the most significant energy cost (Christiansen et al., 2023; Williams and Noren, 2009). Groups were observed with the aid of 7 × 50 Fujinon binoculars for ~5 min before collecting control data or conducting the approaches. Mothers were defined as adult whales >3 m in length, and a calf was described as a whale <2/3 the size of the adult it was accompanying and was in close contact with and nursing from (Arranz et al., 2022). During some occasions, presumed mothers may be another adult female or juvenile, as pilot whales exhibit alloparental care (Augusto et al., 2017; Marsh and Kasuya, 1991). When mothers deep dive for foraging (Aguilar de Soto et al., 2008), calves, with limited diving capabilities, are often observed at the surface where another female or juvenile may join the calf. To account for this, during data filtering, only adults were included (determined by the relative length of the calf to the accompanied whale). The mother/non-parent whale was continuously tracked unless it was impossible (*i.e.*, the adult dove to depth), in which case only the calf was followed. Different sexes may have various sensitivities to stressors (Holt et al., 2021; Symons et al., 2014; Williams et al., 2002a,b); thus, it only assumed that females were targeted to reduce any sex differences. Different age classes may have different sensitivities to stressors; therefore, only adult-calf pairs were the targets. Pilot whales are a social species primarily found in groups. Thus, small group sizes were targeted to limit social factors and changes in behaviour from conspecifics. A pilot whale group was defined as individuals <100 m apart and in the same behavioural state. To control for behavioural type, only resting groups were targeted, and only focal follows where the mother was predominantly resting (>80% of the follows) were included in analyses (following Sprogis et al., 2020a,b). The resting behavioural state offered a standardised behaviour across the beginning of all focal follows, facilitating the detection of behavioural disturbance during the experiments. The resting behavioural state was defined as "a low activity level and included whales logging on the surface, near-stationary a few meters below the surface, swimming and/or surfacing slowly (speed <2 knots)", following Arranz et al. (2021b).

Behavioural focal follows were conducted during single flights using a DJI Mavic 2 Pro UAV (diameter without propellers 354 mm, weight 907 g, 20-megapixel Hasselblad camera recording 4 K video, 3840 × 2160, 30 fps, www.dji.com). The UAV was launched and retrieved by hand from the stern of the whale-watch vessel. The distance between the UAV and the boat was always <400 m to provide a clear line of sight to the UAV. A live-feed iPad 6th gen (9.7″) tablet, equipped with an anti-glare glass and shade hood, was connected to the UAV remote controller and aided whale location (following Sprogis et al., 2020a). Video recording was initiated once the UAV was positioned above the focal mother-calf pair with the camera vertically down (camera sensor in 90° relative to the water surface). In treatments, the vessel started moving at the start of the video recording and for ~15 min each. The UAV hovered above the mother-calf pair at an altitude between 30 and 60 m to minimise potential noise disturbance by the UAV on the animals (Christiansen et al., 2020). UAVs were flown in good weather conditions (wind speed <10 kn and no precipitation). Calibration of the gyro sensors of the UAVs was conducted on land before flying.

All experiments were performed in accordance with relevant guidelines and regulations. Data were gathered with the ethics authorisation of the University of La Laguna Animal Use Ethics Committee. The UAVs were operated under a UAV Operator licence (Register # 2020064914) and an Advanced Certificate of Aircraft piloted by remote control (RPA20605OT and RPA20605OP) under the Spanish Aviation Safety and Security Agency (AESA). All research was conducted under permits from the Spanish Ministry for the Ecological Transition and the Demographic Challenge (permits #AUTSPP/22/2022; #AUTSPP/19/2023).

2.5. *Data processing of UAV videos*

Pilot whale behavioural events were recorded from the UAV videos every 0.5 s using Solomon Coder (v. beta 19.08.02; https://solomon.andraspeter.com/), following (Nielsen et al., 2019; Arranz et al., 2022). Behavioural events recorded in the UAV videos were identified from a pilot whale behavioural ethogram (Arranz et al., 2021b).

