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Blue whale ecology and behavior in a human-impacted marine ecosystem: insights from acoustics and animal-borne tags

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UNIVERSITY OF CALIFORNIA SAN DIEGO

Blue whale ecology and behavior in a human-impacted marine ecosystem: insights from acoustics and animal-borne tags

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy

in

Oceanography

by

Angela Renee Szesciorka

Committee in Charge:

Lisa T. Ballance, Co-Chair
Peter J.S. Franks, Co-Chair
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Ana Širović
Lynne D. Talley

2021

The Dissertation of Angela Renee Szesciorka is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

University of California San Diego

2021

DEDICATION

To Staff Sgt. John William “Zorka” Szesciorka.

EPIGRAPH

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.

Hamlet (1.5.167-8), Hamlet to Horatio

Curiosity killed the cat you know. I KNOW!

The Nightmare Before Christmas

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT OF THE DISSERTAION

Blue whale ecology and behavior in a human-impacted marine ecosystem: insights from acoustics and animal-borne tags

by

Angela Renee Szesciorka

Doctor of Philosophy in Oceanography

University of California San Diego, 2021

Professor Lisa T. Ballance, Co-Chair
Professor Peter Franks, Co-Chair

To avoid missing peak prey abundances, blue whales must detect available environmental cues and time migration by shifting arrival or departure dates to/from feeding grounds and balancing the time they spend foraging versus breeding. Blue whale feeding habitat overlaps with dense vessel traffic, making them vulnerable to vessel strikes — the leading cause of human mortality for blue whales off Southern California. Any changes to migration timing that increase residence time on the feeding grounds may increase vessel strike risk. The contextual factors influencing vessel strike risk are poorly understood and uncertainty remains about whale behavioral response to vessels. Understanding those interactions is important in preventing vessel strikes. Here, I investigated the timing and drivers of blue whale migration and blue whale-vessel interactions using seafloor- and animal-mounted acoustic devices. This allowed me to (a) examine the relationship among migration timing (inferred from blue whale “D” and “B” calls), environmental indices (e.g., sea surface temperature anomalies), and prey (spring krill biomass from annual net tow surveys) during a 10 year period (2008-2017) off Southern California and (b) assess vessel, environmental, and whale contextual variables associated with 216 close passages (<2 km) between 174 vessels and 35 tagged whales and look for differences and uniqueness in dive behavior resulting from close passages. Colder sea surface temperature anomalies the previous season were correlated with greater krill biomass the following year, and earlier arrival by blue whales, demonstrating a plastic response of whales to interannual variability and the importance of krill as a driving force behind migration timing. By the end of the 10-year period, whales were arriving at the feeding grounds more than one month earlier, suggesting climate change has led to blue whales extending their overall time in Southern California. None of the contextual variables showed any relationship with close passage distance with vessels. Whales did not leave the area, even when passages were chronic (>5/day), and we found no evidence of behavioral response. With no evidence of behavioral responses to close vessel passages, we need to continue managing vessel traffic under the assumption that whales do not avoid vessels.

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Timing is everything: Drivers of interannual variability in blue whale migration

Angela R. Szesciorka[1]✉, Lisa T. Ballance[1,2,3], Ana Širović[4], Ally Rice[1], Mark D. Ohman[1], John A. Hildebrand[1] & Peter J. S. Franks[1]

Blue whales need to time their migration from their breeding grounds to their feeding grounds to avoid missing peak prey abundances, but the cues they use for this are unknown. We examine migration timing (inferred from the local onset and cessation of blue whale calls recorded on seafloor-mounted hydrophones), environmental conditions (e.g., sea surface temperature anomalies and chlorophyll *a*), and prey (spring krill biomass from annual net tow surveys) during a 10 year period (2008–2017) in waters of the Southern California Region where blue whales feed in the summer. Colder sea surface temperature anomalies the previous season were correlated with greater krill biomass the following year, and earlier arrival by blue whales. Our results demonstrate a plastic response of blue whales to interannual variability and the importance of krill as a driving force behind migration timing. A decadal-scale increase in temperature due to climate change has led to blue whales extending their overall time in Southern California. By the end of our 10-year study, whales were arriving at the feeding grounds more than one month earlier, while their departure date did not change. Conservation strategies will need to account for increased anthropogenic threats resulting from longer times at the feeding grounds.

Productivity in the California Current Ecosystem (CCE) is fueled by the seasonal, wind-driven coastal upwelling of nutrient-rich waters[1]. Upwelling pulses are followed by phytoplankton blooms ca. one week later, and an increase in zooplankton biomass weeks to months later[2]. Seasonal upwelling and the ensuing assemblage of zooplankton and forage fish create rich feeding grounds that are exploited by highly migratory predators[3,4]. The timing of these physical-biological couplings is strongly influenced by environmental variability on interannual to multi-decadal scales[5].

Environmental variability may create a temporal mismatch between the migration timing of a predator and fluctuations of its prey[6,7]. Migration between discrete feeding and breeding grounds involves complex internal and external processes and species-specific environmental cues[8]. At the feeding grounds, prey availability determines the timing and physical condition of an animal at its departure, which influences the timing of arrival and physical condition at its breeding grounds, ultimately affecting reproductive success[9]. Animals migrating long distances minimize predator-prey mismatches by altering the timing of their migration[10], while balancing time spent on foraging or reproductive-related behaviors[11]. Plasticity in migration has been well studied in terrestrial birds and mammals[12,13], but less in aquatic animals.

Blue whales (*Balaenoptera musculus*) are a model species for investigating the relationship between environmental interannual variability and migration phenology. As a long-lived, highly migratory species, individuals experience interannual to multidecadal-scale environmental variability. Although the cues they use for the timing of migration remain unknown, the Eastern North Pacific blue whale population's general migration phenology has been well established from visual, acoustic, and tag data[14–16]. Previous studies have found that the majority of these whales occupy feeding grounds in the CCE of the United States, including waters west of the Southern California Region (SCR) from May to December before migrating south to their breeding grounds in the Costa Rica Dome (CRD) for the winter where they reproduce or give birth (Supplementary Fig. 1)[14,15,17].

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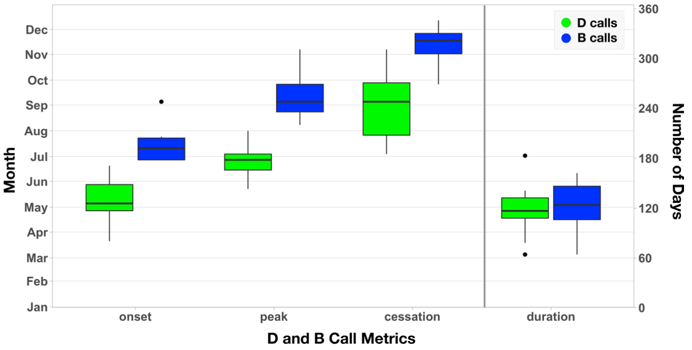

Figure 1. Summarized D and B call metrics for date of onset, peak, cessation, and duration (number of days). Each whisker boxplot displays the median, first and third quartiles (25th and 75th percentiles), upper and lower whiskers (1.5 times the inter-quartile range), and outliers (black circles).

The diet of this population in the SCR is overwhelmingly dominated by two species of euphausiid krill (*Thysanoessa spinifera* and *Euphausia pacifica*)[18–20]. Blue whales are acoustically active at the feeding grounds, producing "D", "A", and "B" calls (Supplementary Fig. 2)[21]. D calls are downswept (~100–40 Hz) and seconds in duration. They are produced by both sexes during the months when they forage and are considered social or contact calls[22]. B calls are tonal, low-frequency (fundamental frequency <20 Hz), and long in duration (10–20 s), produced most often in repeated sequences along with A calls as part of song[23]. These songs are produced only by males and are believed to have a primarily reproductive-related function[22,23]. D calls dominate early in the year and B calls later (Supplementary Fig. 3)[24], which together can be used as a proxy for the timing of blue whale migration. Here we test the hypothesis that the timing and drivers of migration, including the transition from predominately feeding to reproductive-related behaviors, is mediated by available prey resources and physical environmental properties.

Results and Discussion

The 10-year average annual cycles of D and B calls through time indicates that whales arrive at the SCR feeding grounds in May and depart in November, remaining at the feeding grounds an average of 8.4 months (Fig. 1, Supplementary Table 1, Supplementary Fig. 3). The timings of D call onset and cessation displayed greater variability than B call onset and cessation (Fig. 1), suggesting that D calls may be influenced more by external forces than B calls. There was no significant relationship between the duration of overlap of D and B calls in the same year, or between the timings of B call cessation and D call onset the following year. The onset, cessation, and duration of both D and B calls displayed interannual variability, suggesting that the timing of these calls, and, by inference, blue whale arrival and departure, was not associated with photoperiod, as has been documented for many terrestrial birds and mammals[25]. Instead, blue whales must use other cues to detect interannual variability and determine when to migrate to and from their feeding grounds.

Arrival time at the feeding grounds is correlated with sea surface temperature anomalies from the previous feeding season. Eight-day mean sea surface temperature (SST) anomalies integrated over May to November of the previous feeding season (the average time whales are in the SCR) were correlated with the timing of the onset of D calls (i.e., blue whale arrival) in the SCR the following year (multiple regression partial $R^2 = 0.78$, $p < 0.01$; Fig. 2). Specifically, when the previous feeding season was colder, D call onset (i.e., arrival) in the SCR was earlier the following year, and it was later following warmer years.

Temperature is a migratory cue used by many terrestrial taxa—from insects to birds to ungulates[6,26]. In the marine realm, SST is similarly important for highly migratory species, including leatherback sea turtles (*Dermochelys coriacea*)[27] and flounder (*Platichthys flesus*)[28]. Nishiwaki[29] was the first to suggest that changes in SST might influence the timing of humpback whale (*Megaptera novaeangliae*) arrival on their wintering grounds. Visser *et al.*[30] tied the timing of peak baleen whale abundance in the Azores to rising SSTs following the spring bloom, and Tsujii *et al.*[31] found that water temperature was a good predictor of fin whale (*Balaenoptera physalus*) arrival and departure in the southern Chukchi Sea. Our study demonstrates how oceanographic conditions influence migration timing, but also suggests the use of memory.

The idea that memory of past conditions combined with resource tracking allows animals to modify the time, speed, and direction of migration movement has been documented in terrestrial mammals[32] and birds, including demonstrating the memory of high-quality foraging locations for at least 12 months[33]. Among the limited number of studies of the timing of whale migration, to our knowledge, only one examined the role of memory. Abrahms *et al.*[34] found that tagged blue whale latitudinal migratory movements correlated with a 10-year average spring bloom (via chlorophyll-*a* peaks) and hypothesized a long-term memory of the location of highly productive foraging sites. Our findings, and the fact that we could detect no relationship between D call onset and any environmental variable on the breeding grounds prior to arrival at the feeding grounds, support the hypothesis

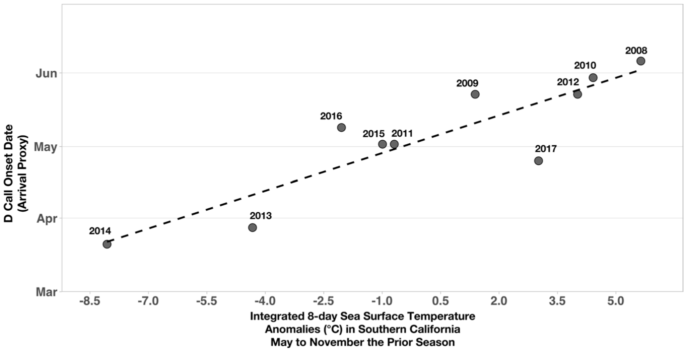

Figure 2. D call onset at the Southern California feeding grounds compared to integrated 8-day sea surface temperature anomalies the prior feeding season. Annual (2008–2017) onset of D calls (our proxy for blue whale arrival at the feeding grounds) correlated with integrated eight-day sea surface temperature anomalies (°C) in Southern California from the prior feeding season (May–November; multiple regression partial $R^2 = 0.78$, $p < 0.01$).

