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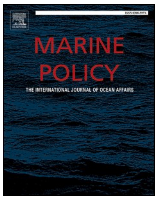

Full length article

Effects of whale-watching activities on southern right whales in Encounter Bay, South Australia

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ABSTRACT

Southern right whales (*Eubalaena australis*) are listed as Endangered under the Australian EPBC Act 1999. They migrate to shallow, coastal waters during the winter to mate, calve and nurse their young. During this time, they are easily accessible to the boat-based whale-watching industry. The aim of the study was to determine if whale-watching at 300 m distance affects the behaviour of southern right whales. To achieve this, behavioural focal follows on mother-calf pairs were conducted using unmanned aerial vehicles (UAVs) in the presence and absence of a commercial whale-watching vessel. There was no significant effect of phase (*control, before, during, after*) on the whales' respiration rate, swim speed, nursing rate and duration, maternal rate of active behaviours, tactile contact or calf pectoral fin contact. There was a significant reduction in resting between *control* and *after* phases, for both mothers (from 62% to 30%) and calves (from 16% to 1%). At 300 m distance and slow speed, vessel noise was measured to be slightly above ambient noise at the lower $\mathrm{TOL}_{0.25\ \mathrm{kHz}}$ band, however, vessel noise was masked by ambient noise within the higher frequency $\mathrm{TOL}_{2\text{–}10\ \mathrm{kHz}}$ bands. A factor which may have contributed to a decline in resting *after* whale-watch approaches, was an increase in vessel speed upon departure, which consequently increased vessel noise. Based on this, we recommend that vessels maintain a slow speed (*e.g.,* ≤10 knots) within 1 km distance from the whales whilst conducting whale-watch activities.

1. Introduction

Southern right whales (*Eubalaena australis*) were hunted to near extinction during the 19th and 20th century, with whaling for the "right" whale in Australia reaching a peak around 1840 [6]. There were no confimed sightings of the species off Australia for a century, until a mother and calf were sighted off Albany, Western Australia, in 1955 [6]. Today, the abudance estimate of southern right whales in the western subpopulation is estimated at 3191 individuals (6.2% p.a. increase) [43] and the eastern subpopulation consists of 268 animals (4.7% p.a. increase) [47]. As their numbers are still far below the estimated historical abundance and range [17], southern right whales remain listed as Endangered under the Environment Protection and Biodiversity Conservation Act [19].

The same year that there was a confirmed sighting of a southern right whale mother-calf off Western Australia, in 1955, boat-based whale-watching was established in the USA. Customers paid $1 USD to watch gray whales (*Eschrichtius robustus*) off San Diego in small boats [25]. Since then, whale-watching has expanded across coastal areas globally with tourists spending more than $2.1 billion USD annually [25]. Australia is the second most popular country in the world for whale-watching, with a total expenditure of $264.3 million (most recent figures from 2008; [38]). The industry brings substantial benefits to local communities, through economic gains and employment opportunities, and to society more broadly through education and environmental conservation [24].

Although there are clear benefits to society from whale-watching, boat-based activities can negatively affect the behaviour of the targeted whales (*e.g.,* [42]), which in turn can result in bioenergetic consequences (reduced energy intake and/or increased energy expenditure)

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[52,8,9]. Short-term responses to boat-based whale-watching include alterations in respiration rates, swim speed and behavioural activity, and a decrease in the amount of time resting and nursing [2,45,7]. Limiting unnecessary energy expenditure in southern right whales on their breeding grounds is of importance as energy lost cannot be regained until the whales return to their feeding ground in the Southern Ocean [32].

There are several factors that influence the level of disturbance experienced by whales during whale-watch activities, including the distance between the vessel and whales, the underwater noise level of the vessel, and the speed/approach type of the vessel [24]. For example, when a whale-watch vessel approaches within 300 m of humpback whales (*Megaptera novaeangliae*) the heading of the whales deviates, and within 100 m agonistic behaviours of whales increase [46]. Cetaceans' primary sensory modality is hearing and louder whale-watching vessels have been correlated with reduced resting times in humpback whales and pilot whales (*Globicephala macrorhynchus*) [2,45]. Although negative disturbance effects from whale-watching are documented, there are not necessarily up-to-date best-practice guidelines in place by permitting agencies, which emphasises the need for continued research and adoption of adaptive management practices [50].

Southern right whales off Australia are a target species for whale-watching during the winter breeding season when whales are present in shallow, coastal waters to mate, calve and nurse their young. There are around13 main sites along the south coast of Australia where southern right whales aggregate [17], which provide predictable locations for whale-watching companies to operate [50]. These aggregation areas in shallow waters (<10 m depth) are preferred habitats by mother-calf pairs [18,40], where mothers use these waters as an anti-predator strategy to protect their calves from predators, such as killer whales (*Orcinus orca*) [37]. As the southern right whale population in Australia is Endangered and still in recovery from whaling, it is of importance to understand any effects of whale-watching on individuals, and manage any adverse effects accordingly.

Off South Australia, whale-watching on southern right whales began in Encounter Bay in 2001. Over two decades later, the potential ecological impact of whale-watching on the whales has not been assessed despite regulatory bodies permitting this tourism. In Encounter