2.6. *Proportion of time resting and nursing*

Behaviours of interest were resting and nursing. These behaviours were of importance to examine, as a vessel with high noise emission (SL $_{\text{MF-LF-}}$ 139–151 dB re 1 μPa RMS @ 1 m) reduces the amount of time resting and nursing in short-finned pilot whales (Arranz et al., 2021b). Resting was defined as a low-energy behavioural event, including the behavioural events of logging, stationary underwater, and moving slowly based on previous short-finned pilot whale research (Arranz et al., 2021b; Hofmann et al., 2004). Logging was defined as remaining motionless on the surface for >5 s. Stationary underwater was defined as remaining motionless or near-motionless for >5 s. Moving slowly was defined as whales swimming <2 kn with slow surfacing. Apparent nursing was defined as when the calf was positioned on the underside of the adult, accompanied by its rostrum pointing towards the genital area. Nursing events were termed as apparent nursing as the contact between the rostrum and genital area for the nursing of milk was out of view and is therefore presumed (e.g., Ejrnæs and Sprogis, 2021; Nielsen et al., 2019; Sprogis et al., 2023). Nursing was registered while the mother was logging on the surface, stationary underwater, moving slowly, and diving (Arranz et al., 2021b). Both resting and nursing were considered as continuous behaviours, where the start and end of each event were registered in Solomon Coder (v. beta 19.08.02), following other behavioural studies (Arranz et al., 2021b; Nielsen et al., 2019; Sprogis et al., 2020a,b). The total time resting and nursing during each focal follow was then divided by the entire duration to obtain a proportion (continuous value between 0 and 1, derived from continuous numbers). If the mother or calf were off the frame, that individual's total duration of the focal follows was adjusted (subtraction of the amount of time off frame).

2.7. *Surfacing patterns and respiration rate*

The surfacing pattern depends on the pilot whales' behavioural state, e.g., resting, foraging, and socialising. Different surfacing patterns were examined, including the proportion of time diving, respiration rate, and inter-breath interval (IBI).

To analyse the proportion of time diving of the mother, diving was defined as when the focal mother swam vertically to depths, and the edges of the body were difficult to discern for continuous periods (diving did not include 'remaining stationary underwater') (Arranz et al., 2021). Adult pilot whales may dive to 800–1000 m depth during the day (Aguilar de Soto et al., 2008). The proportion of time diving consisted of the sum of 'diving' behavioural events divided by the duration of the focal follow (representative of a continuous value between 0 and 1).

To analyse respiration rate, the number of breaths the focal mother and focal calf took were registered in Solomon Coder. A breath was defined as an opening of the blowhole, even if vapour was not visualised, as this accounted for shallow exhalations. The respiration rate for each individual was calculated by dividing the total number of breaths taken during each focal follow, and the duration of the focal follow. The period of the focal follows was from the beginning to the end of the UAV video recording time and was adjusted to individual mother and calf times if either individual was off the frame for any period during the focal follow.

The surfacing patterns of adult pilot whales consist of shallow near-surface submersions between respirations and deeper dives (>20 m deep) which are generally used during foraging (Aguilar de Soto et al., 2008; Owen et al., 2019). The IBI of the focal mother was calculated from the respiration data, beginning on the first registered breath until the last registered breath, and the mean IBI in seconds for each focal follow was used in analyses. The IBI differs from the proportion of time diving, as the behavioural event of diving represents only the occasions where the pilot whale “swam straight down vertically” (Arranz et al., 2021b). In contrast, IBI represents every occasion between breaths (*i.e.,* including shallow submersions and resting on the surface). The IBI for calves was not considered as calves remain near the surface.

2.8. *Statistical analyses for behavioural effects of pilot whales from vessel approaches*

The response variables used in modelling were the proportion of time resting, nursing and diving, respiration rate, and IBI. Explanatory variables investigated were the whale-watching treatment and group size. Small group sizes were targeted. Nevertheless, group size was added as an explanatory variable to examine if the numbers of individuals affected the response variable. Due to logistical difficulties, data could not be collected during the same period. Therefore, the effect of the year was examined on control data. There was no significant difference among control years (2020, 2022, 2023) on respiration rate (an energetics metric) (LM $p = 0.45$, Appendix 2 and 4). Thus, control data were combined (Appendix 3). As there was no effect of year on control data and as behaviour was standardised across years (>80 % resting for the mother), the behavioural responses of pilot whales to vessel noise were considered comparable across years. Control data were not able to be obtained in 2021 due to time and weather constraints. The explanatory variables of the treatment comprised: control, two vessels (2022 inboard petrol engines and 2023 outboard petrol engines), and one vessel (outboard electric and petrol engines).