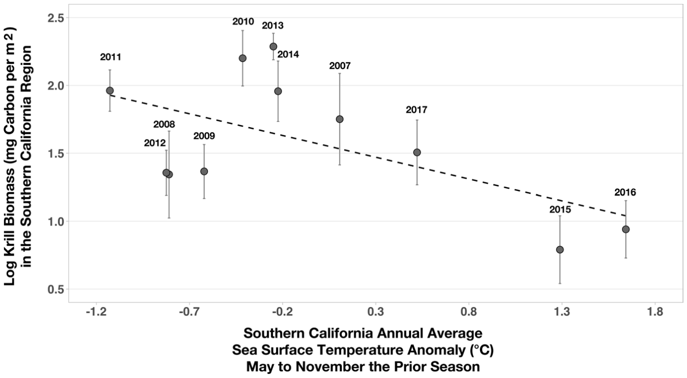

Figure 3. Krill biomass compared to annual sea surface temperature anomalies in Southern California the prior feeding season. Annual (2008–2017) spring biomass (log transformed; mg carbon per m^2 with standard error bars) of adult and juvenile *Euphausia pacifica* and *Thysanoessa spinifera* correlated with annual sea surface temperature anomalies (°C) in Southern California from the prior feeding season (May-November; $R^2 = 0.43$, $p = 0.07$).

of memory use in migratory timing. By integrating the SST anomaly signal at the feeding grounds from the prior feeding season, whales may forecast future conditions and adjust their arrival timing the following year.

Annual sea surface temperature anomalies from the previous season are correlated with krill biomass at the feeding grounds. Colder annual SST anomalies in the SCR the previous feeding season were associated with greater krill biomass the next year, while warmer annual SST anomalies were associated with lower krill biomass ($R^2 = 0.34$, $p = 0.06$; Fig. 3). Previous studies have established that associations between colder water and greater zooplankton biomass result from the upwelling and advection of cold, nutrient-rich water and subsequent primary production[1]. Greater krill biomass in the SCR was also associated with an earlier onset of D calls, when whales arrived at their feeding grounds (multiple regression partial $R^2 = 0.52$, $p = 0.04$; Fig. 4). The relationship between SST anomalies, krill biomass, and D call onset suggest that in addition to anticipating future conditions based on the prior year's conditions, whales could profitably use SST as a proxy for krill biomass. Thus, whales could optimize arrival time at the feeding grounds to take advantage of abundant prey (cold years, early arrival) or limit their effort in the area when they expect prey to be impoverished (warm years, late arrival).

Analyses of blue whale scat collected in the SCR have shown that whales preferentially target *T. spinifera*[20], which has a greater lipid content than *E. pacifica*[35], though both euphausiid species compose their diet and are dominant in the cold waters of the SCR[36]. Zooplankton in cold, high-latitude waters have higher energy

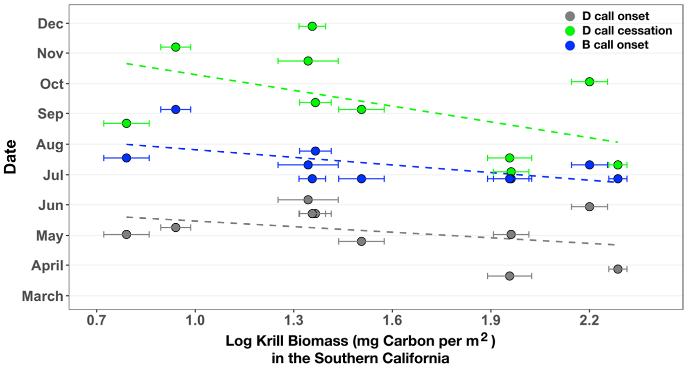

Figure 4. Krill biomass in the Southern California Region compared to D and B call onset and D call cessation. Annual (2008–2017) spring biomass (log transformed mg carbon per m^2 with standard error bars) of adult and juvenile *Euphausia pacifica* and *Thysanoessa spinifera* correlated with the onset of D calls (multiple regression partial $R^2 = 0.52$, $p = 0.04$), cessation of D calls ($R^2 = 0.28$, $p = 0.10$), and onset of B calls ($R^2 = 0.36$, $p = 0.07$).

contents and lipid stores than zooplankton at lower latitudes[37]. Given the potential for a greater caloric value from cold-water compared to warm-water euphausiid prey, there may be a significant feeding advantage for whales to arrive on their feeding grounds earlier when it is colder, and when lipid-rich krill is predictably more abundant.

During warmer years, it is possible that whales delay departure from the CRD to opportunistically feed locally on smaller, less energy-rich krill such as *Euphausia eximia*, *Euphausia gibboides*, *Euphausia distinguenda*, *Nematoscelis gracilis*, *Nematobrachion flexipes*, and *Nyctiphanes simplex* before migrating to the SCR[38,39]. However, while some data suggest that whales may feed in the CRD[15], there is no evidence that the bulk of this population remains year round or that the euphausiid species available at blue whale breeding grounds[40] could support the energetic demands of the population. Another possibility, suggested from analyses of visual, acoustic, and satellite tagging data[15,40,41], is that in warm years blue whales leave the CRD, but stop in the Gulf of California and along Baja California Peninsula, where they feed opportunistically on the subtropical euphausiid *Nyctiphanes simplex* on their way to a relatively less-productive SCR.

Krill biomass mediated the transition to reproductive-related calling behavior at the feeding grounds. Higher krill biomass in the SCR was associated with earlier D call (multiple regression partial $R^2 = 0.52$, $p = 0.04$; Fig. 4) and B call ($R^2 = 0.36$, $p = 0.07$; Fig. 4) onset there, as well as earlier D call cessation ($R^2 = 0.28$, $p = 0.10$; Fig. 4). In years when whales had access to greater-than-average krill biomass, they ceased D calls sooner and started to produce B calls sooner. Also, in years with greater krill biomass, the duration of D calling was shorter, though not significantly ($R^2 = 0.23$, $p = 0.16$). The production of song by male humpback whales has been studied extensively, including on feeding grounds[42,43], and proposed hypotheses regarding the purpose of these songs include intersexual and intrasexual functions[44]. While the production of B calls by male blue whales is likely associated with reproduction, their calling behavior is complex and, like humpback whale song, the precise functions are unknown[22]. However, our discovery of the link between higher krill biomass at the feeding grounds and blue whales' earlier transition to reproductive-related calling behavior (i.e., onset of B calls) reinforces the hypothesized importance of the connections among migration timing, prey quality, and reproductive-related behavior[25,45].

The time of arrival of blue whales to the feeding grounds showed long-term trends. The onset of D calls (our proxy for blue whale arrival at the SCR feeding grounds), showed a long-term trend of earlier onset over the 10-year period (multiple regression partial $R^2 = 0.53$, $p = 0.04$), shifting more than one month (42 days) from June to April. Across the same 10-year period, mean annual SST in the SCR increased by 1 °C ($R^2 = 0.55$, $p = 0.01$; Fig. 5b). We hypothesize that the decadal warming trends are driving the whales to arrive at the SCR feeding grounds earlier. This has led to whales spending more and more time at the SCR feeding grounds.

Long-term change in migration timing has been demonstrated in amphibians, birds, insects, fish, marine invertebrates, marine zooplankton, and mammals[6,46]. There are few studies of long-term temporal changes in migration timing for highly migratory aquatic animals; however, the continued collection of photographic identification, passive acoustic monitoring, and satellite tag data, is revealing early arrival trends in other whale species. Across a 27-year period, fin and humpback whales arrived one month earlier on their feeding grounds in the Gulf of St. Lawrence in the North Atlantic Ocean. Because this timing shift was significantly correlated with increased sea-surface temperature and decreased sea-ice formation, it was hypothesized that the shift in arrival allowed whales to track changes in the timing of the spring bloom[47]. A similar study using telemetry and acoustic data found that over a 22-year period, beluga whales (*Delphinapterus leucas*) in the Eastern Beaufort Sea departed later in years with delayed sea-ice freeze-up, which likely enhanced productivity and zooplankton advection[48].

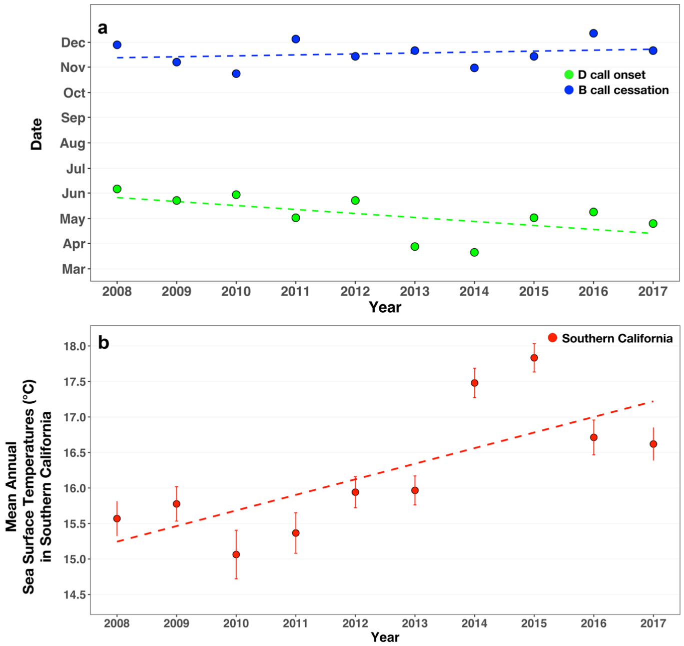

Figure 5. Long-term trends in D call onset, B call cessation, and annual average sea surface temperatures. (**a**) D call onset date (i.e., arrival at the feeding grounds) shifted significantly earlier across the 10-year study period (2008–2017; multiple regression partial $R^2 = 0.53$, $p = 0.04$) while there was no significant shift in b call cessation (i.e., departure from the feeding grounds) ($R^2 = 0.05$, $p = 0.53$). (**b**) Across the same time period, there was a significant increase in average annual sea surface temperatures (°C with standard error bars) in Southern California ($R^2 = 0.55$, $p = 0.01$).

Our findings show that blue whales have altered their timing of migration in the CCE of the United States. We hypothesize that as the waters in the SCR and CRD are warming, the quality and quantity of krill biomass are changing, removing any previous advantage of remaining longer in the CRD or along the coast of Baja to feed on smaller, less energy-rich species of krill. Krill biomass in the SCB also shows a long-term increase[49], suggesting an advantage for blue whales spending more time at the feeding grounds off the California coast. In addition to changes in krill biomass, previous studies have documented krill range contractions, and range shifts coincident with physical oceanographic changes[50], which may further influence blue whale migration behavior.

These long-term adjustments to changes in prey distribution and availability may result in whales following their prey poleward, remaining on feeding grounds longer, or suspending migration. Bioenergetic models indicate that increases in travel time resulting from poleward expansion increase the overall energetic cost of migration and reduce the time available for feeding, reproduction, and calving[51]. A longer migration or feeding period may result in a decreased frequency of migration, especially if the cost of migration becomes too high[51,52]. Any adjustments by the whales to track changes in prey distribution and biomass may also increase their spatial overlap with anthropogenic threats, further threatening this already endangered species. For example, in the case of this population, because of the high volume of ship traffic in the SCR, increased residence time could increase the whales' lifetime risk of being struck by a ship[53].

The time of departure of blue whales from the feeding grounds shows long-term stability. The cessation of B calls, our proxy for blue whale departure from the feeding grounds did not change across the 10-year study period ($R^2 = 0.05$, $p = 0.53$, Fig. 5a). In other mammals, migration phenology has been shown to be influenced by a combination of external biotic and abiotic cues, as well as by endogenous biological clocks regulating the physiological and morphological changes necessary for these behaviors[6]. Hormones linked to migration timing include melatonin[6], adipose and thyroid hormones, and gonadal steroids[54]. Although virtually unstudied in the context of migration for marine mammals, these hormones likely play a role in their transition from feeding to reproductive-related calling, possibly triggering whale migration back to their breeding grounds. Because the cessation of B calls was not related to any environmental indices or krill biomass at the feeding grounds, we hypothesize that the cessation of B calls, our proxy for departure from the feeding grounds, may be partially regulated by seasonal fluctuations in hormone levels.

Leptin, which has been studied in bowhead whales (*Balaena mysticetus*) and beluga whales[55] is a satiety hormone that is released as adipose tissue increases, signaling to the reproductive system that sufficient fuel reserves have been stored to support reproduction[25] and stimulating ovulation in female mammals[56]. Additional evidence of the influence of hormones comes from the analysis of cross-sections of baleen from a stranded male blue whale, which displayed regularly spaced areas of high testosterone peaks[57]. Although the age of the whale was unknown, the cycles mirrored annual cycles of testosterone measured in the baleen of a bowhead whale and North Atlantic right whale (*Eubalaena glacialis*) of known ages[57]. Seasonal fluctuations in testosterone have also been measured from blubber samples of male humpback whales with mean testosterone peaks between November and January[58,59]. The similarity in annual testosterone cycles for these baleen whale species and similarities between humpback and blue whale reproduction support the idea that hormones play a role in migration phenology, especially triggering departure back to the CRD breeding grounds.