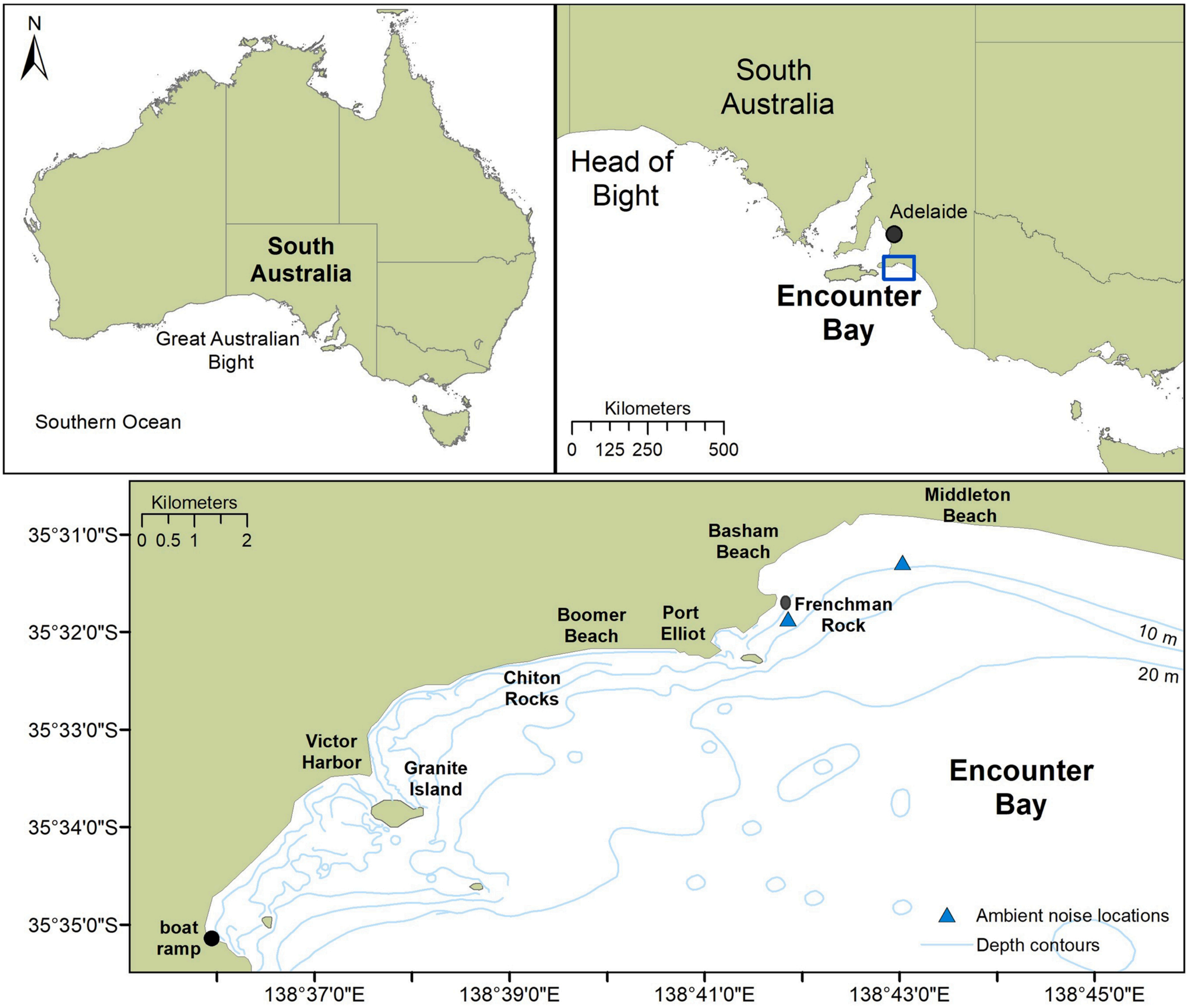

Fig. 1. The study area in Encounter Bay, South Australia. The whale-watching vessel launched from the Encounter Bay boat ramp and transited towards Frenchman Rock and Middleton Beach where the whales were commonly located. Data on the ambient noise were collected at Frenchman Rock (submerged rock platform) and Middleton Beach (surf zone). This area in shallow coastal waters within the Encounter Marine Park is the Encounter Bay Restricted Area, where vessels are not to approach closer than 300 m to any whale [35].

Marine Park, within the Encounter Bay Restricted Area, all vessels (including recreational users) are required to remain 300 m distance from all whale species [35]. When approaching the 300 m distance, skippers are required to operate their vessel at a no-wake speed (*e.g.,* <4 kn) and approach the whales from the rear-side/side [13]. Whale-watching operators are permitted to conduct a maximum of two tours per day, and must not attempt to interact with an individual or group more than two times per tour. The skipper must not allow the vessel to remain within 300 m of the whale for more than 60 mins a day [35]. The aim of this study is to determine if boat-based whale-watching at 300 m distance affects the short-term behaviour of southern right whales. To achieve this, behavioural focal follows on mother-calf pairs were conducted using unmanned aerial vehicles (UAVs) in the presence and absence of a commercial whale-watching vessel. Furthermore, the acoustic source levels (SLs) of two whale-watching vessels were calculated to assess the excess noise whales may hear above their ambient noise surroundings within and beyond 300 m distance.

2. Methods

2.1. Study location and species

Fieldwork was conducted in Encounter Bay, South Australia (Fig. 1), between August 14 and September 14, 2021. Encounter Bay is a former shore-based whaling station and is currently an emerging aggregation ground for southern right whales. Around four mother-calf pairs (mean = 4.4, range = 1–9 pairs) reside in Encounter Bay over winter-spring (Jun-Nov) [27,33]. The average residency for mother-calf pairs is around 50 days, with movement of whales among other aggregation areas [27,33]. One whale-watch company was active in Encounter Bay in 2021. During a whale-watching trip, vessels depart from the Encounter Bay boat ramp and transit towards Frenchman Rock and Middleton Beach where the whales are commonly located across years (Fig. 1) [33].

2.2. Data collection- unmanned aerial vehicle focal follows

Southern right whale behavioural data were collected through individual focal follows using a UAV. Two quadcopter UAVs (DJI Phantom 4 Advanced; www.dji.com; diameter = 350 mm, weight = 1368 g; video = 4 K, 3840 ×2160, 50 fps) were used to record focal follow videos of mother-calf pairs over several consecutive flights. Flights were conducted from land-based vantage points from Chiton Rocks to Middleton Beach (Fig. 1). The UAV was flown above the whales at an altitude of 25–30 m with the UAV camera pointing vertically down at a 90° angle with the centre of the frame on the mother. At this altitude, there are no apparent acoustic or behavioural effects on southern right whales from the UAV [10,11]. The video allowed for registering of behaviours *post hoc*, and the movement of the whales through the GPS location (latitude and longitude recorded every 100 ms). The UAV hovered above the focal whale for around 15–20 min during each flight (the duration of one battery). The UAV was flown on consecutive days over the same focal whales, which were photo-identified from the unique callosity patterns on their heads [28,39]. Focal follows of the same mother-calf pair were < 3 hrs in duration within a day, to adhere to permit requirements. Two researchers were present, to help spot for whales and collect data. Data were collected in Beaufort sea states (BSS) 0–3 in which whale-watching tours were conducted.

Different phases of data were collected during focal follows, including:

- *Control* (*i.e.,* natural scenario): data were collected in the absence of vessels on days when the whale-watch vessel was not operating, and earlier in the morning prior to the whale-watch vessel arriving for an 11:00 whale-watch tour (*e.g.,* 07:00). No other vessels were present during *control* data collection. The UAV was flown over the whale, regardless of behaviour type, to capture a range of behaviours in which may be exposed to during whale-watch activites.
- *Before*: data were collected 60 min immediately prior to the whale-watch vessel arriving (*e.g.,* from 10:00 before the 11:00 tour, and from 13:00 before the 14:00 tour). '*Before* data' included periods before both the 11:00 and 14:00 tour on the same day (*i.e.,* on some occasions the whales had already been exposed earlier in the morning to a whale-watching approach).
- *During* (*i.e.,* impact at 300 m distance): data were collected in the presence of a single whale-watching vessel. This phase began/ended once the whale-watch vessel arrived/departed within 1000 m distance to the whales. The 1000 m distance ensured that the vessel noise whilst at higher speeds when approaching and departing the whales was included in the impact.
- *After*: data collection continued after the whale-watch vessel had departed (distance >1000 m) to examine any behavioural responses (*e.g.,* recovery) after the vessel departed.

Data collection among phases (*before, during* and *after*) was continuous to near-continuous (*i.e.,* if the whale travelled along the coast, the reserachers were required to reposition on land to obtain a closer UAV flying distance). Therefore, the time-frame between phases (*i.e.,* from *during* to *after* data) had limited breaks (*e.g.,* 0–20 mins). To determine the distance between the whale-watching vessel and the focal whales during tours, a handheld GPS (Garmin Etrex 22x) was placed on the vessel, which made it possible to calculate the distance between the vessel and the UAV GPS when it was hovering above the whales. Vessel GPS tracks were downloaded onto Garmin Basecamp.

2.3. Data collection- vessel noise and ambient noise

Two different rigid hull inflatable boats (RHIBs) were used by the whale-watching company; 1) the *Observer* a 11.3 m RHIB with outboard engines (3 ×250 hp Honda 4-stroke, 3 propeller blades) and 2) the *Kondoli* a new, larger 12.5 m RHIB with outboard engines (3 ×250 hp Yamaha 4-stroke, 3 propeller blades). The acoustic SLs and signatures of the vessels were calculated by driving past a sound recorder at a known speed and distance. To do this, an autonomous acoustic recorder (SoundTrap 300 STD, Ocean Instruments, New Zealand, www.oceaninstruments.co.nz) was used with a 144 kHz sampling rate (16 bit, 20 Hz–60 kHz (± 3 dB) bandwidth, clip level 174 re 1 μPa (high gain)). The SoundTraps were calibrated by the manufacturer prior deployment using a piston phone. The SoundTrap was placed in the water on a vertical, taught rope that was weighted to the bottom of the ocean floor off Victor Harbor. The SoundTrap was 8 m above the ocean floor. The recording of the 11. 3 m RHIB was made on 3 September 2021 at 10:50 in 12 m water depth (35.55982°S, 138.63649°E). The recording of the 12.5 m RHIB was made on 6 September 2021 at 14:50, in 11 m water depth (35.59672°S, 138.59416°E). The vessels transited past the SoundTrap with ~300 m approach and departure distance, to a ~50 m distance at the closest point of approach (CPA) (*n* = four transits each). Distance to the SoundTrap buoy was measured with a laser rangefinder. The vessels were driven at slow speed (4 kn, <1000 rpm) past the SoundTrap, representing the slow speed in whale-watching guidelines. The speed of the vessel was obtained from a GPS onboard the vessel, and by the researcher onboard the vessel checking the speed in real-time. The approach type of the vessel was the same for repeated transits past the SoundTrap. The echosounder was turned off during all sound recordings. Recordings were conducted in good weather conditions with no to low wave action (BSS <2).