Data exploration was followed by Zuur et al. (2010). Models were constructed in *R* v2023.03.1 (R Development Core Team, 2023), following Zuur and Ieno (2016). Regression analyses were conducted where $Y = \alpha + \beta X$, where Y represents the response variable, α the intercept, β the slope, and X the explanatory variable (Zuur et al., 2009). Linear models (LMs) or generalised linear models (GLMs) were used (McCullagh and Nelder, 1989). For the proportion response data (resting, nursing, and diving), the variance is generally not constant across the range of the explanatory variable. Therefore, GLMs with binomial distribution were used. A link function was applied to GLMs as data were non-normal, with a logit link used to ensure Y was bounded by 0 and 1 and linked the expected values to X. For respiration rate and IBI, LMs were used with a Gaussian distribution and identity link. Model validation was conducted where residuals versus fitted values were examined to assess if the model met the assumptions, whereby homogeneity, normality, influential points, temporal autocorrelation, and overdispersion were considered (following Arranz et al., 2021b; Sprogis et al., 2020a,b). Data were log-transformed (log10) if over-dispersed.

3. Results

3.1. *Survey effort*

Data were collected from 30th March - April 2, 2022 and 21st - March 25, 2023 with ∼40 and 50 h on the water, respectively. Data were collected in daylight from 7:30 a.m.–6:00 p.m. local time. Overall, 13–14 controls and 15–10 treatments were conducted in 2022 and 2023, respectively. After filtering data from 2020 to 21 (Arranz et al., 2021b) and 2022–23, focal follows consisted of 26 controls and 44 treatments, with an average flight duration of 11.47 min and 11.72 min, respectively (Table 3). The CPA distance the vessel passed the pilot whales during treatments varied and ranged from 54 to 64 m (mean 59 m, SD 15 m) (Table 3). The average time duration of passes was 11.13 (2.59) mins (Table 3). The average group size for the controls was 6.23 animals and 5.93 animals for the treatments (Table 3). Experiments were conducted at an average water temperature of 19.35 °C (18.1° - 20.2 °C).

3.2. *Vessel noise and ambient noise levels*

The CPA distance the vessel passed the SoundTrap varied and ranged from 33 to 58 m (Table 4). Fig. 3 shows the whale-watch vessel SL_{TOLs} (deep-water offshore) for single and twin engines vessel passes. Combined $SLs_{MF\text{-}LF}$ from two vessels were ∼2 and 9 dB lower than the single loudest vessel used (Table 4). Median ambient noise levels in deep waters (SoundTrap at ∼400 m depth from the surface) were $NL_{TOL\ 2\ kHz} =$ 78 dB re 1 μPa RMS (2 s), 95th percentile 82 dB re 1 μPa RMS (2 s) and $NL_{TOL10\ kHz} =$ 76 dB re 1 μPa RMS (2 s), 95th percentile 79 dB re 1 μPa RMS (2 s) (Fig. 3). Median ambient noise levels in shallow waters (SoundTrap at ∼4 m depth from the surface) were $NL_{TOL2\ kHz} =$ 79 dB re 1 μPa RMS (2 s), 95th percentile 81 dB re 1 μPa RMS (2 s) and $NL_{TOL10\ kHz} =$ 73 dB re 1 μPa RMS (2 s), 95th percentile 80 dB re 1 μPa RMS (2 s).

3.3. *Behavioural effects on pilot whales*

3.3.1. *The proportion of time resting for mother-calf pairs*

Resting mother-calf pairs, where the mother was predominantly resting (>80 %), were the target for focal follows. The average time resting decreased during treatments compared to control data (Table 5, Fig. 4A). During 9 % of treatments where two vessels passed, the mother rested for 100 % of her time (1/10 in 2023 and 1/11 in 2022). Group size did not significantly affect the proportion of time resting for the mother (GLM $p = 0.80$, Appendix 4). When comparing treatments (control, electric engine, petrol engine, and two vessels), the petrol engine had a significant effect reducing the proportion of time resting (GLM prop. resting.mother ∼ treatment, slope (se) $= -2.14$ (0.99), $t = -2.17$, $p = 0.03$). Two vessels passing did not significantly affect the proportion of time resting for the mother (GLM 2022 $p = 0.09$ and 2023 $p = 0.07$, Appendix 4).

The average proportion of time resting for calves during control data was lower than the mother and lower during controlled exposure experiment treatments (Table 5, Fig. 4B). Group size did not

Table 3
Data collected in each treatment, showing the total sample sizes for controls and controlled exposure experiment treatments, and the Unmanned Aerial Vehicle (UAV) flight duration, the time that the focal individuals (mother and calf) were in the frame of the UAV, the average closest point of approach (CPA) to the focal pair, the duration of the vessel approach and the group size. Times are in minutes and CPA in meters. The values across columns are averages and standard deviation is in parentheses.