Conclusions

The timing of blue whale arrival at their feeding grounds and start of reproductive calling behavior appears to be driven by an interaction with temperature and prey. We hypothesize that in addition to real-time perceptual cues, blue whales use the memory of the previous year's integrated SST anomalies at the feeding grounds as an indicator of next year's krill biomass and to time their arrival at the SCR feeding grounds. Fluctuations in krill biomass were not only correlated with D call onset (our proxy for blue whale arrival at the feeding grounds), but also with the timings of the cessation of D calls and the onset of B calls at the SCR feeding grounds. These relationships suggest that krill — in particular lipid-rich, cold-water krill biomass — is an important driver of the timings of migration and the start of reproductive calling behavior. The phenotypic plasticity exhibited by blue whales has apparently allowed them to accommodate interannual variability while balancing these biological imperatives. However, despite the interannual variability in arrival time, a long-term trend emerged from our data showing that although blue whales departed at the same time each year, they arrived at their summer feeding grounds more than one month earlier by the end of our 10-year study. There may come a time when adjustments in timing without geographic displacement will not be sufficient to allow both feeding and reproduction during a single year. These whales may be forced to follow their prey poleward, to remain on feeding grounds longer, or to suspend migration, with potential costs to the time available for mating and reproduction. Long-term changes in the migration phenology of endangered blue whales present pressing conservation and management issues, such as possible increases in the spatial or temporal overlap of the whales with commercial ships, fishing gear, and other anthropogenic threats.

Methods

Acoustic data collection and processing. Acoustic data were collected from 2008 to 2017 at five sites in the SCR using seafloor-mounted high-frequency acoustic recording packages (HARPs; Supplementary Fig. 4, Supplementary Table 2)[60]. The data were decimated by a factor of 100 to create an effective acoustic bandwidth from 10 to 1,000 Hz (for data sampled at 200 kHz) or 10 to 1,600 Hz (for data sampled at 320 kHz). Long-term spectral averages with 5-s temporal and 1-Hz frequency resolution were created for each deployment using the custom software package Triton in MATLAB[61]. A modified version of the generalized power-law detector[62] was used to automatically detect blue whale D calls. All D call detections were manually verified, and false detections were removed from subsequent analyses. Blue whale B calls were automatically detected using the spectrogram cross-correlation method[63], described by Širović *et al.*[64]. All B call detections from February to May (when blue whale calls are scarce) were verified by a human analyst to remove false detections. Because D and B calls are generally temporally offset (Supplementary Fig. 3), together they encompass the majority of the period when whales are present in the SCR and calling.

Call and migration metric calculations. We multiplied the daily number of calls by the fraction of daily sampling time to correct for any partial recording effort. We then pooled calls into weekly median bins and normalized the calls to be between 0 and 1 by scaling with the maximum number of daily calls per year. Annual cycles were defined as February through January to ensure late calls from one migration cycle did not get counted in the beginning of another. Four migration timing metrics were defined per call type: onset, peak, cessation, and duration. Because there can be low levels of calls recorded year-round, the onset and cessation of each call type were calculated as thresholds that encompassed 90% of the total number of calls relative to the day with the peak number of calls (Supplementary Fig. 5, Supplementary Table 1). Thus, onset and cessation specified the start and end of the bulk of calls, respectively. Duration was calculated as the number of days from onset to cessation (Supplementary Table 1). The onset of D calls and cessation of B calls in each year were used as proxies for arrival and departure date, respectively.

Environmental indices. Call metrics were compared with environmental indices of various spatial and temporal scales (Supplementary Table 3). Basin-wide Pacific Ocean environmental indices included the monthly North Pacific Gyre Oscillation (NPGO) index and the monthly Pacific Decadal Oscillation (PDO) index as indicators of overall productivity. The equatorial-specific index included the Oceanic Niño Index (ONI), a 3-month running mean of ERSST.v5 SST anomalies in the Niño 3.4 region (5°N-5°S, 120–170°W) as an indicator of El Niño and La Niña events. Regional 8-day environmental indices included area-averaged SST (4 microns, night only; °C) and chlorophyll *a* (mg/m^3) in the SCR 32–35°N, 121–117°W; Supplementary Fig. 1) and CRD (5–15°N, 100–85°W; Supplementary Fig. 1) derived from MODIS-Aqua level-3 data as proxies for conditions in those regions. Additional SCR environmental indices included the cumulative upwelling index (CUI; 33°N, 119°W), which was calculated from integrated mean daily upwelling indices, and spring adult and juvenile *E. pacifica* and *T. spinifera* biomass, the preferred prey of Eastern North Pacific blue whales in the SCR[18–20]. Spring krill biomass data (mg carbon per m^2) were retrieved from the Brinton and Townsend Euphausiid Database, converted to organic C biomass from relationships described in Lavaniegos & Ohman[65]. All samples were collected with a 0.71-m diameter, 0.505 mm mesh bongo net towed from 210–0 m during California Cooperative Oceanic Fisheries Investigations (CalCOFI) cruises (Supplementary Table 4). Sample processing was conducted by the Ohman lab and the Scripps Institution of Oceanography Pelagic Invertebrate Collection. Annual spring biomass data were averaged from CalCOFI lines 80 to 93 and stations 26 to 60 (Supplementary Fig. 6) and log $(x + 1)$ transformed. Only nighttime tow samples were included in the calculations to account for diel vertical migration and net avoidance[66].

Statistical analyses. Because D and B call metrics were not cross correlated, they were investigated as independent response variables. To investigate environmental cues that could influence when whales leave the CRD or before they arrive in the SCR, we first examined individual linear regressions of D and B call metrics and environmental indices (with seasonal cycles removed) at various lagged durations to investigate the potential explanatory power of each environmental index. Only D and B call onset, peak, and cessation were used because durations did not correspond to specific dates, and durations were correlated with their respective call cessation dates. Environmental indices with high coefficient of determination (R^2) or goodness of fit were then used in forward and backward selection stepwise multiple regression using the 'MASS' package in R to examine the relationships between significant environmental indices and call metrics. Only one model required multiple regression (Supplementary Table 5); the remaining models presented were individual linear regressions. Model selection was based on Akaike's Information Criterion[67]. The partial R^2 for each variable in the multiple regression was determined using the 'rsq' package in R. Significance level was set at 0.10, in order to minimize the probability of Type II errors in studies with limited sample sizes[68]. Recording effort varied over time and at each site per call (Supplementary Fig. 7; Supplementary Methods and Analyses).

Data availability

The datasets generated for this study are available upon request to the corresponding author.

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Author contributions

A.R.S. conceived of the presented idea. J.A.H. funded the data collection and provided the raw passive acoustic data. A.R. and A.R.S. performed the call analysis. A.R.S., P.J.S.F., L.T.B., and A.Š. developed the data analysis approaches. The M.D.O. lab carried out analysis of all euphausiid samples. A.R.S. wrote the initial manuscript. All authors discussed the results and contributed to the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Timing is everything: Drivers of interannual variability in blue whale migration

Supplementary Materials

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Supplementary Tables

Supplementary Table 1. D and B call migration metrics from 2008 to 2017, including Julian date of onset, peak, cessation and duration. Onset and cessation date of each call type were calculated as thresholds that encompass 90% of the calls relative to the day with the peak number of calls.

annual cycle	D onset	D peak	D cessation	D duration	B onset	B peak	B cessation	B duration
2008-2009	157	171	297	141	192	269	332	141
2009-2010	143	213	255	113	206	248	311	106
2010-2011	150	178	276	127	192	220	297	106
2011-2012	122	150	185	64	178	304	339	162
2012-2013	143	297	332	190	178	262	318	141
2013-2014	87	178	192	106	178	234	325	148
2014-2015	80	164	199	120	178	227	304	127
2015-2016	122	185	234	113	199	269	318	120
2016-2017	129	185	311	183	248	311	346	99
2017-2018	115	143	248	134	178	241	325	148

Supplementary Table 2. High-frequency acoustic recording package (HARP) deployment information, including site, deployment number, start and end datetime, location, depth (m), sample rate, duty cycle, and data start and end datetime.

Site	Deployment	Latitude	Longitude	Depth_m	Sample_Rate	Cycle_Int	Duty_Dur	Data_Start_Date	Data_Start_Time	Data_End_Date	Data_End_Time
B	1	34-16.520 N	120-01.505 W	580	200	0	0	2/14/08	20:00:00	4/9/08	2:20:00
B	2	34-16.584 N	120-01.512 W	610	200	7	5	4/17/08	0:00:00	6/6/08	5:48:45
B	3	34-16.621 N	120-01.661 W	580	200	7	5	7/23/08	0:00:00	10/1/08	23:58:45
B	4	34-16.617 N	120-01.492 W	576	200	0	0	10/16/08	0:00:00	12/3/08	1:10:23
B	5	34-16.528 N	120-01.132 W	580	200	10	5	12/4/08	20:00:00	2/21/09	11:14:28
B	6	34-16.667 N	120-01.613 W	580	200	0	0	5/13/09	0:00:00	7/6/09	6:17:30
B	8	34-16.634 N	120-01.506 W	580	50	0	0	7/30/09	0:00:00	9/1/09	23:09:13
B	9	34-16.732 N	120-01.664 W	580	200	0	0	9/3/09	0:00:00	10/27/09	6:17:30
B	10	34-16.720 N	120-01.614 W	580	200	10	5	11/3/09	22:50:00	2/20/10	11:11:15
B	12	34-16.704 N	120-01.620 W	581	200	0	0	3/2/10	0:00:00	6/11/10	23:33:45
B	13	34-16.968 N	120-01.684 W	549	200	0	0	6/25/10	22:00:00	9/19/10	10:48:41
B	14	34-16.985 N	120-01.696 W	580	200	0	0	10/8/10	20:00:00	1/25/11	4:53:45
B	16	34-16.991 N	120-01.697 W	580	200	0	0	4/6/11	17:00:00	7/10/11	5:26:15
B	17	34-16.970 N	120-01.706 W	580	200	0	0	10/27/11	0:00:00	3/19/12	15:56:15
B	18	34-17.126 N	120-01.632 W	580	200	0	0	3/24/12	0:00:01	7/26/12	1:58:46
B	19	34-17.156 N	120-01.473 W	900	200	0	0	8/2/12	0:00:00	12/3/12	22:16:21
B	20	34-17.131 N	120-01.636 W	900	200	0	0	12/16/12	21:00:00	5/2/13	20:27:30
B	21	34-17.112 N	120-01.640 W	580	200	0	0	5/2/13	22:00:00	9/20/13	15:23:45
B	22	34-17.115 N	120-01.639 W	535	200	0	0	9/21/13	0:00:00	1/8/14	18:06:15
B	23	34-17.098 N	120-01.685 W	573	200	0	0	1/8/14	20:00:00	4/9/14	21:36:14
B	24	34-17.099 N	120-01.639 W	580	200	0	0	4/9/14	23:59:59	5/22/14	8:29:33
B	25	34-17.143 N	120-01.650 W	NULL	200	0	0	7/29/14	6:00:00	11/4/14	4:37:30
B	26	34-16.588 N	120-01.536 W	582	200	0	0	6/7/08	0:00:00	7/21/08	2:12:30
B	26	34-17.157 N	120-01.695 W	600	200	0	0	11/4/14	6:00:00	2/5/15	19:35:00
B	27	34-17.168 N	120-01.717 W	600	200	0	0	2/6/15	0:00:00	6/10/15	18:10:00
B	28	34-17.097 N	120-01.634 W	580	200	0	0	6/12/15	3:00:00	9/28/15	13:31:15
B	29	34-17.105 N	120-01.666 W	579	200	0	0	10/5/15	0:00:00	12/16/15	1:05:06
B	30	34-16.532 N	120-01.112 W	585	200	0	0	12/16/15	0:00:00	5/29/16	0:07:36
B	31	34-17.095 N	120-01.630 W	578	200	0	0	7/27/16	18:00:00	11/9/16	16:37:30
B	32	34-16.528 N	120-01.129 W	577	200	0	0	2/12/09	18:00:00	5/6/09	0:15:00
B	32	34-17.104 N	120-01.603 W	580	200	0	0	11/9/16	16:05:00	1/18/17	2:01:21