The ambient noise was recorded to calculate the excess noise of the vessel. The ambient noise is the natural noise in the surrounding environment (*i.e.,* control). Excess noise is the amount of noise (from the vessel) in excess above ambient noise. Ambient noise recordings were made on 10 September 2021 in two locations: 1) off Middleton Beach (at Chapman Road) behind the surf zone (35.52146°S, 138.7172°E), where whales frequented in shallow waters, with the SoundTrap in 5.3 m water depth at 2.8 m from the surface, and 2) off Frenchman Rock where a mother-calf pair commonly rested in shallow waters (35.53114°S, 138.6976°E), the recording was made in 7 m water depth at 4.5 m from the surface (Fig. 1). Middleton Beach is composed of a shallow, sandy bottom, with breaking surf waves along the shore. Frenchman Rock was generally more protected from the swell, compared to Middleton Beach, however waves and surge would break on the rock, and the coast was composed of a rocky headland. Recordings were made for 3.38–2.23 h long periods in varied sea conditions (BSS = 1–3) to represent a range of ambient noise conditions exposed to the whales.

2.4. Data processing- respiration rate, swim speed and behavioural events

Data on southern right whale swim speed, respiration rate and behavioural events were collected from UAV focal follows. The behavioural variables described in this section were all estimated within each UAV flight (sample unit) within each focal follow. Videos were processed in the open-source software *Solomon Coder* v19.08.02 (https://solomon.andraspeter.com/).

2.4.1. Respiration rate

Respiration rate (breaths min^{-1}) relates to an animals' energy expenditure (*i.e.*, oxygen consumption), where the number of breaths relates to the amount of oxygen that is required at any point in time [22, 41]. A change in the number of breaths when disturbed by anthropogenic stressors reflects a change in field metabolic rate [9]. A respiration was registered every time a blow was observed or the opening of the blowhole for shallower breaths. The respiration rate was calculated for mother and calves separately by dividing the total number of breaths by the duration of the video recording during the flight.

2.4.2. Swim speed

An increase in swim speed can be likened to a horizontal avoidance strategy by whales [30]. Maternal swim speed was known from the GPS location recorded by the UAV. The swim speed of the calf was dependent on the mother, therefore, was not considered here. Location data was only used when the UAV was hovering directly above the mother, with the camera facing directly down (−89 to −90°). The swim speed was calculated between every GPS position in *R*, and the total was divided by the total distance travelled. To avoid overestimating speed due to small corrective movements made by the UAV, the positional data was sub-sampled to one position every 15 s (Azizeh et al. [4]).

2.4.3. Behaviour (nursing, resting, behavioural events)

Behavioural events were identified from a behavioural ethogram (definitions in Table A1 and visualised in Fig. 2). Behaviours were categorised as either continuous (*e.g.,* logging and nursing, occurs over a longer duration) or instantaneous (*e.g.,* dive, occurs at a precise time) [1] (Table A1). During nursing, the direct transfer of milk was not always confirmed, therefore, the behaviour was registered as 'apparent nursing' (for different nursing positions see Fig. A1). Resting by the mother constituted the behavioural events of logging (surface and sub-surface) and lying upside-down. Calves did not perform upside-down resting for extended periods of time, therefore, resting by the calf constituted the total time logging (surface and sub-surface). Active behaviours which represented an increase in activity level were included; breach, pectoral slap, tail slap, head slap, roll, and active dives (Fig. 2). Tactile contact between mother and calf included any tactile contact, pectoral fin contact and back-riding (Fig. 2). Behavioural variables calculated were nursing rate, nursing bout duration, proportion of time resting, active behaviour rate, proportion of time in tactile contact, and proportion of time the calf was in pectoral fin contact (for more details see Appendix 1).

2.4.4. Covariates and data filtering

Data were filtered in multiple ways because short sampling (flight) durations can bias estimates of respiration rates [52,9], therefore video recordings < 5 min duration were removed to avoid over- or underestimation of respiration rates (based on Azizeh et al. [4]). Additionally, intraspecies interactions occur commonly in southern right whales, as whales are attracted to aggregation areas if there are conspecifics present [40]. The behaviour of mother-calf pairs could be affected by the close proximity of other conspecifics, and might obscure the effect of the whale-watching vessels. To avoid this, flights that included close (<50 m distance) encounters with other southern right whales were excluded from analyses. A close interaction was defined as when the UAV camera was facing vertically downwards, and multiple whales were viewed in the frame (*e.g.,* two mother-calf pairs). Furthermore, several instances of non-offspring nursing occurred (Fig. A1c; [5]), therefore these interactions were removed from analyses. Interspecies interactions with bottlenose dolphin (*Tursiops* spp.) groups were also excluded for the same reason. The presence of some behaviours (*e.g.,* nursing) may not be observed reliably when the water visibility is poor (see the effect in Fig. A2). Therefore, water visibility was scored from 0 to 3 [36]. The scores were scored as 0 excellent, 1 good, 2 fair, and 3 poor (water visibility definitions and examples Fig. A3). For nursing, sub-surface logging, logging and upside-down, only flights when the water visibility was 0–2 were included in analyses (Fig. A2).

The body size of mothers and calves were included as covariates in the analyses, since structural size influences the mass-specific energy expenditure, and hence respiration rate, of southern right whales. The body length of the whales was estimated using aerial photogrammetry methods [12]. Measurements were scaled (converted from pixels to meters) using the built-in barometric altitude of the UAV, while accounting for (adding) the take-off altitude of the UAV above sea level. The relative sizes of the mothers, and relative length of calves compared to maternal length (ML), were confirmed from comparison of body lengths during interactions.

2.5. Data analyses- effect of whale-watching vessel on whale behaviours

A power analysis was conducted to determine the minimum sample size required to detect an effect of a given magnitude for four of our response variables; maternal respiration rate, calf respiration rate, maternal swim and nursing rate (Appendix 2). Our power analysis showed that the sample size was sufficient to detect a difference in maternal respiration rate of 20%, calf respiration rate of 15%, maternal swim speed of 25% and nursing rate of 70% (Appendix 2).

Mixed effects models were constructed to explore if there were effects from whale-watch vessel approaches on mother-calf pairs (Table 1). The response variables of interest included respiration rate, swim speed, nursing rate and bout duration, the proportion of time resting, the rate of active behavioural events, the proportion of time in tactile contact and the proportion of time in pectoral fin contact (Table 1). The response variables that were continuous were analysed using linear mixed effect models (LMMs), and response variables that were proportions or binary were analysed using generalised linear mixed models (GLMMs) with a logit link (Table 1).

Models were developed in *R* v4.0.3 [14]. Prior to modelling, data were explored for outliers. The effect of phase (*control, before, during* and *after*) was the explanatory variable of interest. The sample unit was each flight. Since multiple consecutive flights were often conducted over the same mother-calf pair within a focal follow, the focal follow number was included as a random effect to account for variation in the intercept between focal follows caused by individual variation (Table 1). To account for the temporal dependence between flights within the same focal follow, a temporal auto-correlation structure with lag one was incorporated in the models (Table 1). For each model, the R^2 marginal (R^2_m) and conditional values (R^2_c) were calculated to quantify the variance explained by the fixed effects, and the fixed and random effects,

Fig. 2. Illustrative behavioural ethogram representing southern right whale mother-calf behaviours on a breeding ground. Photographic examples of behaviours from UAV focal follows (a) back-riding, (b) breach, (c) bubble blow, (d) dive (peduncle), (e) fluke slap, (f) head slap, (g) surface logging, (h) sub-surface logging (i) apparent nursing, (j) pectoral fin contact from calf, (k) pectoral slap, (l) roll, (m) spy hop, (n) tactile contact from calf moving tail along its mother's body and (o) upside-down motionless resting below the surface [inset; upside-down on the surface]. Full text definitions are available in Table A1.

Table 1
Models used in analyses to investigate the effect of phase (*control, before, during, after*) on whale behaviour. All models included focal follow ID as a random effect (1|followID) and a temporal auto-correlation structure within follow ID with a lag of one. LMM = Linear mixed effect model, GLMM = generalised linear mixed model.