Data	*n*	Flight duration	Time in a frame (mother)	Time in frame (calf)	CPA	Approach duration	Group size
control	26	11.47 (3.30)	10.46 (3.68)	10.57 (3.48)	NA	NA	6.23 (4.97)
two vessels_23	10	11.22 (1.35)	10.41 (2.56)	9.73 (2.44)	64 (23)[a]	11.05 (1.71)	5.40 (3.66)
two vessels_22	11	11.97 (2.89)	11.63 (3.27)	11.25 (4.04)	58 (13)[a]	11.70 (3.33)	5.27 (3.23)
petrol_21	10	11.67 (1.54)	11.45 (1.38)	11.13 (1.66)	54 (14)	11.18 (2.08)	6.60 (3.86)
electric_20	13	11.92 (2.58)	11.05 (3.25)	11.42 (2.74)	63 (11)	10.63 (3.80)	6.38 (2.99)
Treatment totals	44	11.72 (2.20)	11.04 (2.75)	10.93 (2.85)	59 (15)	11.13 (2.59)	5.93 (3.34)

[a] CPA of vessels # 1 & 4, respectively.

Table 4

Individual and combined source levels of vessels used in each treatment, showing Vessel #: Unique identification number of the vessel assigned to preserve the anonymity of the vessel. SL: Source level for TOL bands (RMS) with 2 and 10 kHz centre frequency and for low-frequency (LF) and mid-frequency (MF) weighting, in dB re 1 µPa RMS @ 1 m. CPA: closest point of approach for a single vessel passing. Cumulative SL: Cumulative source level for low-frequency (LF) and mid-frequency (MF) weighting, in dB re 1 µPa RMS @ 1 m 'na' not applicable. CPA represents the average. The standard deviation is in parentheses across columns.

Data	Vessel #	$SL_{TOL2\ kHz}$	$SL_{TOL10\ kHz}$	SL_{LF}	SL_{MF}	CPA single vessel pass	*Cumulative* SL_{LF}	*Cumulative* SL_{MF}
two vessels_23	1	126 (4)	125 (1)	140 (3)	135 (4)	52 (2)	142	137
	2	127 (4)	124 (1)	139 (1)	130 (2)	48 (7)		
two vessels_22	3	121 (1)	118 (1)	141 (2)	93 (0)	62 (13)	143	95
	4	117 (1)	116 (1)	136 (2)	92 (1)	54 (9)		
petrol_21	5a	137 (1)	132 (1)	151 (1)	139 (2)	57 (3)	na	na
electric_20	5b	132 (1)	130 (1)	136 (1)	140 (1)	33 (9)	na	na

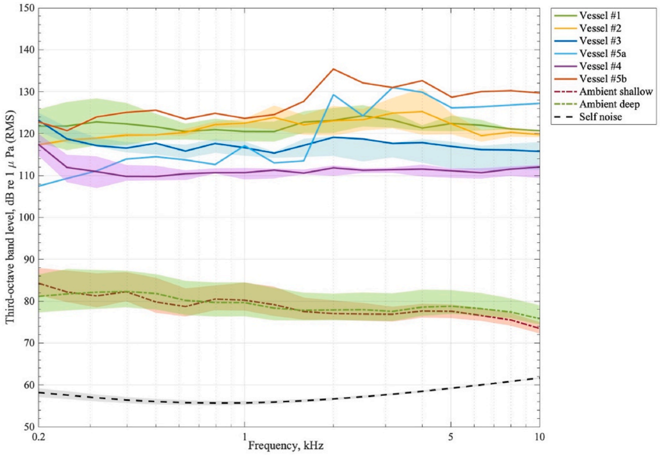

Fig. 3. Source levels of vessels used during treatments quantified as third-octave level bands in dB re 1 µPa @ 1 m RMS. The shaded outline represents the 25th and 95th exceedance levels. The figure extends from 0.2 to 10 kHz, where the hearing range of short-finned pilot whales is likely above 2 kHz. Ambient noise presented from ~1000 m water depth, with the SoundTrap at ~400 m and ~4 m depth from the surface in 2019. The self-noise of the SoundTrap is the dotted black line.

significantly affect the proportion of time resting for the calf (GLM p = 0.64, Appendix 4). The treatment did not affect the proportion of time resting for the calf; specifically, two vessels passing the whales did not significantly affect the proportion of time resting for the calf (GLM 2022 $p = 0.28$ and 2023 $p = 0.19$).

3.3.2. *The proportion of time spent nursing for the calf*

The average proportion of time nursing for the calf, while the mother was predominantly resting, was 19 % (SD = 0.22, range = 0–0.74). During treatments, the average proportion of time nursing overall was lower than for the controls at 14 % (SD = 0.15, range = 0–0.54; Fig. 4C). Group size did not significantly affect the proportion of time nursing (GLM $p = 0.72$, Appendix 4). Two vessels passing the calf did not significantly affect the time the calf was nursing (GLM 2022 $p = 0.71$ and 2023 $p = 0.82$, Appendix 4).