Supplementary Table 2, Continued

Site	Deployment	Latitude	Longitude	Depth_m	Sample_Rate	Cycle_Int	Duty_Dur	Data_Start_Date	Data_Start_Time	Data_End_Date	Data_End_Time
C	1	34-19.123 N	120-47.954 W	749	200	0	0	2/13/08	0:00:00	4/3/08	21:00:00
C	2	34-19.074 N	120-48.212 W	750	200	7	5	4/18/08	0:00:00	7/24/08	1:33:30
C	3	34-19.094 N	120-48.282 W	750	200	7	5	7/24/08	0:00:00	10/2/08	5:26:30
C	4	34-19.110 N	120-48.333 W	700	200	0	0	10/15/08	0:00:00	12/4/08	1:02:30
C	5	34-18.902 N	120-48.370 W	700	200	10	5	12/3/08	0:00:00	2/28/09	4:25:00
C	9	34-18.906 N	120-48.385 W	799	200	0	0	9/3/09	0:00:00	10/27/09	6:17:30
C	10	34-19.108 N	120-48.465 W	780	200	10	5	11/4/09	0:00:00	2/20/10	12:32:30
C	12	34-19.097 N	120-48.445 W	801	200	0	0	3/3/10	0:00:00	6/13/10	17:10:00
C	13	34-19.000 N	120-48.410 W	915	200	0	0	6/24/10	23:00:00	9/21/10	3:43:45
C	15	34-18.997 N	120-48.412 W	850	200	0	0	11/16/10	0:00:00	3/2/11	3:30:00
C	16	34-19.007 N	120-48.349 W	850	200	0	0	4/5/11	21:00:00	7/11/11	23:12:36
C	17	34-19.007 N	120-48.337 W	825	200	0	0	10/27/11	0:00:00	3/3/12	12:28:45
C	18	34-19.500 N	120-48.400 W	758	320	0	0	3/25/12	0:00:00	8/2/12	17:20:57
C	19	34-19.384 N	120-48.384 W	800	320	0	0	8/2/12	0:00:00	12/7/12	20:19:37
C	20	34-19.020 N	120-48.336 W	800	320	0	0	12/18/12	0:00:00	4/28/13	15:16:21
C	21	34-19.013 N	120-48.333 W	814	320	0	0	5/2/13	20:00:00	6/17/13	10:54:00
C	22	34-19.013 N	120-48.333 W	823	200	0	0	9/22/13	0:00:00	1/14/14	19:35:00
C	23	34-18.973 N	120-48.295 W	828	320	0	0	1/14/14	21:00:00	4/9/14	17:41:02
C	24	34-19.452 N	120-48.369 W	754	320	0	0	4/9/14	20:00:00	7/29/14	7:22:17
C	26	34-19.474 N	120-48.474 W	600	320	0	0	11/4/14	14:00:00	2/5/15	14:53:26
C	27	34-19.562 N	120-48.407 W	755	320	0	0	2/6/15	0:00:00	6/10/15	22:17:59
C	28	34-19.562 N	120-48.405 W	754	320	0	0	6/11/15	0:00:00	10/4/15	21:06:08
C	29	34-19.560 N	120-48.416 W	NULL	320	0	0	10/5/15	0:00:00	12/18/15	2:35:29
C	30	34-19.430 N	120-48.412 W	755	320	0	0	3/17/16	0:00:00	7/27/16	20:21:58
C	31	34-19.477 N	120-48.417 W	756	320	0	0	7/28/16	0:00:00	11/9/16	21:19:42
C	32	34-18.885 N	120-48.367 W	802	200	0	0	3/12/09	12:00:00	5/5/09	18:18:45
C	32	34-19.455 N	120-48.426 W	760	320	0	0	11/10/16	0:00:00	2/22/17	8:36:03
H	26	32-50.823 N	119-10.606 W	1012	200	0	0	6/5/08	0:00:00	7/25/08	20:58:45
H	27	32-50.841 N	119-10.489 W	1018	200	0	0	8/4/08	12:00:00	9/27/08	18:18:00
H	29	32-50.823 N	119-10.624 W	1015	200	0	0	10/21/08	0:00:00	12/14/08	6:15:00
H	30	32-50.754 N	119-10.387 W	1010	200	0	0	12/21/08	11:00:00	1/12/09	19:10:04
H	31	32-50.587 N	119-10.170 W	1004	200	0	0	1/13/09	0:00:00	3/8/09	6:18:56
H	32	32-50.587 N	119-10.170 W	935	200	0	0	3/14/09	0:00:00	5/7/09	6:18:55
H	34	32-50.569 N	119-10.294 W	992	200	0	0	7/23/09	12:00:00	9/15/09	18:17:30
H	35	32-50.564 N	119-10.279 W	995	200	0	0	9/25/09	15:00:00	11/18/09	21:17:30
H	36	32-50.550 N	119-10.266 W	997	200	0	0	12/6/09	0:00:00	1/29/10	6:17:30
H	37	32-50.554 N	119-10.272 W	992	200	0	0	1/30/10	18:00:00	3/22/10	23:16:15
H	38	32-50.555 N	119-10.252 W	989	200	0	0	4/10/10	15:00:00	7/22/10	23:31:15
H	40	32-50.552 N	119-10.254 W	1004	200	0	0	7/23/10	0:00:00	11/8/10	9:26:15
H	41	32-50.553 N	119-10.247 W	1002	200	0	0	12/6/10	20:00:00	4/17/11	20:57:30
H	44	32-50.558 N	119-10.287 W	989	200	0	0	5/11/11	17:00:00	10/12/11	15:57:30
H	45	32-50.537 N	119-10.217 W	1008	200	0	0	10/16/11	0:00:00	3/5/12	11:48:45

Supplementary Table 2, Continued

Site	Deployment	Latitude	Longitude	Depth_m	Sample_Rate	Cycle_Int	Duty_Dur	Data_Start_Date	Data_Start_Time	Data_End_Date	Data_End_Time
H	46	32-50.529 N	119-10.191 W	993	320	0	0	3/25/12	0:00:00	7/21/12	12:25:15
H	47	32-50.806 N	119-10.575 W	1006	200	0	0	8/10/12	2:00:00	12/20/12	23:51:15
H	48	32-50.536 N	119-10.245 W	1000	320	0	0	12/21/12	2:00:00	4/30/13	22:29:03
H	50	32-50.307 N	119-10.006 W	NULL	200	0	0	9/10/13	12:00:00	1/7/14	0:18:51
H	51	32-50.307 N	119-10.006 W	960	200	0	0	1/7/14	2:00:00	4/3/14	20:01:15
H	52	32-50.800 N	119-10.588 W	986	200	0	0	4/4/14	0:00:00	7/30/14	6:25:06
H	53	32-50.693 N	119-10.564 W	NULL	200	0	0	7/30/14	12:00:00	11/5/14	0:47:30
H	54	32-50.775 N	119-10.544 W	1000	200	0	0	11/5/14	6:00:00	2/4/15	20:33:45
H	55	32-50.778 N	119-10.584 W	1000	200	0	0	2/5/15	0:00:00	6/1/15	16:16:21
H	56	32-50.777 N	119-10.569 W	1000	200	0	0	6/2/15	0:00:00	10/3/15	0:27:36
H	58	32-50.749 N	119-10.620 W	NULL	200	0	0	11/21/15	18:00:00	4/25/16	8:51:21
H	59	32-50.703 N	119-10.583 W	1000	200	0	0	7/6/16	18:00:00	11/9/16	5:16:21
M	31	33-30.582 N	119-15.282 W	895	200	0	0	1/13/09	6:00:00	3/8/09	12:18:13
M	32	33-30.579 N	119-15.280 W	1123	200	0	0	3/11/09	0:00:00	5/4/09	6:17:00
M	33	33-30.580 N	119-15.253 W	1120	200	0	0	5/17/09	0:00:00	7/8/09	14:55:00
M	34	33-30.927 N	119-14.794 W	902	200	0	0	7/27/09	12:00:00	9/16/09	13:35:58
M	35	33-30.923 N	119-14.779 W	912	200	0	0	9/25/09	6:00:00	11/17/09	17:08:00
M	36	33-30.937 N	119-14.798 W	912	200	0	0	12/5/09	0:00:00	1/24/10	20:54:45
M	37	33-30.915 N	119-14.960 W	891	200	0	0	1/30/10	0:00:00	3/25/10	6:18:45
M	38	33-30.897 N	119-14.896 W	917	200	0	0	4/10/10	0:00:00	7/12/10	17:45:00
M	40	33-30.891 N	119-14.832 W	909	200	0	0	7/22/10	0:00:00	11/7/10	8:49:59
M	41	33-30.897 N	119-14.888 W	919	200	0	0	12/5/10	20:00:00	4/24/11	8:52:30
M	44	33-30.887 N	119-14.875 W	928	200	0	0	5/11/11	0:00:00	10/2/11	10:06:15
M	45	33-30.886 N	119-14.886 W	927	200	0	0	10/27/11	0:00:00	3/18/12	0:00:00
M	46	33-30.826 N	119-14.880 W	926	200	0	0	3/24/12	0:00:00	7/22/12	15:40:00
M	47	33-30.547 N	119-14.444 W	660	200	0	0	8/10/12	0:00:00	12/19/12	23:30:07
M	48	33-30.599 N	119-15.305 W	907	200	0	0	12/20/12	2:00:00	4/25/13	18:41:15
M	49	33-30.607 N	119-15.305 W	882	200	0	0	4/30/13	22:00:00	9/5/13	6:17:30
M	50	33-30.584 N	119-15.252 W	NULL	200	0	0	9/10/13	0:00:00	1/6/14	20:43:44
M	51	33-30.577 N	119-15.251 W	877	200	0	0	1/6/14	22:00:00	4/4/14	19:08:45
M	52	33-30.595 N	119-15.305 W	890	200	0	0	4/4/14	20:00:00	7/6/14	8:34:45
M	53	33-30.842 N	119-14.911 W	900	200	0	0	7/30/14	2:00:00	11/3/14	17:35:00
M	54	33-30.837 N	119-14.943 W	900	200	0	0	11/4/14	0:00:00	2/5/15	1:53:45
N	31	32-22.204 N	118-33.908 W	1295	200	0	0	1/14/09	0:00:00	3/9/09	6:18:00
N	32	32-22.205 N	118-33.905 W	1295	200	0	0	3/14/09	6:00:00	5/7/09	12:18:45
N	33	32-22.197 N	118-33.893 W	1295	200	0	0	5/19/09	15:00:00	7/12/09	21:17:00
N	34	32-22.186 N	118-33.885 W	1287	200	0	0	7/22/09	20:00:00	9/15/09	2:18:45
N	35	32-22.191 N	118-33.887 W	1295	200	0	0	9/26/09	3:00:00	11/19/09	9:17:30
N	36	32-22.186 N	118-33.769 W	1282	200	0	0	12/6/09	12:00:00	1/26/10	8:53:45
N	37	32-22.184 N	118-33.768 W	1280	200	0	0	1/31/10	0:00:00	3/26/10	6:17:30
N	38	32-22.180 N	118-33.800 W	1284	200	0	0	4/11/10	3:00:00	7/18/10	21:41:15
N	40	32-22.182 N	118-33.803 W	1288	200	0	0	7/23/10	14:00:00	11/8/10	23:26:15
N	41	32-22.183 N	118-33.802 W	1271	200	0	0	12/7/10	3:00:00	4/9/11	22:02:30

Supplementary Table 2, Continued

Site	Deployment	Latitude	Longitude	Depth_m	Sample_Rate	Cycle_Int	Duty_Dur	Data_Start_Date	Data_Start_Time	Data_End_Date	Data_End_Time
N	44	32-22.189 N	118-33.803 W	1282	200	0	0	5/12/11	16:00:00	9/23/11	7:00:00
N	45	32-22.199 N	118-33.894 W	1295	200	0	0	10/16/11	0:00:00	2/13/12	18:40:40
N	46	32-22.200 N	118-33.903 W	1292	200	0	0	3/25/12	0:00:00	8/5/12	20:10:00
N	47	32-22.157 N	118-33.938 W	1285	200	0	0	8/10/12	12:00:00	12/6/12	11:38:45
N	48	32-22.196 N	118-33.917 W	1300	200	0	0	12/20/12	20:00:00	5/1/13	6:13:45
N	49	32-22.194 N	118-33.892 W	1292	200	0	0	5/2/13	18:00:00	9/11/13	7:32:30
N	51	32-22.194 N	118-33.892 W	1230	200	0	0	1/7/14	20:00:00	2/16/14	15:15:00
N	52	32-22.197 N	118-33.913 W	1154	200	0	0	4/4/14	3:59:59	7/30/14	13:23:44
N	53	32-22.185 N	118-33.820 W	NULL	200	0	0	7/30/14	18:00:00	11/5/14	8:02:36
N	54	32-22.180 N	118-33.951 W	NULL	200	0	0	11/5/14	12:00:00	2/5/15	0:07:15
N	55	32-22.211 N	118-33.937 W	1000	200	0	0	2/5/15	0:00:00	6/1/15	21:38:57
N	56	32-22.223 N	118-33.841 W	NULL	200	0	0	6/2/15	0:00:00	10/3/15	14:52:36
N	57	32-22.212 N	118-33.871 W	1260	200	0	0	10/3/15	18:00:00	11/21/15	10:17:30
N	59	32-22.251 N	118-33.863 W	1200	200	0	0	7/7/16	0:00:00	11/8/16	23:57:30
N	60	32-22.159 N	118-33.848 W	1200	200	0	0	11/9/16	6:00:00	2/21/17	15:00:33

Supplementary Table 3. Environmental indices used in the multivariate linear regression modeling. The two Pacific Ocean basin indices include North Pacific Gyre Oscillation (NPGO) and the Pacific Decadal Oscillation (PDO). The Equatorial index is the Oceanic Niño Index (ONI). The regional environmental indices included sea surface temperature anomalies (SSTs) and chlorophyll *a* (Chl *a*) in the Southern California Region (SCR) and Costa Rica Dome (CRD). The other two SCR environmental indices included the cumulative upwelling index (CUI) and spring adult and juvenile *Euphausia pacifica* and *Thysanoessa spinifera* biomass (Krill).