Model	Response variable ~ Phase	Variable type	Model	Link function	Turbidity	Flights	Follows
1	Maternal respiration rate	Continuous	LMM	Gaussian	0–3	137	40
2	Calf respiration rate	Continuous	LMM	Gaussian	0–3	137	40
3	Maternal swim speed	Continuous	LMM	Gaussian	0–3	137	40
4	Calf nursing rate	Continuous	LMM	Gaussian	0–2	83	27
5	Log(Calf nursing bout duration)	Continuous	LMM	Gaussian	0–2	46	23
6	Maternal surface logging	Proportion	GLMM	Logit	0–2	83	27
7	Calf surface logging	Proportion	GLMM	Logit	0–2	83	27
8	Maternal sub-surface logging	Proportion	GLMM	Logit	0–2	83	27
9	Calf sub-surface logging	Proportion	GLMM	Logit	0–2	83	27
10	Maternal total logging	Proportion	GLMM	Logit	0–2	83	27
11	Calf total logging * *	Proportion	GLMM	Logit	0–2	83	27
12	Maternal resting *	Proportion	GLMM	Logit	0–2	83	27
13	Calf resting * *	Proportion	GLMM	Logit	0–2	83	27
14	Maternal rate of active behaviours	Continuous	LMM	Gaussian	0–3	137	40
15	Calf rate of active behaviours	Continuous	LMM	Gaussian	0–3	137	40
16	Tactile contact	Proportion	GLMM	Logit	0–3	137	40
17	Calf pectoral fin contact	Binary	GLMM	Logit	0–3	137	40

* Maternal resting = surface logging, sub-surface logging, and upside-down resting combined.

** Calf resting = surface logging and sub-surface logging (calves did not display motionless upside-down behaviour for long stationary periods). Thus, for calves' model 11 and 13 are the same input and output.

respectively [34]. Model validation tests included scatterplots of model residuals *versus* fitted values (to assess homogeneity of residuals) and histograms of residuals (to assess normality of residuals). All models fulfilled the model assumptions.

2.6. Data analyses- vessel noise and ambient noise

Acoustic analyses were run in MATLAB (R2017a v9.2.0.556344) using custom written scripts [29], following [3,2]. Vessel audio samples comprising 30 s before and 30 s after the vessel's CPA were extracted for noise level calculations. Extracted 60 s audio samples were analysed to quantify root-mean-square (RMS) in one-third octave levels (TOLs). TOLs were estimated in 2 s windows (Hann window, 50% time segment overlap, 1 s resolution).

With no audiograms available for large baleen whales, the hearing range for southern right whales is unknown, however, baleen whales are considered as low frequency (LF) hearing specialists [44]. Thus, to relate received levels (RL) to the auditory capabilities of the southern right whales, LF-weighting of the audio samples were computed using the 'fileweighting' package with 125 ms time window [48]. Running time averages were computed using default exponential decaying kernel windows.

To correct for the range dependent decrease of the sound intensity between the source and receiver, the vessel's SL was estimated using a back-calculation of 20 x log10(R(m)), where R the geometric mean of the range (distance in m) of the vessel to the acoustic recorder at the CPA. Back-calculated SLs were estimated as median, 5th and 95th percentiles of the 2 s and 125 ms time windows at 1 m, for TOLs ($n = 59$ samples per vessel) and frequency weighting measurements ($n = 472$ samples per vessel), respectively. TOLs at 0.25 kHz were extracted to compute vessel SLs in the band covering peak frequencies of southern right whale mother-calf vocalisations [37], and at 2 and 10 kHz which are bands typically used for noise assessment [23], *herein* $SL_{0.25\ kHz}$, $SL_{2\ kHz}$ and $SL_{10\ kHz}$, respectively.

For analyses of ambient noise level (NL), records were subsampled into 60 min blocks and RMS noise levels quantified in TOLs (2 s time averaging window, Hann window with 50% overlap). The 2 s analysis window was moved in 1 s steps, resulting in a number of samples per record equal to its 1 s duration. The same relevant TOL bands (0.25, 2 and 10 kHz) were selected for evaluating ambient noise in relation to vessel noise using the median, and the 5th and 95th percentiles. Within these TOL bands, the received level of the vessel to the whale located at a given range, as perceived above ambient noise, can be calculated considering the transmission loss (from 20 x log10(R)) across the water column (assuming that excess noise dissipates proportionally to the distance from the noise source to the whale).

3. Results

3.1. Summary statistics

Data were collected across 19 days between 14 August and 14 September 2021. Effort to search for the whales and track their movements consisted of 138 hrs, from 07:00–17:00. There was a total of 168 UAV flights, which included 81 *control*, 33 *before*, 27 *during* and 27 *after* flights (Table 2). During data filtering, 12 flights were removed due to short (<5 min) sampling duration, and 19 flights were removed due to interactions with dolphins ($n = 3$) and conspecifics ($n = 16$). The remaining 137 videos comprised 65 *control*, 29 *before*, 20 *during* and 23 *after* phases.

A total of 18 whale-watching vessel approaches were recorded (example of *during* a whale-watching approach Fig. 3). During whale-watching tours the whales were located off Middleton Beach, Basham Beach and Frenchman Rock (Fig. 1). The minimum distance between the whale-watching vessel and the focal whales *during* an encounter was on average 369 m (SD = 170, range = 235–908 m). The mean vessel speed *during* an encounter was 3.0 kn (range = 0–18 kn) (Fig. 4). The average speed arriving and departing the whales in the *before* and *after* phase at 1.0–1.5 km from the whales was 6.7 kn (min = 2.7 kn, max = 12.9 kn) and 12.1 kn (min= 3.1 kn, max = 24.2 kn), respectively. The mean water temperature during whale-watching was 12. 9 °C (SD = 0.18, range = 12.6–13.3 °C).

There were three mother-calf pairs during the study period, which

Table 2
The survey effort displaying the number of UAV flights and hours of UAV video recording of mother-calf southern right whales. Behavioural focal follows included the phases *control*, *before*, *during*, and *after* the whale-watch interaction.

Phase	No. focal follows	Follow duration (min)		No. flights (hh:mm total)
		Mean ± SD	Range	
Control	25	58.4 ± 41.5	4–170	81 (18:57)
Before	14	37.8 ± 21.1	11–78	33 (6:11)
During	18	19.3 ± 10.1	6–37	27 (5:01)
After	14	29.9 ± 28.9	6–87	27 (5:08)
Totals	44	65.6 ± 48.1	4–192	168 (35:17)

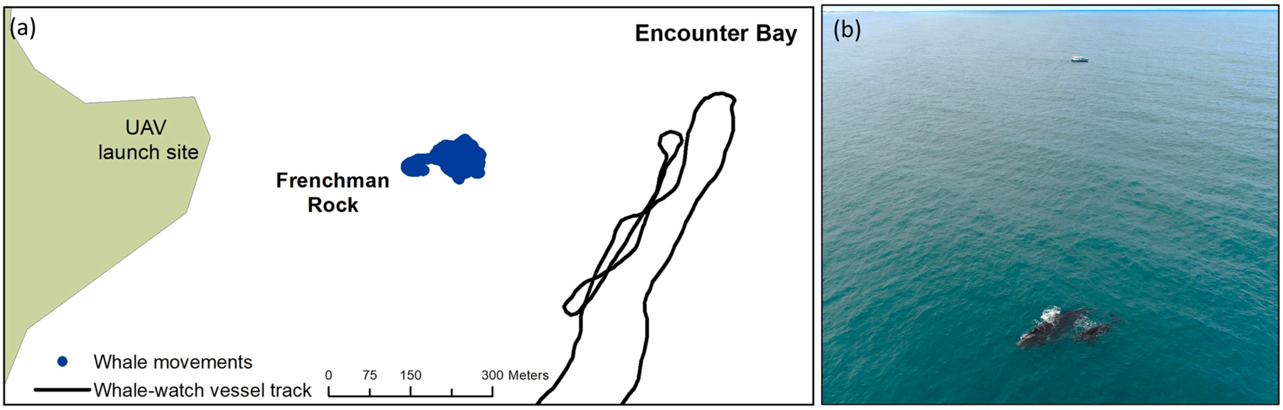

Fig. 3. During a whale-watch example of a mother-calf pair resting next to Frenchman Rock (a submerged rock platform where the waves commonly broke over), showing a) whale-watch vessel approach tracks at 300 m distance (black) and mother-calf pair tracks (blue), whom were drifting with the wave water movement next to Frenchman Rock, and b) the mother-calf in the foreground and whale-watch vessel in the background.