3.3.3. *The proportion of time diving for mothers*

The average proportion of time diving for the mother during control data was 4 % (SD = 0.06, range = 0–0.17). During treatments, the average proportion of time diving for the mother was 20 % (SD = 0.18, range = 0–0.74), with diving occurring on average more often during the petrol engine treatment at 28 % (SD = 0.25, range = 0–0.74; Fig. 4D). Group size did not significantly affect the proportion of time diving (GLM $p = 0.83$, Appendix 4). Treatment did not significantly affect the proportion of maternal time diving; specifically, two vessels passing did not significantly affect the proportion of time diving (GLM 2022 $p = 0.13$ and 2023 $p = 0.54$, Appendix 4).

3.3.4. *Respiration rate for mother-calf pairs*

The average respiration rate for mothers during control data was 2.50 breaths min^{-1} (SD = 1.08, range = 1.25–5.25). Across treatments, the average respiration rate for the mother overall was 2.43 breaths min^{-1} (SD = 1.02, range = 1.26–5.31; Fig. 4E). Treatment did not significantly affect maternal respiration rate; specifically, two vessels passing did not significantly affect respiration rate (LM, 2022 $p = 0.60$ and 2023 $p = 0.80$, Appendix 4). Respiration rate was influenced by group size (LM: log(respiration.rate.mother) ~ group. size, $R^2 = 0.10$, $F_{1,68} = 8.90$), where there was a decrease in respiration rate with an increase in group size (slope (se) = −0.03 (0.01), t = −2.98, $p = 0.003$, Appendix 4 and 5).

The average respiration rate for calves during control data was 2.37 breaths min^{-1} (SD = 0.89, range = 0.99–4.63). Across treatments, the average respiration rate for the calf overall was 2.44 breaths min^{-1} (SD = 1.35, range = 1350–6.62; Appendix 6). Group size did not significantly affect the respiration rate for calves (LM $p = 0.34$, Appendix 4). Treatment did not significantly affect calf respiration rate; specifically, two vessels passing did not significantly affect respiration rate (LM, 2022 $p = 0.80$ and 2023 $p = 0.38$, Appendix 4).

3.3.5. *Inter-breath interval for mothers*

The average maternal IBI during control data was 27.15 s (SD = 9.26, range = 9.93–46.75). Across treatments, the average maternal IBI was 27.75 s (SD = 11.40, range = 8.87–52.94; Fig. 4F). IBI was influenced by group size (LM: log (IBI.mother) ~ group.size, $R^2 = 0.10$, $F_{1,68} = 6.97$), where there was an increase in IBI with an increase in group size (slope (se) = 0.03 (0.01), t = 2.64, $p = 0.01$, Appendix 4 and 7). Treatment did not significantly affect maternal IBI; specifically, two vessels passing did not significantly affect IBI (LM, 2022 $p = 0.92$ and 2023 $p = 0.89$, Appendix 4).

4. Discussion

There is an increase in underwater noise from anthropogenic sources in today's Anthropocene (Duarte et al., 2021; Frisk, 2012). This increase is mainly associated with vessel noise, including shipping traffic (Erbe

Table 5

The average proportion of time resting for mother and calves across different treatments (control and treatments), and across all treatment (electric, petrol, two vessels 2022 and 2023) with the standard deviation and range in parentheses.

	Control	Electric	Petrol	Two vessels 2022	Two vessels 2023	Across all treatments
Mother	92% (0.06, 0.81–1.00)	73% (0.12, 0.44–0.98)	59% (0.30, 0.12–0.94)	70% (0.27, 0.23–1.00)	67% (0.21, 0.41–1.00)	67% (0.23, 0.12–1.00)
Calf	70% (0.25, 0.13–1.00)	56% (0.24, 0.12–0.85)	43% (0.28, 0.12–0.87)	46% (0.22, 0.06–0.93)	51% (0.21, 0.11–0.95)	48% (0.23, 0.06–0.95)