Covariate	**Date period**	**Spatial scale**	**Temporal scale**	**Source**
NPGO	2008-2017	Pacific Ocean basin	Monthly index	o3d.org/npgo
PDO	2008-2017	Pacific Ocean basin	Monthly index	research.jisao.washington.edu/pdo
ONI	2008-2017	Equatorial (Nino 3.4)	3-mo running mean	origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php
SST	2008-2017	SCR (32-35N, 121-117W)	8-day mean	giovanni.gsfc.nasa.gov/giovanni/
Chl *a*	2008-2017	SCR (32-35N, 121-117W)	8-day mean	giovanni.gsfc.nasa.gov/giovanni/
CUI	2008-2017	SCR (33N, 119W)	Cumulative mean	pfeg.noaa.gov/products/PFEL/modeled/indices/
SST	2008-2017	CRD (5-15N, 100-85W)	8-day mean	giovanni.gsfc.nasa.gov/giovanni/
Chl *a*	2008-2017	CRD (5-15N, 100-85W)	8-day mean	giovanni.gsfc.nasa.gov/giovanni/
Krill	2008-2017	CalCOFI lines 80-93, stations 26-60	Annual, spring only	oceaninformatics.ucsd.edu/euphausiid/secure/login.php

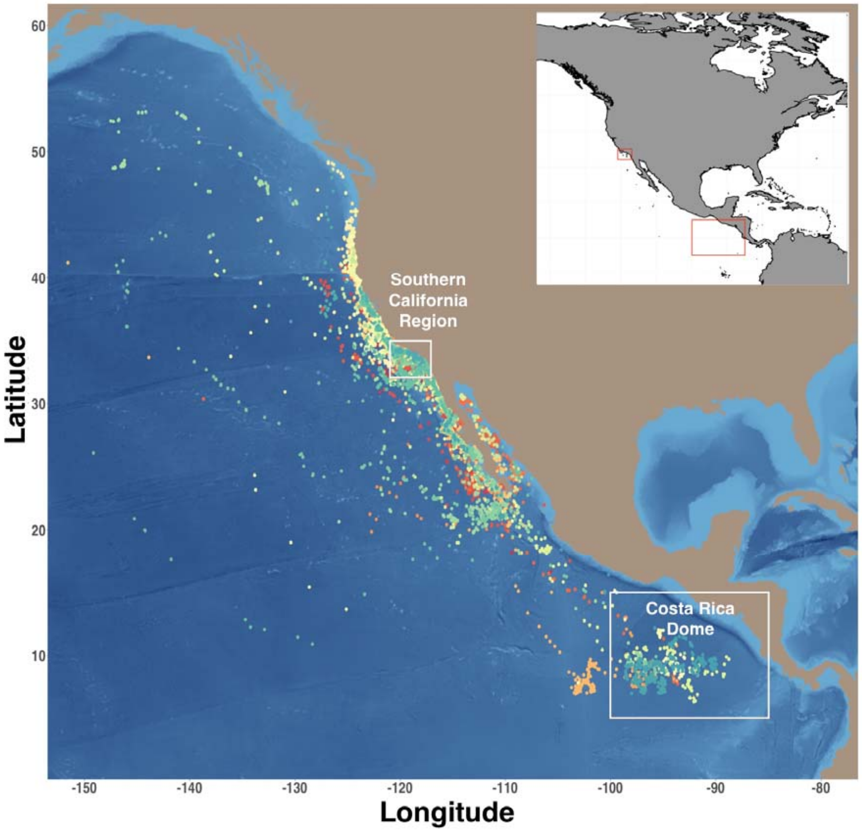
Supplementary Table 4. California Cooperative Oceanic Fisheries Investigations (CalCOFI) cruise information, including cruise number, ship name, dates, lines, and total number of stations from 2008 to 2017 where adult and juvenile *Euphausia pacifica* and *Thysanoessa spinifera* biomass were enumerated (mg Carbon per m^2) from night tows at lines 80-93 and stations 26-60 (see Supplementary Fig. S6).

Cruise	Ship	Dates	Lines	Stations
CALCOFI 0804	RV David Star Jordan	3/24/08-4/6/08	6	10
CALCOFI 0903	RV David Star Jordan	3/7/09-3/20/09	6	11
CALCOFI 1004	RV Miller Freeman	4/27/10-5/16/291	5	10
CALCOFI 1104	RV Bell M Shimada	4/10/11-4/23/11	6	7
CALCOFI 1203	RV Bell M Shimada	3/24/12-4/1/12	4	10
CALCOFI 1304	RV Bell M Shimada	4/6/13-4/10/13	5	9
CALCOFI 1404	RV Ocean Starr	3/28/14-4/12/14	4	7
CALCOFI 1504	RV New Horizon	4/4/15-4/16/15	4	7
CALCOFI 1604	RV Bell M Shimada	4/1/16-4/16/16	5	8
CALCOFI 1704	RV Bell M Shimada	3/28/17-4/9/17	4	6

Supplementary Table 5. Stepwise multiple regression with Akaike information criterion (AIC) for estimating factors acting on D call onset. Adjusted R^2 for full model: 0.9178. Significant denoted with asterisks.

Response variable	**Regression equation**	**R^2**	**AIC**
D call onset	ssta + year + krill biomass*	0.9178	77.1979
D call onset	ssta + year*	0.8273	82.61483
D call onset	ssta + krill biomass*	0.8254	82.72651
D call onset	year + krill biomass*	0.6339	90.13061
D call onset	ssta*	0.7894	82.60289
D call onset	year*	0.3271	94.21786
D call onset	krill biomass	0.1414	96.65491

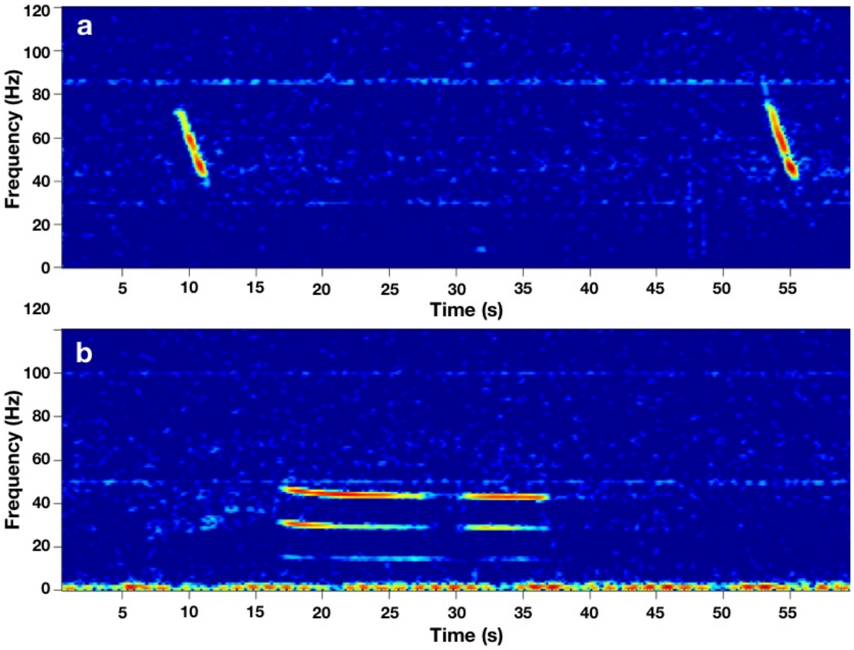
Supplementary Figures



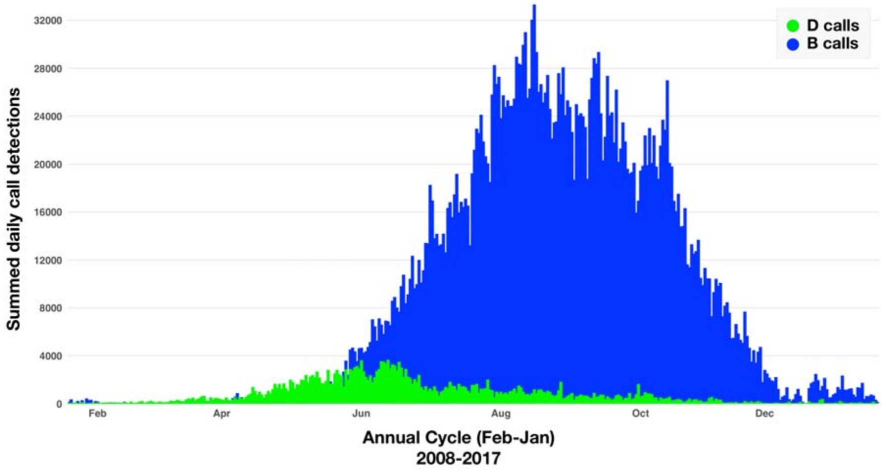
Supplementary Figure 1. GPS positions from satellite tagged blue whales (n=122) showing movement between summer feeding grounds in and north of the Southern California Region (32-35N, 121-117W) and winter breeding grounds in the Costa Rica Dome (5-15°N, 100-85°W). Colors correspond with individual whales. Only Argos location classes with accuracy estimations were plotted. Tag locations included Northern California (n=22), Central California (n=17), Southern California (n=78), Baja California (n=3), and the Costa Rica Dome (n=2). Tagging dates spanned 1993–2008, and tags

Supplementary Figure 1, Continued

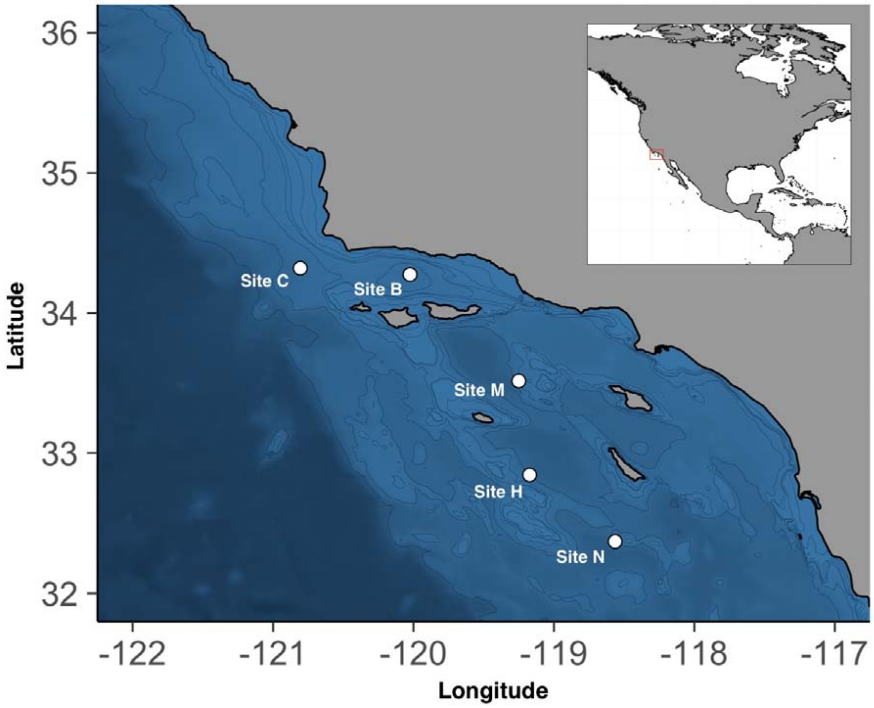
remained attached from 1 to 504 days with an average of 95 days. The bounding boxes were also used for 8-day area-averaged environmental indices derived from satellite imagery, including sea surface temperature (night only; °C) and chlorophyll (mg/m^3) from MODIS-Aqua level-3 data. Telemetry data downloaded from Movebank's data repository.[1,2] Bathymetry data came from the marmap package (v1.03, https://github.com/ericpante/marmap)[3] in R.[4] Land polygons were made with Natural Earth (v4.1.1, naturalearthdata.com) in R.[4]