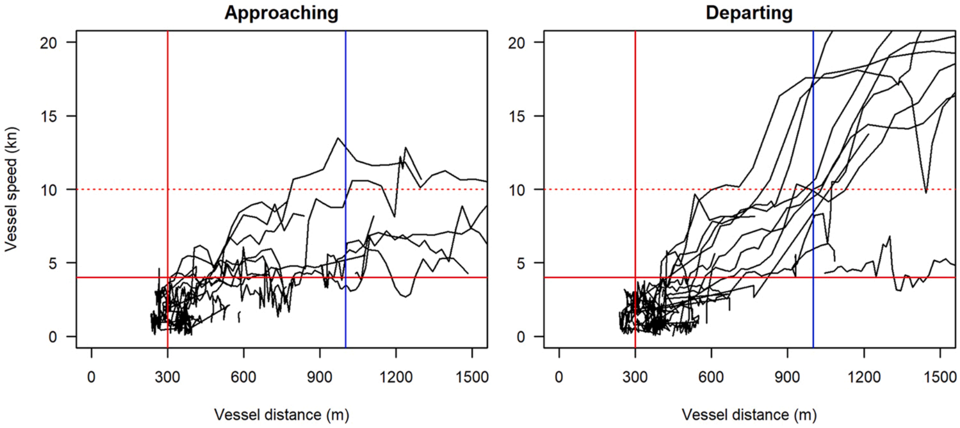

Fig. 4. Vessel arriving (left) and departing (right) speed *versus* distance to the focal whales whilst whale-watching in Encounter Bay, South Australia. Black lines = the GPS data from the different whale-watching trips plotted on top of each other. The solid vertical and horizontal red lines show the vessel distance (300 m) and speed (*e.g.,* low speed, no wake) permitted in Encounter Bay Restricted Area. The vertical blue line highlights the designated 1000 m distance threshold (which encapsulated the *during* phase). The red dotted line indicates the proposed 10 kn vessel speed recommendation to be maintained within 1 km distance from the focal whale.

were identified from their callosity patterns (Fig. A4). Mother-calf pair 1 was located in the region for the duration of the study, pair 2 was encountered across three sampling days, and pair 3 arrived in the study area towards the end of the season. 66% ($n = 90$) of focal follow videos were of pair 1, 13% ($n = 18$) of pair 2% and 21% ($n = 29$) of pair 3. Mother 1 was 16.5 m in length and the calf ranged from 7.5 to 8.5 m (45–51% ML). Mother 2 was 13.3 m in length and the calf ranged from 6.0 to 6.1 m (45–46% ML). Mother 3 was 15.3 m in length and the calf ranged from 7.4 to 7.8 m (48–51% ML). Due to the small number of mother-calf pairs sampled, and the short range of relative calf sizes (45–51% ML), data on maternal length and calf length were not able to be included as covariates in analyses.

3.2. *Effect of whale-watching vessels on whale behaviours*

There was no significant effect of phase (*control, before, during, after*) on maternal respiration rate, calf respiration rate, maternal swim speed, nursing rate, nursing bout duration, maternal rate of active behaviours, tactile contact or calf pectoral fin contact (Fig. 5). Phase had a significant effect on the rate of active behaviours for calves (Model 15: $F_{1,3} = 2.85$, $p = 0.04$, $R^2_m = 6.0\%$, $R^2_c = 21.1\%$, Fig. 4G), with the rate being significantly higher *before* the vessel approach compared to *control* (Model 15 - *control vs. before* : t-value = 2.758, $p = 0.01$). For further results of all behavioural analyses, including effect sizes, see Appendix 3. For all models, there was no difference in residuals among individual mother-calf pairs, indicating that there was no individual bias in the behaviour of the whales (Fig. A5), and there was no effect of time of day.

Mothers rested for ~60% of their time (*control* data), comprising ~25% surface logging, ~30% sub-surface logging and ~5% upside-down resting. There was a significant effect of phase (*control, before, during, after*) on maternal resting behaviours, including surface logging, sub-surface logging, total logging and resting. Specifically, there was a decline between the *control* and *after* phase for surface logging (Model 6 - *control vs. after* : t-value = −2.168, $p = 0.04$, delta-$R^2_m = 2.2\%$, delta-$R^2_c = 8.0\%$), sub-surface logging (Model 8 - *control vs. after* : t-value = −2.324, $p = 0.02$, delta-$R^2_m = 6.1\%$, delta-$R^2_c = 11.8\%$, decline from 62% to 22%, respectively), total logging (Model 10 - *control vs. after* : t-value = −2.622, $p = 0.01$) and resting (Model 12 - *control vs. after* : t-value = −2.311, $p = 0.025$, delta-$R^2_m = 5.0\%$, delta-$R^2_c = 23.2\%$, decline from 62% to 30%, respectively) (Fig. 6A). There was also a decline between *control* and *during* for sub-surface logging (Model 8 - *control vs. during* : t-value = −2.750, $p = 0.01$) and total logging (Model 10 - *control vs. during* : t-value = −2.033, $p = 0.05$, delta-$R^2_m = 7.3\%$, delta-$R^2_c = 20.8\%$) (Fig. 6A).

Calves rested for ~16% of their time (*control* data), comprising ~9% surface logging and ~7% sub-surface logging. There was a significant effect of phase (*control, before, during, after*) on calf resting behaviours, including sub-surface logging and total logging/resting. Specifically, there was a decline in sub-surface logging from *control* to *before* (Model 9 - *control vs. before* : t-value = −2.172, $p = 0.03$, delta-$R^2_m = 8.1\%$, delta-$R^2_c = 9.9\%$) and *during* (Model 9 - *control vs. during* : t-value = −2.150, $p = 0.04$) vessel approaches (Fig. 6B). Total logging/resting also declined *after* whale-watching approaches compared to *control* (Model 11 - *control vs. after* : t-value = −2.212, $p = 0.03$, delta-$R^2_m = 9.2\%$, delta-$R^2_c = 16.0\%$, decline from 16% to 1%, respectively) (Fig. 6B).