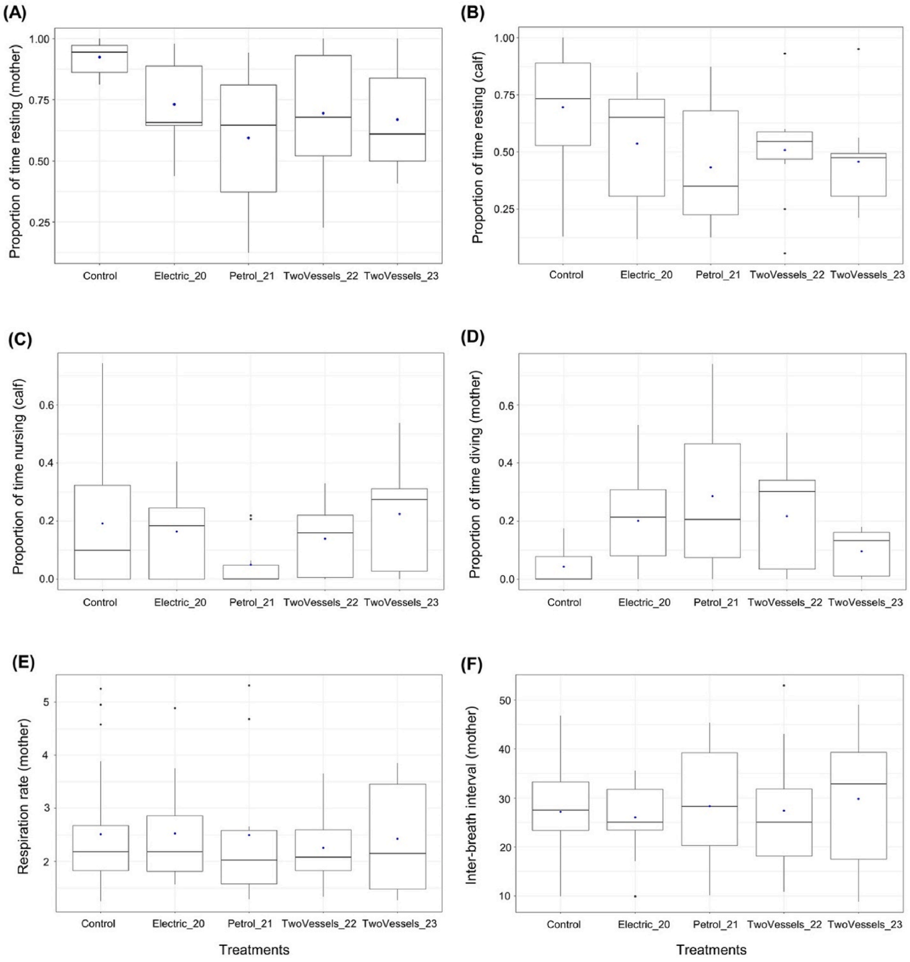

Fig. 4. Metrics explored to examine if there were any significant changes in pilot whale behaviour and respiration patterns compared to natural behaviour (control); proportion of time resting for the mother and calf (A, B), proportion of time nursing (C), proportion of time diving (D), respiration rate (E) and inter-breath-interval (F) for the mother. Graphs are displayed as box and whisker plots showing the data for the control in 2020, 2022 and 2023 combined ($n = 26$), one vessel approach with electric engine treatment (2020, $n = 13$), one vessel approach with petrol engine treatment (2021, $n = 11$) and two vessel approach treatments (2022, $n = 11$ and 2023, $n = 10$). The box shows the middle median value (solid horizontal line), the mean value (blue dot) and the upper and lower quartiles, whilst the whiskers show the minimum and maximum value.

et al., 2019) and small vessel operations (Parsons et al., 2021). Whale-watching vessels are part of these smaller vessels that contribute to ocean noise (Arranz et al., 2021a). During whale-watching tours, there is commonly more than one vessel motoring near an individual or group of cetaceans simultaneously, as currently permitted in some countries (Appendix 1, Table 1). Here, we examined the effects of underwater vessel noise from two motorised vessels compared to single vessel passes on the behaviour of short-finned pilot whales.