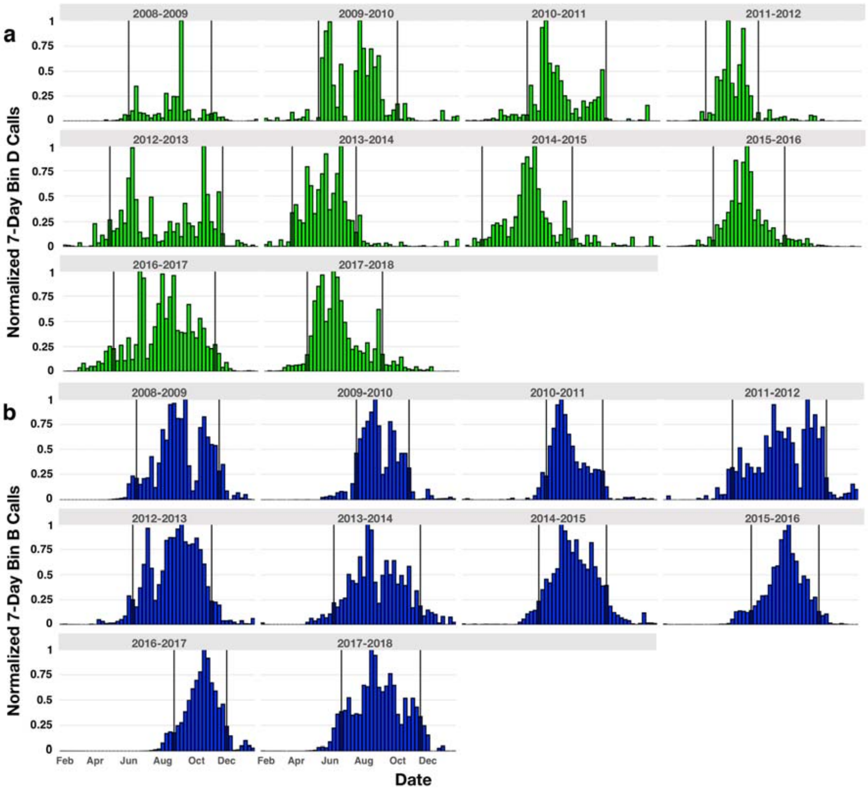
Supplementary Figure 2. Spectrograms of (a) two D calls recorded at site B on April 11, 2015 00:45:12 UTC and (b) one B call recorded at the same location on September 1, 2015 00:42:42 UTC. Spectrogram created with 2000-point fast Fourier Transform and 95% overlap, with Hanning window.



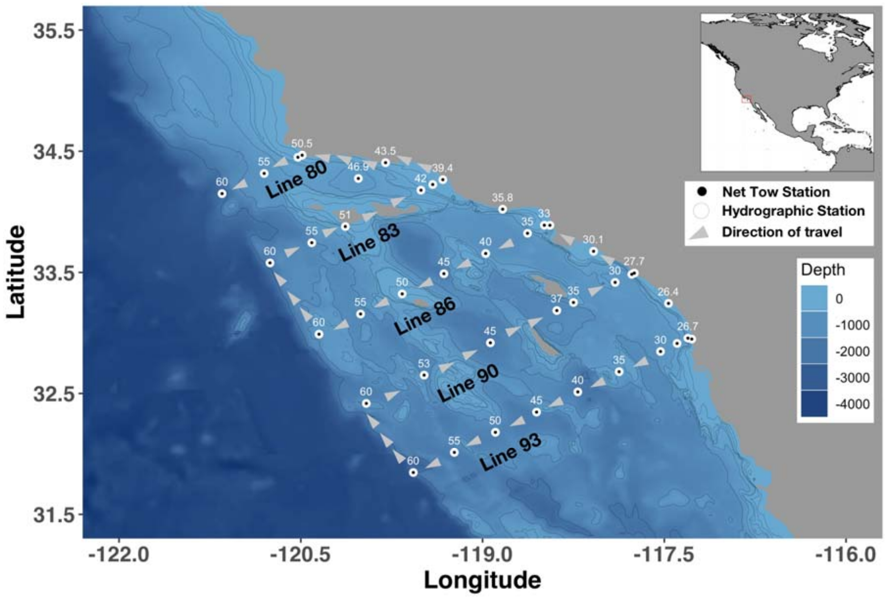
Supplementary Figure 3. The canonical distribution of daily D and B call detections (combined from all sites and all years) showing the temporal separation between two call types recorded on high-frequency acoustic recording package (HARP) deployment at five sites (see Fig. S5) from 2008 to 2017 in the Southern California Region.



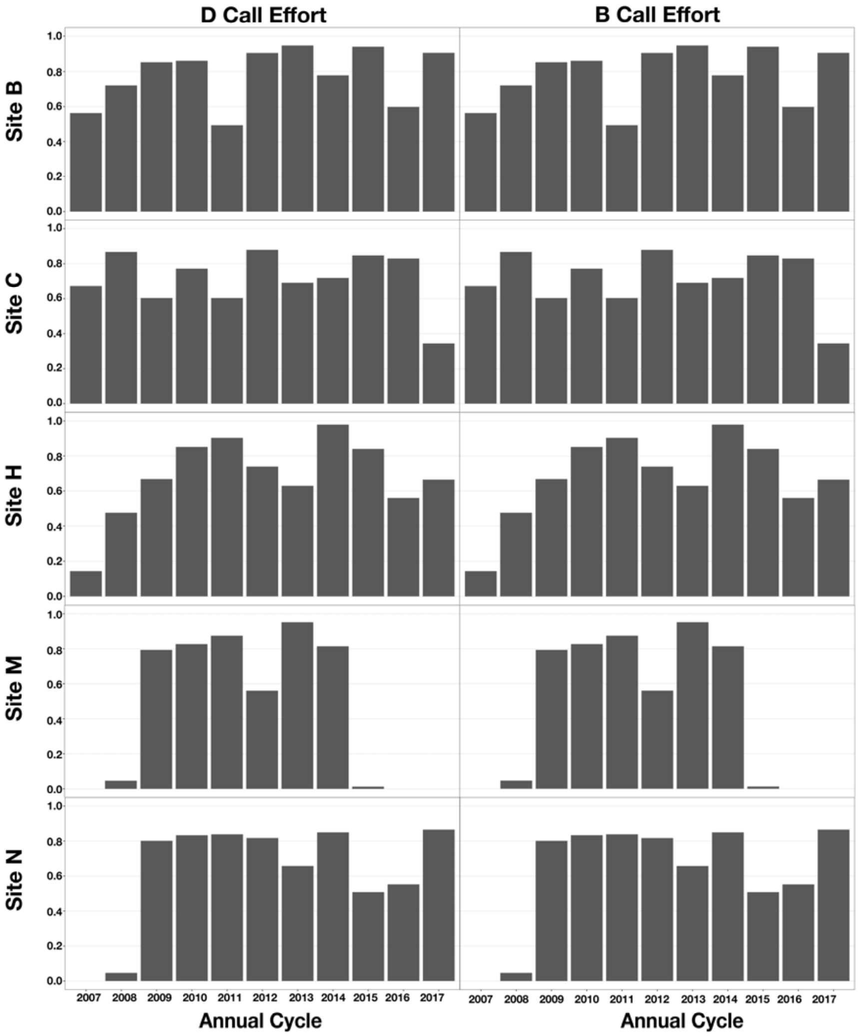
Supplementary Figure 4. Five high-frequency acoustic recording package (HARP) deployment sites (white circles) from 2008 to 2017 in the Southern California Region (see inset box map), including sites B, C, H, M, and N. Bathymetry data came from the marmap package (v1.03, https://github.com/ericpante/marmap)[3] in R.[4] Land polygons were made with Natural Earth (v4.1.1, naturalearthdata.com) in R.[4]



Supplementary Figure 5. Annual distribution of for (a) D calls and (b) B calls from 2008 to 2017. Calls have been pooled across sites, binned into weekly medians, and normalized to be between 0 and 1 by scaling with the maximum number of calls per annual cycle. The black bars around each annual cycle indicate the call cutoffs, which encompass 90% of calls from the day with the peak number of calls.



Supplementary Figure 6. Location of bongo net tow and hydrographic sampling stations and direction of travel during springtime California Cooperative Oceanic Fisheries Investigations cruises in the Southern California Region from 2008 to 2017, where adult and juvenile *Euphausia pacifica* and *Thysanoessa spinifera* were collected from night tows at lines 80-93 and stations 26-60. Bathymetry data came from the marmap package (v1.03, https://github.com/ericpante/marmap)[3] in R.[4] Land polygons were made with Natural Earth (v4.1.1, naturalearthdata.com) in R.[4]



Supplementary Figure 7. Acoustic recording effort (as a fraction from 0 to 1) for D and B calls by site for D calls (left panel) and B calls (right panel).

Supplementary Methods and Analyses

Using calls as a proxy for presence/absence

We used the presence of calls as a proxy for the presence of blue whales in the SCR, ultimately to determine their arrival and departure dates. While the absence of calls recorded on the HARPs could be indicative of whale absence on the feeding grounds, it could also indicate the presence of silent whales. However, the goal for this study and impetus behind our call threshold method was to examine the main period of presence. Historic whaling records[5], visual sighting data[6], satellite tags[1,2] , and acoustic recordings[7,8] all result in similar estimates of blue whale presence in this area, so our method is likely capturing presence well.

Call pooling

To ensure our pooling method for the calls did not create a bias, we compared the weekly binned medians that we used in this study with other pooling methods, including bin sizes at 5, 7, 10, and 14 days. We also tested various weekly binning methods, including summation, site-specific maximums, site-specific medians, and sites binned separately and then combined. In all comparisons, the relationship between the call metrics (i.e., onset, peak, cessation, duration) was comparable, and plotted with roughly one-to-one slope. This suggested that our method for pooling calls would result in a similar outcome as any other method for pooling the calls.

Call normalizing

In this study we were not interested in the total number of calls or quantifying the density of animals present in the SCR. There was also no way to account for whale movement among HARP sites, which could result in double counting. Because we were concerned only with the timing of whales' presence in the SCR, the weekly binned medians were normalized to be between 0 and 1 by scaling with the maximum number of calls per annual cycle. This gave us relative values that we could use to determine when blue whales were present in the Southern California Region.

Call cutoffs

We tested for differences in call cut-offs for defining onset and cessation for each call. There was no significant difference in 0.85, 0.90, or 0.95 percent call cut-offs. We chose a cutoff of 90 percent so that we would only eliminate five percent of calls either side from the day with the peak number of calls.

HARP effort differences

There were differences among HARP sites both in terms of recording effort and overall patterns in D and B call occurrence (Fig. S7). However, there were no significant differences in the number of HARPs operating the month of each call metric, or in the month preceding call onset dates and following call cessation dates. The differences in call occurrence across site are also due to difference in whale distribution in the area, but differences in detection probability could also play a role.[9] Comparing the location of HARP sites to the predicted density of blue whales in the Southern California Region[10], no site stood out as having a greater predicted density relative to other sites. There could also have been annual variability in the recording quality at any one site, which could result in systemic bias in a portion of the data. However, by combining all sites we believe we have captured the general pattern of blue whale presence in the Southern California Region.