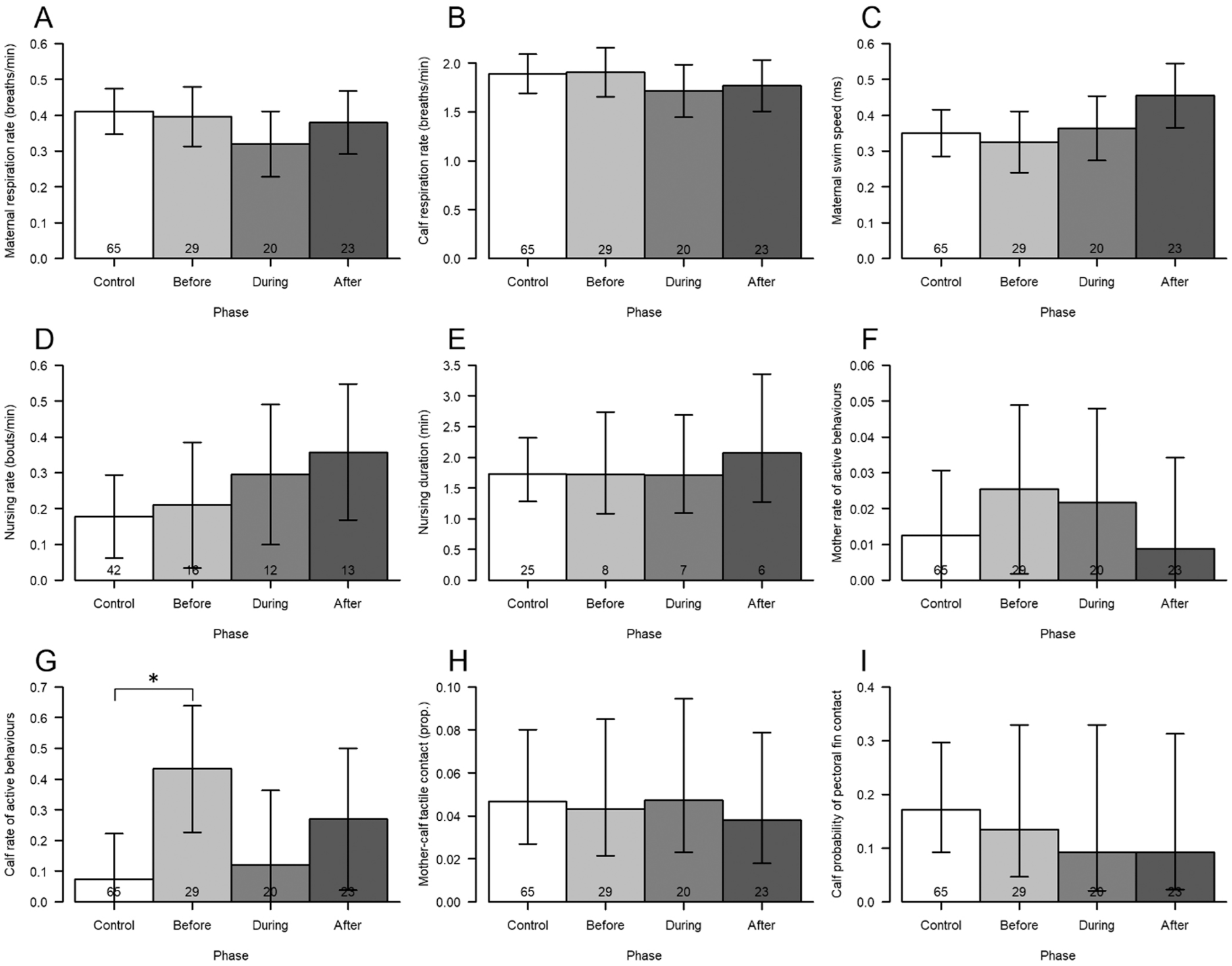

Fig. 5. Behaviour of southern right whale mother-calf pairs in *control, before, during* and *after* phases. (A) Maternal respiration rate of mother, (B) calf respiration rate, (C) maternal swim speed, (D) nursing rate, (E) mean nursing bout duration, (F) probability of mother performing active behaviours, (G) probability of calf performing active behaviours, (H) proportion of time mother-calf pair spent in tactile contact, and (I) and probability of the calf initiating contact with its pectoral fin. Asterisks indicate significant differences among phases. The sample size (number of flights) of each phase is given at the bottom of each bar.

3.3. *Vessel noise and ambient noise levels*

There were 18 whale-watch approaches recorded, 16 (89%) of which were conducted with the shorter RHIB and two (11%) with the new, longer RHIB. A total of four of the closest passes were used in acoustic analyses of the shorter RHIB (40 and 41 m CPA) and longer RHIB (31 and 35 m CPA) (see spectrogram Fig. A6; Table 3). The LF-weighting represented the highest SLs, where the measurements for the longer vessel were louder than for the shorter vessel (SL_{LF}=150 and 144 dB re 1μPa @ 1 m RMS, respectively) (Table 3).

Ambient noise was composed of biological sound sources (*e.g.,* fish, shrimp, cetaceans), physical sound sources (*e.g.,* wave action and wind action) and anthropogenic sound sources (*e.g.,* distant vessels). At both Frenchman Rock and Middleton Beach, ambient noise had lower contributions in low frequency levels, and greater contributions in higher frequency levels (Fig. 7). Frenchman Rock had greater levels of ambient noise at mid and higher frequencies compared to Middleton Beach, but not in the lower frequencies (Fig. 7). At Middleton Beach, the median ambient noise levels ranged from $NL_{0.25\ kHz}$ = 74 dB re 1 μPa RMS (2 s) (95th percentile 87 dB re 1 μPa RMS (2 s)), $NL_{2\ kHz}$ = 74 dB re 1 μPa RMS (2 s) (95th percentile 81 dB re 1 μPa RMS (2 s)) and $NL_{10\ kHz}$ = 84 dB re 1 μPa RMS (2 s) (95th percentile 86 dB re 1 μPa RMS (2 s)) (Fig. 6). At Frenchman Rock, the median ambient noise levels ranged from $NL_{0.25\ kHz}$ = 65 dB re 1 μPa RMS (2 s) (95th percentile 71 dB re 1 μPa RMS (2 s)), $NL_{2\ kHz}$ = 85 dB re 1 μPa RMS (2 s) (95th percentile 87 dB re 1 μPa RMS (2 s)) and $NL_{10\ kHz}$ = 90 dB re 1 μPa RMS (2 s) (95th percentile 91 dB re 1 μPa RMS (2 s)) (Fig. 7).

Vessel SLs were in excess above ambient noise by, on average for the two vessels, 45, 43 and 31 dB off Middleton Beach and 55, 33 and 25 dB off Frenchman Rock, for the $SL_{0.25\ kHz,}$ $SL_{2\ kHz}$ $SL_{10\ kHz}$, respectively (Fig. 7). Considering a 300 m distance to the whale, there is a transmission loss of 49 dB. This infers that vessel noise may be in excess slightly above ambient noise at the lower 0.25 kHz TOL band (which is the case for the louder 12.3 m RHIB), however ambient noise will mask the noise of the vessels at 300 m distance within the 2 and 10 kHz TOL bands.

4. Discussion

Whale-watching has increased substantially off Australia, for example, over a ten year period the number of whale-watchers doubled to over 1.6 million people (2008 numbers, [38]). It is therefore imperative that any negative impacts are minimised to ensure the long-term sustainability of this multi-billion-dollar industry, while

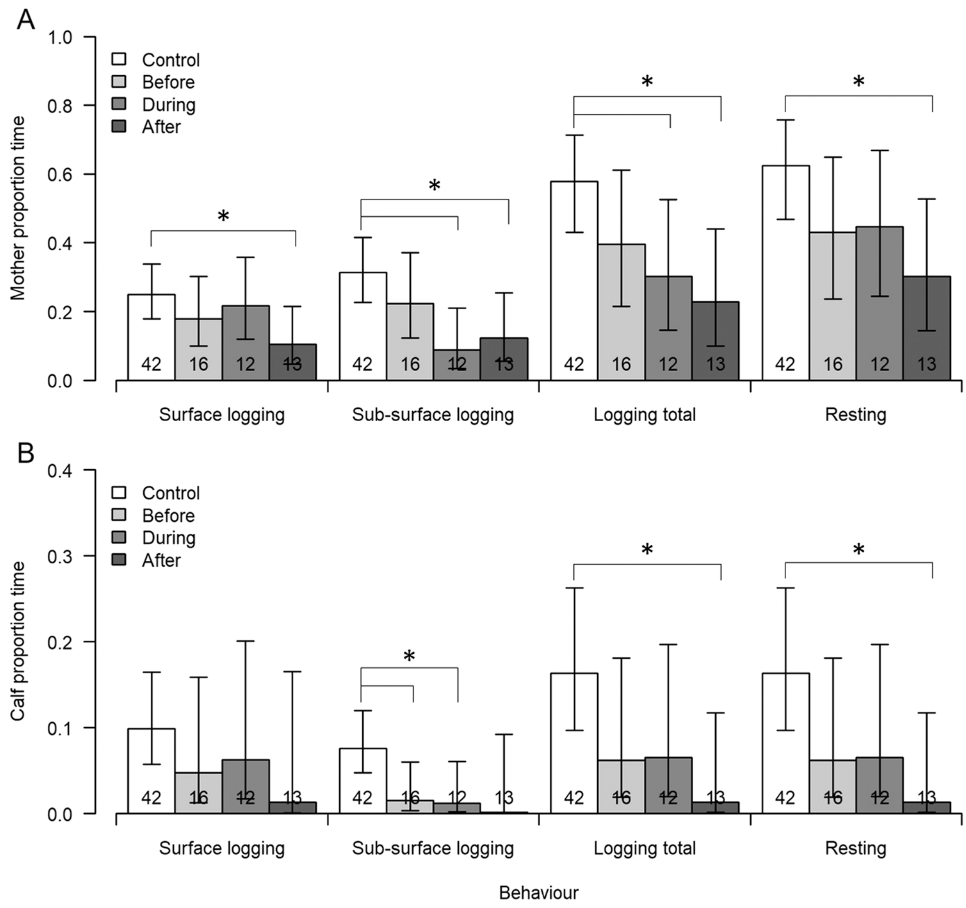

Fig. 6. Logging and resting behaviour of southern right whale mother-calf pairs in *control*, *before*, *during* and *after* phases. The behaviours have been split into surface logging, sub-surface logging, total logging, and resting behaviour for mothers (top panel) and calves (bottom panel). Asterisks indicate significant differences among phases. The sample size of each phase is given at the bottom of each bar. Maternal resting = surface logging, sub-surface logging, and upside-down resting combined. Calf resting = surface logging and sub-surface logging (calves did not display motionless upside-down behaviour for long stationary periods), thus, the models for logging total and resting are the same.