4.1. *Vessel noise level and distance effects on pilot whale behaviour*

There were no significant behavioural changes on the proportion of time resting, nursing, diving, and respiration parameters (rate and IBI) of pilot whales during approaches of two motorised vessels or one electric vessel compared to control data. The maximum cumulative SL of the two vessels was $SL_{MF\text{-}LF}$ of 137–143 dB, and for the electric engine vessel was $SL_{LF\text{-}MF}$ 136–140 dB. Consequently, these approaches during whale-watch scenarios had maximum cumulative SLs underwater of ≤150 dB re 1 μPa @ 1 m. Similarly, no significant behavioural changes of these parameters were recorded in humpback whales when the vessel noise was ≤150 dB dB re 1 μPa @ 1 m (Sprogis et al., 2020a,b). However, in the current study, there were behavioural changes from pilot whales from a louder, single vessel approaches (average 54 m distance) compared to control data, where there was a significant reduction in resting for the mother ($p = 0.03$). These louder single vessel approaches, which had twin petrol outboard engines, had a $SL_{MF\text{-}LF}$ of 139–151 dB, significantly decreased the proportion of time resting time for the mother and nursing for the calf as shown in Arranz et al. (2021b). The current study accepts the hypothesis that a single vessel passing pilot whales with a higher SL will elicit significant behavioural changes on pilot whales compared to two vessels passing with low cumulative SLs. These findings highlight the importance of overall underwater vessel noise level, regardless of the number of vessels present. The minimum difference in SLs recorded between the experimental vessels used in this study was 8 dB in SL_{LF} (Table 4). A 6–10 dB difference represents a considerable (>75%) increase of the instantaneous acoustic footprint of a vessel (the area exposed to underwater radiated noise above the ambient at a point in time), based on the work of Findlay et al. (2023). In this study, an 8 dB increase resulted in significant behavioural changes on pilot whales.

Results may have also been influenced by the distance of the vessels to the pilot whales. Overall, during vessel approaches, the CPA distance differed with a 10 m variation to the pilot whales (mean 59 m, SD 15, min 54 m, max 64 m). Distance to the whales was measured with a range-finder and was roughly the same during each experiment. However, the average distance to the pilot whales for the petrol vessel treatment (with the highest SL) was the closest to the whales among the treatments (at 54 m, SD 14). Thus, the closer average distance may have contributed to a significant reduction in resting for the mother. Although, a 10 m distance variation is limited and the distance to the whales also differs to this extent in real-world whale-watching scenarios. Ultimately, when considering the results and the effect of underwater noise at closer distances, this mean distance should be taken into account.

4.2. Cumulative vessel noise effects

The combination of noise from different sources leads to cumulative noise exposure to the animals (Wright and Weilgart, 2011). Some studies have addressed the cumulative effects of vessels presence in odontocetes, using the number of vessels present as a proxy of cumulative impact. For example, the surfacing behaviour of sperm whales (*Physeter macrocephalus*) was not significantly affected by the number of whale-watch vessels present (1–3 vessels) (Markowitz et al., 2011). In contrast, bottlenose dolphins (*Tursiops truncatus*) varied their resting behaviour significantly with school size and to the number of boats present (Constantine et al., 2004). The IBI of killer whales (*Orcinus orca*) also considerably reduced, and dive time tended to be longer as the number of boats increased within 400 m of the focal whales (Williams et al., 2009). Furthermore, the behaviour of humpback whales was significantly altered during swim-with-whale attempts, where three vessel approaches 50 m distance to the whales were permitted to place swimmers in the water. The disturbance effect could be due to the cumulative effects of the approaching vessel noise and/or the swimmers being placed in the water multiple times (Sprogis et al., 2017, 2020a,b). Here, we presented the cumulative effects in terms of underwater vessel noise from two vessels, complimenting the literature on cumulative anthropogenic impacts on cetaceans. To add complexity, there is sliding scale of cumulative effects, from the cumulation of noise from two vessels simultaneously, to a few hours in duration where the whales are targeted daily, to tens of hours over a whale-watching season (for a migratory species) or over a year (for a resident species). Short-term effects alone are unlikely to lead to long-term energetic effects, as animals may be able to compensate for an increase in energetic demands (or a decrease in energy acquisition) by feeding and/or resting more when the disturbance is absent (*e.g.*, in-between whale-watching tours, or a night) (Christiansen and Lusseau, 2014). However, if cumulative noise is frequent and chronic over the day, season or year, the animals may not be able to easily compensate for any lost energetic costs, a concept known as allostasis (McEwen and Wingfield, 2003; Wright, 2008). If this is the case, this suggests that chronic disturbance may need to be investigated. It remains unknown if there are any long-term effects of whale-watching on the pilot whales off Tenerife, *e.g.*, chronic disturbance could lead to a long-term reduction in resting resulting in energy deficits. Elsewhere, long-term effects were shown in resident bottlenose dolphin populations (*Tursiops* spp.) targeted by whale-watching vessels for several hours per day across the year (Lusseau, 2006; Lusseau et al., 2006; Bejder et al., 2006). Further research monitoring any changes in body condition and stress levels of individual pilot whales is required to identify potential negative long-term impacts of whale-watching on the resident population off Tenerife where the tourism is intensive.