Additional upwelling indices

To best capture the phenology of environmental conditions in the SCR, we also investigated the relationship between call metrics and the Coastal Upwelling Transport Index (CUTI) and the Biologically Effective Upwelling Transport Index (BEUTI). CUTI provides estimates of vertical transport near the coast (i.e., upwelling or downwelling), while BEUTI provides estimates of vertical nitrate flux near the coast (i.e., amount of nitrate upwelled or downwelled).[11] The lags matched the lag from cumulative upwelling index in the SCR and thus did not add any additional information about blue whale migration timing.

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A Case Study of a Near Vessel Strike of a Blue Whale: Perceptual Cues and Fine-Scale Aspects of Behavioral Avoidance

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Despite efforts to aid recovery, Eastern North Pacific blue whales faces numerous anthropogenic threats. These include behavioral disturbances and noise interference with communication, but also direct physical harm – notably injury and mortality from ship strikes. Factors leading to ship strikes are poorly understood, with virtually nothing known about the cues available to blue whales from nearby vessels, behavioral responses during close encounters, or how these events may contribute to subsequent responses. At what distance and received levels (RLs) of noise whales respond to potential collisions is difficult to observe. A unique case study of a close passage between a commercial vessel and a blue whale off Southern California is presented here. This whale was being closely monitored as part of another experiment after two suction-cup archival tags providing acoustic, depth, kinematic, and location data were attached to the whale. The calibrated, high-resolution data provided an opportunity to examine the sensory information available to the whale and its response during the close encounter. Complementary data streams from the whale and ship enabled a precise calculation of the distance and acoustic cues recorded on the tag when the whale initiated a behavioral response and shortly after at the closest point of approach (CPA). Immediately before the CPA, the whale aborted its ascent and remained at a depth sufficient to avoid being struck for ∼3 min until the ship passed. In this encounter, the whale may have responded to a combination of cues associated with the close proximity of the vessel to avoid a collision. Long-term photo-identification records indicate that this whale has a long sighting history in the region, with evidence of previous ship encounters. Therefore, experiential factors may have facilitated the avoidance of a collision. In some instances these factors may not be available, which may make some blue whales particularly susceptible to deadly collisions, rendering efforts for ship-strike reduction even more challenging. The fine-scale information made available by the integration of these methods and technologies demonstrates the capacity for detailed behavioral studies of blue whales and other highly mobile marine megafauna, which will contribute to more informed evaluation and mitigation strategies.

Keywords: ship strike, blue whale, near collision, active avoidance, behavioral response, perceptual cues

INTRODUCTION

Like most baleen whales, blue whales (*Balaenoptera musculus*) were greatly depleted by commercial whaling (Monnahan et al., 2014). Abundance estimates from mark-recapture data suggest no evidence of an increase in this population since the early 1990s (Calambokidis, 2013), with the population currently estimated at 1,647 individuals. With pre-whaling abundance estimates modeled at between 1,823 and 3,721 individuals, this has led some to the conclusion that blue whales had returned to carrying capacity (Monnahan et al., 2014). However, the coastal habitats where blue whales feed on euphausiid aggregations (Rice, 1974; Croll et al., 1998; Fiedler et al., 1998; Calambokidis et al., 2009, 2015) overlap with human activities. As a result, these whales are vulnerable to many anthropogenic threats, including ship strikes.

Ship-strikes off California have resulted in the death of at least nine blue whales from 2007 to 2011 (Berman-Kowalewski et al., 2010; Carretta et al., 2013), though this is an underestimate of the true number due to the small proportion of large whale mortality that is documented (Heyning and Dahlheim, 1990; Kraus et al., 2005; Williams et al., 2011). A recent model estimated a true mortality of 18 blue whales per year off the United States West Coast (Rockwood et al., 2017). That is nearly eight times greater than the potential biological removal limit (Carretta et al., 2011), defined under the United States Marine Mammal Protection Act of 1972 as the maximum number of animals, not including natural mortalities, that may be removed while allowing that stock to reach or maintain its optimum sustainable population. The factors leading to a ship strike are poorly understood, difficult to predict, and subsequently difficult to prevent. Despite mitigation efforts, including ship speed limits and adjustments to the size and location of the major shipping lanes (DeAngelis et al., 2010; McKenna et al., 2012a; Redfern et al., 2013), ship strikes continue, and questions remain about the role the behavioral response of the animal plays in ship-strike risk.

Previous research found that during nine close encounters with large commercial ships, blue whales did not respond by moving horizontally, but may have altered their diving behavior. These dives were only observed when ships were within a few hundreds of meters of the whales, a range that might not allow for much avoidance time (McKenna et al., 2015). Their constrained response time may result from external cues that are only detectable – or interpreted as a threat – at limited distances, making them vulnerable to ship strikes. The detectable perceptual cues (e.g., visual and acoustic) corresponding to the presence of close-range vessels that provoke these types of avoidance responses are unknown. It is hypothesized that blue whales use visual cues to identify prey patches on the surface (Goldbogen et al., 2013a; Friedlaender et al., 2017) and could conceivably use vision to identify a large ship. Although whales may be able to visually detect ships at or below the surface over short ranges and under ideal ambient light conditions, sound propagates much further in water than light, likely making sound the primary sensory cue for whales orienting to their surroundings. Blue whales are acoustically active animals (Oleson et al., 2007) and noise from commercial ships directly overlaps with their vocalization frequency range. These ships emit a significant amount of low-frequency underwater noise (<1,000 Hz), which poses additional threats to this endangered population (e.g., masking whale communication, increasing stress, and resulting in habituation to ship presence, potentially limiting avoidance responses and times) (McKenna et al., 2012b).

A unique incident involving a well-documented close passage between a large ship and a tagged blue whale arose during an experimental study of blue whale behavioral response to military sonar (see: Southall et al., 2019). Fine scale movement and acoustic data were collected, including estimated distances between the whale and ship, vessel noise received levels (RLs) on the tag, and three-dimensional fine-scale kinematic behavioral response. We use this unique event to gain insights into the various perceptual cues that may be used by whales to avoid ships, and to evaluate implications for ship strike risk.

MATERIALS AND METHODS

Data Collection

On September 13, 2014, a blue whale was dual tagged with a TDR10 tag (Wildlife Computers, Redmond, WA, United States) and a digital acoustic recording tag (DTAG-3; Woods Hole Oceanographic Institution, Woods Hole, MA, United States; Johnson and Tyack, 2003), in the Santa Barbara Channel (SBC) (33.66°N, 118.30°W). Both tags were simultaneously attached *via* suction cups in a single tagging approach at 0848 (local time henceforth). The animal was tagged as part of ongoing studies of whale behavior in shipping lanes (McKenna et al., 2015) and the Southern California Behavioral Response Study (SOCAL-BRS), a multi-year study of the response of different cetaceans to exposure of Navy sonar sounds conducted in the Southern California Bight (see Southall et al., 2019). As part of the SOCAL-BRS experiment, the animal was exposed to a 30-min experiment involving simulated mid-frequency (3–4 kHz) active sonar (MFAS), which ended 62 min prior to the close encounter with a large commercial ship.

A tagging boat (5.9 m rigid-hull inflatable boat; RHIB) was used to deploy the tags with a ∼5-m carbon fiber pole. The whale exhibited no visible reaction during tagging and resumed the behavior observed prior to tagging (i.e., consistent traveling). The animal was photographed and compared with known individuals in the Cascadia Research photograph identification catalog database (Calambokidis et al., 2009, 2015). While a skin sample was collected *via* biopsy, the sex of the animal was identified as female from a previous biopsy of this individual. The tagged animal's positions were recorded during a focal follow in order to provide georeferenced positions for the pseudotrack generated from tag data (see section "Distance Calculations"). In the focal follow two vessels were involved in observing the tagged whale. The RHIB stayed 100–200 m away until the whale made its terminal dive, then slowly approached the location to record the exact dive position from the whale's footprint. A larger (22 m) vessel remained at distances of 362 to 2,750 m (on average 500–1,500 m) from the whale when it was at the surface and provided visual tracking support. Both vessels followed the methodology developed for the SOCAL-BRS experiment to ensure the presence of small boats would not impact behavior (see: Southall et al., 2012, 2016).

The DTAG-3 recorded dual-channel acoustics at a 240-kHz sampling rate, while pressure, temperature, and a tri-axial accelerometer and magnetometer were sampled at 250 Hz. The TDR10's pressure sensor recorded at 1 Hz and the FastGPS sensor took sub-second instantaneous satellite position snapshots when the tag emerged from the water during surfacings of the whale. Both tags were deployed with VHF transmitters used for locating the tagged whale and for tag recovery. The DTAG-3 remained attached to the animal for 5.7 h while the TDR10 remained attached for 15 hr. The data from the two tags were synchronized based on the timestamps.

Kinematic Analysis

The three-axis accelerometer and magnetometer data from the DTAG-3 were down-sampled to 5 Hz and corrected in MATLAB (Mathworks, Natick, MA, United States) so the axes aligned with the "whale frame" using periods of known orientation (Johnson and Tyack, 2003). Animal orientation (i.e., pitch, roll, and heading) was calculated using custom-written MATLAB scripts (Johnson and Tyack, 2003; Cade et al., 2016). Animal speed was determined from the root-mean-square (RMS) amplitude of flow noise from tag acoustics (Goldbogen et al., 2006; Simon et al., 2009). Lunges indicative of feeding were detected from the DTAG-3 data using a custom-developed lunge detection algorithm [similar to Allen et al. (2016)]. Depths recorded by the TDR10 pressure sensor were assessed in R (R Core Team, 2019) using the package "diveMove" (Luque, 2007) to determine the number of dives and maximum depth per dive performed by the tagged whale. Dives recorded only on the TDR10 were manually audited for the presence of vertical lunges as a coarse determination of presumed feeding. Dives were classified as lunge-feeding or non-lunge feeding based on the presence or absence of lunges during each dive. This gave us four generalized behavioral states for each dive.

Distance Calculations

Ship positions from the Automatic Identification System (AIS), the global ship tracking system used by vessel traffic services, were obtained for the period when the whale was tagged from an AIS receiver on Santa Cruz Island (33.995°N, 119.632°W). Whale surface locations were resolved from satellite position snapshots for surfacings detected on the TDR10's FastGPS sensor during which an adequate number of satellites (>4) were identified. We generated a georeferenced pseudotrack at 1 Hz sampling rate using the depth, pitch, speed, and known geographic reference points of the tagged animal (GPS positions from the TDR10 and focal follow positions) (Wilson et al., 2007). Ship positions were interpolated to 1-s intervals with the "ST_Line_Interpolate_Point" function in PostGIS assuming a constant speed and course over ground. The PostGIS "ST_Distance_Sphere" function was used to calculate horizontal distances from the tagged whale to every ship present in the AIS data. Three-dimensional straight-line distances were calculated as the hypotenuse of the horizontal and vertical distance between the ship and the whale and rounded to 10-m intervals. Horizontal distances were calculated as distance between the whale and the closest point to the ship after accounting for the location of the AIS transmitter on the ship and orientation relative to the whale. Vertical distances were calculated as the distance between the ship's reported draft and the whale's depth (determined from the TDR10's pressure sensor).

Acoustic Analysis

The acoustic data from the DTAG-3 were initially viewed as 60-s spectrograms calculated from 10 Hz to 120 kHz in MATLAB using Triton, custom-written software (Wiggins, 2003), to identify ship noise. To extract sound levels from the DTAG-3, the acoustic data were first decimated to 48 kHz, and the broadband (0 Hz–48 kHz) RMS received sound pressure levels (dB re 1 μPa) were calculated in 1-s intervals. Additionally, the power spectral density was calculated at a 1s-resolution and then summed over 1/3-octave band sound pressure levels (dB re 1 μPa) for bands with center frequencies ranging from 160 Hz to 20 kHz, using methods described in Merchant et al. (2015).

Noise generated from water flowing over the tag hydrophone (flow noise) can contribute to acoustic measurements of actual noise in the environment at frequencies up to 1 kHz. Flow noise highly correlates with whale swim speed and fluking (Goldbogen et al., 2006; Simon et al., 2009) and the noise tends to predominate at frequencies below 100 Hz (Fletcher et al., 1996). Therefore, this study excluded 1/3-octave bands below 140 Hz from the calculations of noise levels associated with the vessel. Flow noise above 140 Hz, to the extent it was present, was considered to be a relatively constant element of overall noise and included as part of the noise level calculations.