Table 3
Acoustic characteristics of recorded whale-watching vessels. Length: from bow to stern. Engine: the number of engines multiplied by the maximum power of the engine (in horsepower). Speed: approximate speed of the boat when passing the SoundTrap. SL: Source levels for third-octave level (TOL) bands (RMS) with 0.25, 2 and 10 kHz centre frequency and low frequency ($_{LF}$) weighting, in dB re 1μPa @ 1 m.

Vessel type	Length (m)	Engine (Hp)	Speed (kn)	$SL_{0.25\ kHz}$ (dB 1μPa)	$SL_{2\ kHz}$ (dB 1μPa)	$SL_{10\ kHz}$ (dB 1μPa)	SL_{LF} (dB 1μPa)
RHIB *Observer*	11.3	3 × 250	4	116	118	117	144
RHIB *Kondoli*	12.5	3 × 250	4	122	118	113	150

simultaneously protecting target species. Here, we provide a quantitative assessment of whale-watching regulations on the behaviour of southern right whale mother-calf pairs. There was one whale-watch company present in the study area, with a maximum of two tours conducted on weekends. During whale-watch approaches, the distance to the whales was on average 369 m (SD = 170), at 3 kn slow speed, and with vessels with low SLs (≤150 dB re 1μPa @ 1 m). There was no significant effect of phase (*control*, *before, during* or *after*) on respiration rate, maternal swim speed, nursing rate and bout duration, the rate of active maternal behavioural events, the proportion of time in tactile contact and the proportion of time in pectoral fin contact (Appendix 4). However, the rate of active behaviours for calves was significantly higher in the *before* phase compared to the *control* data. This may be due to the calf hearing the whale-watch vessel upon approach and reacting to the vessel in the *before* phase, and/or due to other external factors. Furthermore, *after* whale-watching approaches there was a significant decrease on the proportion of time resting for mother and calves when compared to natural *control* behaviour. Reducing anthropogenic disturbance to southern right whales is particularly important in aggregation areas on a species that is recovering from whaling.

4.1. Effect of whale-watching on resting

Resting is crucial for baleen whales as they are capital breeders and rely on a finite amount of stored energy reserves whilst on their breeding grounds. We found that for *control* phases, southern right whale mothers rest for ~60% of their time, comprising ~25% surface logging, ~30% sub-surface logging and ~5% upside-down resting. For calves, resting is also important, and constituted ~16% of the time for *control* phases, composing of ~9% surface logging and ~7% sub-surface logging. By resting, the whales can minimise the daily energetic cost of activity, and instead allocate the required amount of energy to reproduction for the mother and growth for the calf [15]. This is particularly important for lactating mothers, who carry a large energetic burden and lose around 25% of their body weight over the first three months of lactation [12]. If resting is frequently disturbed by anthropogenic stressors, then the cumulative effects could have significant long-term consequences on the bioenergetics of the whales.

In this study, the proportion of time resting for mothers and calves significantly decreased *after* whale-watching approaches, when compared to the *control*. Specifically, resting for mothers halved (62–30%) and declined to near null (16–1%) for calves. Furthermore, *during* whale-watching, a sub-set of resting behaviour (sub-surface

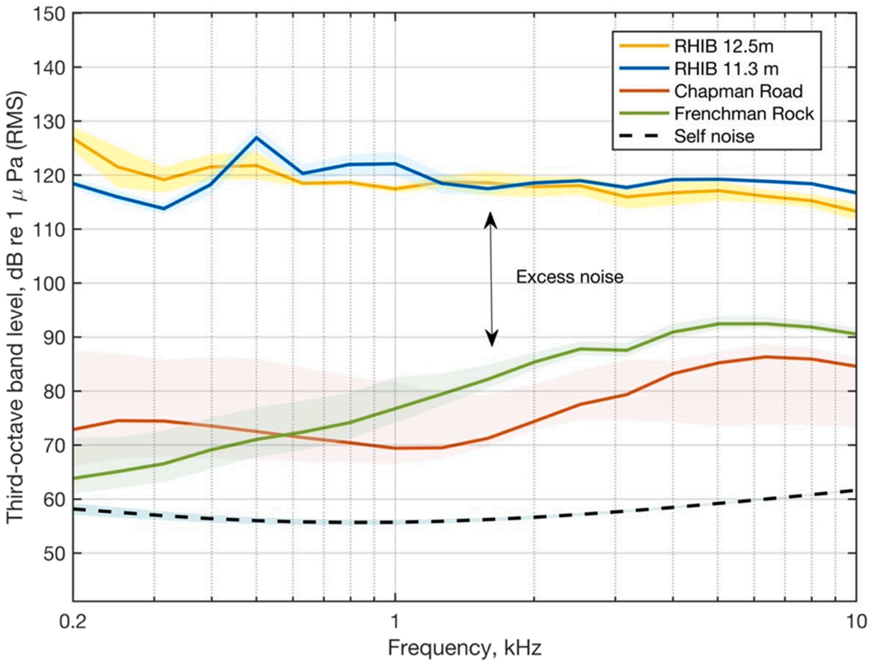

Fig. 7. Source levels of whale-watching rigid hull inflatable boats (RHIBs) and ambient noise levels quantified as third-octave levels (TOLs) across frequencies from 0.2 to 10 kHz (200 to 10,000 Hz). Vessels recorded at ≤4 kn speed, at average 368¯6 m CPA (range = 31-41 m) and in 10-12 m water depth, and reported as back-calculated source levels for each vessel (re 1 μPa @ 1 m RMS). Ambient noise recorded in locations where the whales frequented off Middleton Beach (Chapman Road) and Frenchman Rock, recorded ~4 m depth from the surface (5-7 m water depth). The transparent area around each median corresponds to the 25th and 95th exceedence levels. The dashed line is the selfnoise of the SoundTrap. Although the hearing range of the whales extends lower than 200 Hz (e.g., possibly to at least 20 Hz, Nielsen et al. [37], Ward et al. [51]), the graph begins at 200 Hz, as low-frequencies from vessels will cancel out due to the Lloyds mirror effect at/near the surface, which is where the whales rest whilst on the breeding ground. Note: this figure represents the vessel source level, not the received noise level at the whale (take transmission loss into account to estimate the received level at a given distance).

logging) significantly decreased for mother and calves. These results suggest that whale resting behaviours may have been disturbed in the presence of the vessel and this disturbance was sustained once the vessel departed. A reduction in time spent resting during whale-watching has been a typical behavioural response shown in other species, including humpback whales [46,45], pilot whales [2], Risso's dolphins (*Grampus griseus*; [49]) and bottlenose dolphins (*Tursiops truncatus*, [16,31]). Here, the reduction in resting does not clearly impact the energy budget of the mothers and calves, as the respiration rate, an indirect measure of energy expenditure [22,41], did not differ among phases. If the current disturbance in the reduction of resting *after* whale-watching remains as a short-term disturbance, then the effects may be negligible for the whale's energy budget. If we assume that each 'disturbance' event is 30 min (the duration of the after phase) on average, and there is a maximum of two such events per day (the maximum number of trips offered in a day in Encounter Bay) for the same mother and calf pair, this would equal an exposure level of ~10% of the daylight hours in August/September. Based on the time spent resting in the *control* and *after* phases, the proportion of daylight hours spent resting would equal 58.8% ($0.62 \times 0.9 + 0.30 \times 0.1$) for mothers and 14.5% ($0.16 \times 0.9 + 0.01 \times 0.1$) for calves. Compared to the control proportions (62% for mothers and 16% for calves), this would correspond to a daily decline in resting of 5.2% and 10.4% for mothers and calves, respectively. It is unknown if this cumulative reduction in resting on mother and calf pairs is sustainable, or could lead to long-term energy deficits (by increasing energy expenditure). It might also be possible for mothers and calves to compensate for this disturbance by resting at other times in the day, and/or at night. To address this question, research examining the exposure level (*i.e.,* intensity) of whale-watching over the duration of the breeding season is required.