4.3. Management considerations

Despite the global effort for implementing best-practice principles, to date, there are no regulations on whale-watch vessel noise levels, partially due to the difficulties in conducting longitudinal studies that contemplate the variety of vessels used in the whale-watch industry (Arranz et al., 2021a). Underwater noise effects from whale-watch vessels are likely complicated as there are many different types of motorised whale-watch vessels, ranging from catamarans, monohulls, sailboats, rigid-hulled inflatable boats (RHIBs, incl. zodiacs), and wooden boats. For the same speed and distance, different whale-watching vessels will produce different received noise levels (Arranz et al., 2021a). The noise from commercial whale-watch vessels ranges from 138 to 169 dB re 1 μpa @ 1m (Arranz et al., 2021a; Jensen et al., 2009; Wladichuk et al., 2019). Furthermore, depending on their hearing ranges and sensitivity to specific frequencies, cetaceans will hear this sound differently. Noise exposure criteria have been developed to define the RLs when noise-induced effects are predicted to occur (Lucke et al., 2020). Some challenges arise from metrics used in different studies to quantify these criteria (*e.g.*, estimated frequency-weighted sound exposure level, underwater sound pressure level, estimate species audiograms or weighting functions) (Southall et al., 2007). Nonetheless, these criteria should be considered caveats and the expectation of subsequent revision.

The probability that animals are affected will also vary as a function of noise propagation conditions of the habitat and ambient noise levels. For example, ambient noise from shallow coastal waters and deep oceanic waters differs by generally having lower ambient noise levels in deep water habitats. The lower the ambient noise level, the larger the excess noise from a noise source (Arranz et al., 2021a). If there is a spectral overlap, then the noise can interfere actively with the ability of toothed whales to echolocate, communicate and navigate (Erbe et al., 2016; Jensen et al., 2009; Parks et al., 2011; Veirs et al., 2016). Management of noise in different habitats should therefore be considered at the local ambient noise conditions and through propagation modelling, as both may affect the perceived levels of the animals. Standardization on how to quantify whale-watching vessel SLs under predictable propagation conditions is thus needed.

Using quieter engines in motorised vessels will consequently minimise the probability that the animals are affected by noise. For example, transferring whale-watching vessels to hybrid (e.g., electric and petrol engines) or full electric capacity could aid in reducing noise levels. These electric vessels appear to have quieter SLs than petrol and diesel engines (Arranz et al., 2021a; Parsons et al., 2021). These options are already available for use, for example, hybrid whale-watch vessels (Arranz et al., 2021a), solar electric ferries (Parsons et al., 2020), and wind energy-powered vessels (Pascual et al., 2021). Management actions in reducing vessel noise have been successful in the past, for example, efforts to reduce vessel noise were put in place to assist in the recovery of endangered killer whales off Canada (Williams et al., 2021).

Management implications of noise impacts include multiple challenges, such as, establishing noise thresholds, reducing noise levels as a precautionary principle and defining marine protected areas or long-term monitoring programs able to detect cumulative and synergistic effects (Weilgart, 2007). Evidence-based noise threshold for whale-watching vessels of SL (0.2–10 kHz) limit of <143 dB re 1 μPa RMS @ 1 m is recommended for vessels operating around whales as close as 100 m (Sprogis et al., 2020b, Arranz et al., 2021b; Sprogis et al., 2023). In this study, the approaches to the whales with two whale-watch vessels simultaneously at low speed and with a cumulative low SL, were within this noise emission recommendation. However, since in the Canary Islands 60 m is the current allowed minimum distance for watching whales, a lower LF-weighted SLs is recommended (Arranz et al., 2021).

5. Conclusion

Noise from two whale-watching vessels with low SLs did not significantly affect mother-calf pilot whale behaviour, whereas a single vessel with louder SL did. In this case, the most effective way to reduce the impact of disturbance during whale-watching is to incorporate a noise emission threshold, to ensure no single loud vessel is represented in a whale-watching fleet. Indirectly, this will lessen any potential for heightened noise effects. Researching underwater noise effects on cetaceans in an empirical approach has been challenging. Scientists require adequate baseline data of natural scenarios and an understanding of the single stressor before cumulative stressors are applied in order to fully appreciate the combination of cumulative impacts (either stressor types or levels) and the differences in the magnitude of the responses (Pirotta et al., 2022). Assessing the noise effects from multiple vessels is important in assessing noise pollution of today's oceans. These results are applicable to other whale-watching locations globally to aid in developing best-practice, sustainable guidelines, including a noise threshold.

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CRediT authorship contribution statement

P. Arranz: Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **R. De la Cruz-Modino:** Writing – original draft, Visualization, Project administration. **K.R. Sprogis:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2024.106574.

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