While there was a significant reduction in resting between *control* and *after* phases, no difference was observed among *before* and *during*, or *before* and *after* phases. Hence, it is not clear that the effect is caused by the whale-watching interaction itself, since one would expect to see a reduction in resting also for the *during* phase. It is possible, that the effect of the whale-watch vessel was already apparent when the vessel was approaching in the *before* phase at greater distances (> 1 km away), which could have negatively biased the *before* phase. However, the acoustic analysis indicated that the noise level of the whale-watching vessels at these greater distances is low, based on the relatively slower approaching speeds (Fig. 4). Based on controlled exposure experiments of vessel noise at different levels on humpback whales [45], it is unlikely that the whales would have reacted to lower noise levels. Alternatively, the effect of the vessel noise might occur at the end of the *during* phase, when the vessel accelerated in speed to depart from the whales (Fig. 4), as this timing directly lead into the *after* phase.

Factors which may contribute to a decline in resting *after* whale-watch approaches, include but are not limited to, 1) an increase in vessel speed when departing the whales as mentioned above, 2) the total number of gear-shifts made, and/or 3) the accumulated length of time the vessel was in operation near the whales. An increase in vessel speed may affect resting whales, as a rise in speed increases underwater vessel noise [20]. For example, with an increase in speed from 5 to 30 kn, the noise of RHIBs (<9.1 m length, 1–2 engines) increases from 134 to 171 dB re 1 μPa @ 1 m [21]. The average speed arriving and departing the whales in the *before* and *after* phase in the current study was 6.7 kn (max = 12.9 kn) and 12.1 kn (max = 24.2 kn), respectively, at 1.0–1.5 km distance from the whales. At these speeds, based on an approximation it may be likely that the whales hear the noise of the vessel when it is departing. Based on Erbe et al. [21], there is a 10–15 dB (100 Hz to 20 kHz band) increase in RHIB's engine noise and with transmission loss at 1.0–1.5 km to the whales of 60–63 dB, rendering an excess noise of 25–30 dB above ambient for $\mathrm{TOL}_{0.25\ \mathrm{Hz}}$ (Fig. 7). However, the SL of the vessels used in this study at higher speeds is unknown, and every vessel has a different acoustic signature at different speeds. There are many factors affecting the received level to the whale, therefore, it remains unknown as to how much the whale can hear the vessel at these higher speeds. Further research is required to investigate at which distance whales are able to perceive a whale-watch vessel at different speeds (*i.e.,* speed and distance threshold), for example, to test if faster speeds at greater distances contribute to disturbance (including both $\mathrm{TOL}_{0.25\ \mathrm{kHz}}$ and LF-weighting). Furthermore, the total number of gear-shifts when positioning the vessel may disturb the whales, as gear-shifts produce loud high-intensity transient sounds which are "gun-shot-like" broadband sounds beginning around 20 Hz and may disturb the whales [26]. Similarly, the accumulated length of time during tours was 19.3 min (SD = 10.1), and this duration may be significant enough to affect resting. Based on the above factors which may contribute to a decline in resting, we recommend 1) when approaching/departing mother-calf pairs, maintain a slow speed (*e.g.,* ≤10 kn) within 1 km distance from the whales, 2) use minimal gear-shifts within 1 km distance from the whales, and 3) limit the amount of time spent in the presence of mother-calf pairs.

4.2. Vessel noise source levels, ambient noise and excess noise

The vessels were operating at 300 m distance and slow speed (4 kn) to mother-calf pairs. The whale-watch vessel SLs at 4 kn speed were 116 dB re 1μPa @ 1 m for the 11.3 m RHIB and 122 dB re 1μPa @ 1 m for the larger 12.5 m RHIB ($TOL_{0.25\ kHz}$). These SLs are reported within the frequency band overlapping the peak in southern right whale mother–calf calls of 0.25 kHz (250 Hz) (*sensu* [34]). The surrounding ambient noise conditions were relatively low at 65 ± 6 dB re 1 μPa RMS ($TOL_{0.25\ kHz}$). Thus, the noise of the whale-watching vessels was in excess above ambient by, on average, 45 dB off Middleton Beach and 54 dB off Frenchman Rock ($TOL_{0.25\ kHz}$). Considering a 49 dB transmission loss across 300 m from the vessel to the whale, the excess noise of the vessel received at the whale is very close to ambient. With a low-frequency hearing range, it is inferred that the whales may hear the vessel within the 0.25 kHz band, and more so at Frenchman Rock compared to Middleton Beach, but with relatively low intensity (Fig. 7). In the higher frequency bands (2–10 kHz), the whales may not hear the vessel as the ambient noise likely masks the vessel noise at 300 m distance (Fig. 7).

The vessel SLs, in LF-weighting for baleen whales, were 144 dB re 1μPa @ 1 m for the 11.3 m RHIB and 150 dB re 1μPa @ 1 m for 12.5 m RHIB at 4 kn speed. These SLs_{LF} were within the acoustic range of other whale-watch vessels at low speeds (<8 kn), ranging from 136 to 164 dB re 1μPa @ 1 m [3]. Currently, there are no noise standards for whale-watching vessels, thus, a loud vessel is able to approach whales at the same distance as a quieter vessel, even though there are known disturbance effects from louder vessels [2,45]. It is recommended that whale-watching vessels, which evidently spend targeted time around cetaceans, meet a broadband $SL_{0.2–10\ kHz}$ limit of $<$ 150 dB re 1 μPa (RMS) when within 500 m of cetaceans [3,45]. In this case in Encounter Bay, the whale-watch vessel remained around 300 m distance from the whales at low speed, with a low SL, therefore adhering to this noise emission recommendation if the engines are well maintained.

4.3. Management implications and recommendations

There was no significant effect of whale-watching approaches at a 300 m distance regulation with relatively quiet vessels on the respiration rate, maternal swim speed, nursing rate and bout duration, the rate of maternal active behavioural events, the proportion of time in tactile contact and the proportion of time in pectoral fin contact. There was a significant difference *after* whale-watching approaches on the proportion of time resting for mother and calves when compared to natural *control* behaviour. It is unknown if the current short-term disturbance on resting on mother-calf pairs is negligible on their energy budget or if the disturbance could lead to long-term energy deficits. Further research examining the intensity of whale-watching over the duration of the breeding season is required. We recommend that certain measures which are already permitted are kept, including 1) distance and speed: a 300 m distance at a slow no-wake speed, and 2) number of tours: two tours permitted per day (which generally occurred on the weekends). We suggest that any whale-watching vessel used in the future has a low noise source level, and that the number of vessels used to conduct whale-watching activities is not increased, as then there may be potential cumulative effects to disturbance. Further research will be required if additional stressors are placed on the whales, for example, from additional whale-watching vessels with louder engines and/or an increase in the number of tours permitted, which might have additive or even synergistic effects on the whales. To further minimise disturbance to resting whales, we suggest that when approaching/departing mother-calf pairs to maintain a slow speed (*e.g.,* ≤10 kn) and use minimal gear-shifts within 1 km distance to the whales, and limit the overall amount of time spent with the whales. Ultimately, these results are applicable for other whale-watching locations nationally and internationally, to aid in the development of best-practice, sustainable whale-watching practices.

CRediT authorship contribution statement

Kate Sprogis: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Visualization, Resources, Writing – original draft. **Dirk Holman**: Funding acquisition, Project administration, Writing – review & editing. **Patricia Arranz**: Formal analysis, Visualization, Writing – review & editing. **Fredrik Christiansen:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Visualization, Writing – review & editing.

Declaration of Interest

The authors declare no conflicts of interest.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2023.105525.

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