Controlled Exposure Experiment

As part of the SOCAL-BRS project, the animal was exposed to simulated MFAS from 1045 to 1115 PDT (local), during which a stationary experimental sound source (deployed from the M/V Truth) was positioned at ranges from ∼800 m to >2 km from the whale. Prior to the controlled exposure experiment (CEE), prey mapping with a calibrated multi-beam echosounder occurred from 0910 to 1008 [as in Friedlaender et al. (2016)]. From tag deployment, until the CEE began (117 min), the animal's baseline behavior was recorded during focal follow. After 30 min of MFAS exposure, post-exposure focal follow and prey mapping began, which ended at 1238. The animal was feeding before, during, and after the CEE and while behavioral changes were identified as a result of the experiment CEEs (Southall et al., 2019), these were ephemeral in nature. The animal exhibited typical deep feeding dives for the 62 min-period following the CEE and prior to the vessel encounter. The DTAG-3 detached from the whale at 1416 and the TDR10 detached at 2346.

Photograph Identification

Based on the identification of the whale from matches in Cascadia Research's catalog and database, the animal was a known female that had been seen previously 23 times off the California coast in eight different years beginning in 1987. Most of the sightings were in the Southern California Bight in the vicinity of Palos Verdes Peninsula, a region near the shipping lanes leading to the port of Los Angeles/Long Beach and near where the animal was tagged in this study. The animal was also sighted off Pt. Reyes, California, a region near the northbound shipping lanes leaving San Francisco Bay. The animal was previously tagged during the 2011 SOCAL-BRS on August 3, 2011, however the tag remained attached for only 1 hr and therefore no playback experiment occurred. This whale was also sighted when the tagged whale and another whale were involved in the capsizing of a 23-foot private vessel off San Diego on July 2, 2014 (∼2 months prior to the encounter described here), after the boat approached the whales to take photographs. There were no reports of injury to the whales following the incident.

RESULTS

The R package "diveMove" detected 118 dives from the TDR10 pressure sensor data (**Figure 1**). The DTAG-3 pressure sensor captured the first 33 of these dives. Of the 118 dives detected, 12 were deep lunge-feeding dives, 35 were deep non-lunge feeding dives, 4 were shallow lunge-feeding dives, and 67 were shallow non-lunge feeding dives. At the onset of tagging, the whale was making a series of deep non-lunge feeding dives interspersed with lunge-feeding dives as she traveled southeast along the 200-m contour line (**Figure 1**). Two lunge-feeding periods were identified, one from 0910 to 1057, which occurred during the CEE and included 1 deep and 3 shallow lunge-feeding dives, and one from 1613 to 1930, which included 8 deep and 4 shallow lunge-feeding dives. Sunset occurred at 1854. From 1930, the onset of civil twilight, until the TDR10 tag detached at 2346, the dive record suggested a resting bout of 4 h and 15 min during which the whale stayed shallower than 35 m and no lunges were detected.

The TDR10 collected 122 resolvable GPS locations. Distance calculations between the ship and whale tracks revealed three instances where an underway ship was within 2 km of the tagged whale. The closest point of approach (CPA) between the Mokihana, a 263-m container ship traveling at 11.3 knots, and the tagged whale occurred at a horizontal distance of 93 m while the whale was at a depth of 67.5 m (**Figures 1**, **2**). The corrected horizontal distance from the AIS transmitter on the boat at the starboard side closest to the whale was 77 m and the corrected vertical distance between the whale and the reported draft of the ship (10 m) was 57.5 m. The 3D straight-line distance between the Mokihana and the tagged female blue whale was approximately 100 m. The other two ships passed at horizontal distances greater than 1.5 km from the whale and occurred after the MFAS CEE during the post-exposure focal follow and prey mapping.

Behavioral Response During CPA With Mokihana

Prior to the CPA with the Mokihana, the tagged whale was ascending from a deep non-lunge feeding dive (max depth = 277.5 m). The whale began to slow its ascent ∼90 s before

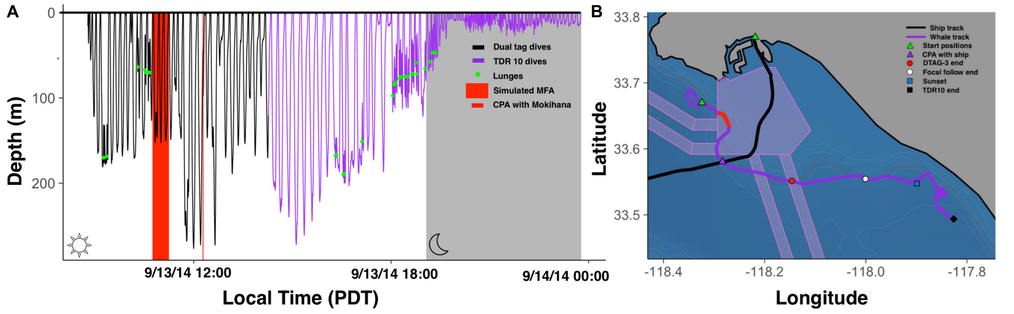

FIGURE 1 | (A) Dive record from DTAG-3 data (black) and TDR10 data (purple). Detected lunges are indicated by green circles. Red shading indicates simulated mid-frequency (3–4 kHz) active sonar playback as part of the SOCAL-BRS CEE. Red line indicates closest CPA with container ship Mokihana. **(B)** Horizontal tracks of Mokihana (black) and tagged whale (purple). Green triangles represent start positions for ship and whale. Red shading indicates period of the CEE. Purple triangle indicates the whale location during the CPA. Red circle indicates end of DTAG-3 recording, white circle indicates conclusion of focal follow, the blue square indicates sunset, and black square indicates end of TDR10 attachment. Shipping lanes are pink polygons and contour lines are represented in light gray from 50 to 500 m (in 50 m increments), with the 200-m contour in dark gray.

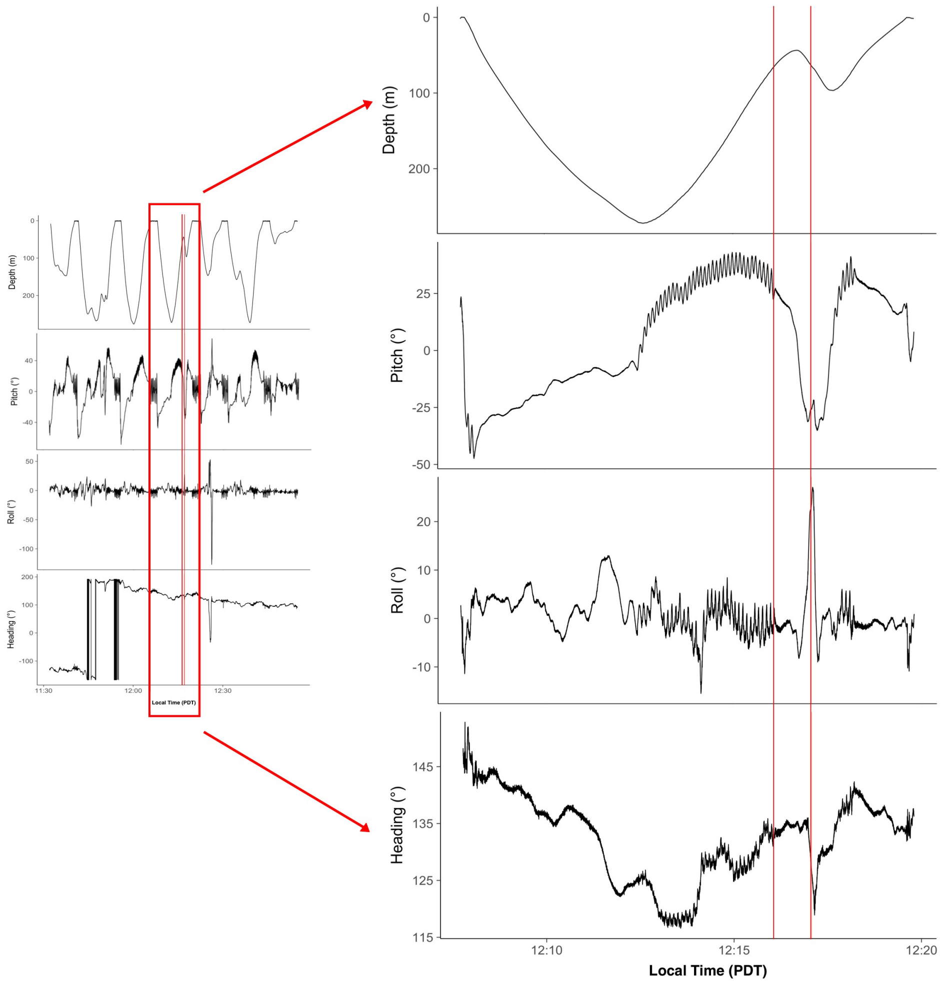

FIGURE 2 | Close up of fine scale kinematic data recorded during the CPA with the Mokihana. The first panel illustrates the depth (meters), the second panel shows pitch (degrees), the third panel illustrates roll (degrees), and the fourth panel illustrates heading (degrees). The first solid red line indicates the onset of a behavioral response by the whale. The second solid red line indicates the CPA with the Mokihana.

the CPA. Forty-seconds before the CPA, while the ship was at an approximate 3D straight line distance (hypotenuse between the ship and the whale) of 300 m from the whale, the tagged whale reversed into a descent. Kinematic data from the DTAG-3 shows a change in pitch, which corresponds to the switch to descent. The CPA occurred as the whale was at a depth of 57.5 m from the ship's draft. By this time the ship was approximately 100 m away from the whale at a 3D straight line distance. The data also indicate that the whale rolled to the left and changed its heading quickly at the CPA. The tagged whale resumed its ascent and surfaced after a ∼3-min delay from the previous projected surfacing time (**Figure 2**).

Before the close approach of the vessel, the broadband (RMS) ambient noise was generally ∼125–130 dB re 1 µPa (**Figures 3**, **4**). The overall ambient conditions in this environment were likely strongly influenced by aggregate vessel noise in the general area, including the Mokihana. However, as the ship approached, there was a rapid increase in the acoustic energy at higher frequencies (>1 kHz) with a typical spectral and temporal pattern associated with large vessels (McKenna et al., 2012b). The lower frequency

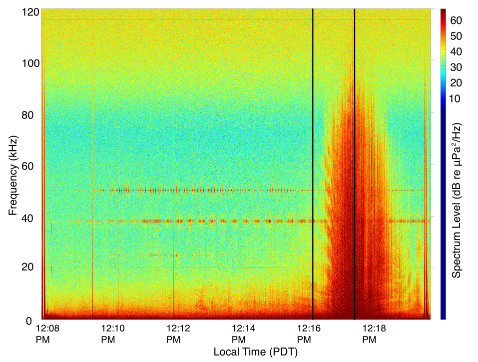

FIGURE 3 | Spectrogram showing the acoustic signal of the Mokihana during the CPA as recorded on the DTAG-3 hydrophone. The first black vertical line indicates the onset of a behavioral response by the whale. The second black vertical line indicates the CPA with the Mokihana. Spectrogram parameters: NFFT = 240000, 90% overlap, Hanning window.

bands ($<$1 kHz) exhibited an initial drop, associated with the cessation of fluking by the whale. These lower frequency bands then exhibited a rapid increase in levels, with no concurrent increase in fluking activity. The increase was instead associated with the passing of the ship within 100 m of the whale. The broadband sound level at CPA peaked at 135 dB re 1 μPa compared to $\sim$125 dB re 1 μPa at the last approximate point with similarly no fluking activity (**Figure 4**), representing a 10-dB increase over ambient broadband levels. Higher frequency ($>$1 kHz) 1/3-octave levels increased by up to 40 dB over pre-ship ambient levels. Additionally, as indicated in the noise spectra (**Figure 3**) and the broadband RMS RLs (**Figure 4**), there was a relatively abrupt change in the received sound levels around the point at which the whale initiated a change in behavior. There was a subsequent peak in the noise in all frequencies corresponding to the CPA of the Mokihana. The 1/3-octave band sound levels (**Figure 4**) indicate that the whale initiated a response dive when higher frequency ($>$1 kHz) RLs were only a few dB above ambient levels, just prior to reaching their maximum values. The whale only resurfaced after the vessel passed and was moving away, at which point RLs and the prevalence of higher frequency noise energy from the vessel were decreasing. The broadband RMS sound levels indicate a second peak after the passage of the ship, which corresponds to the resumption of fluking (evident in pitch, **Figure 2**) as the whale ascends. This peak in acoustic energy is only evident in the low frequency components of the 1/3-octave band levels, further indicating the second peak in broadband sound levels is due to increased flow noise associated with fluking.

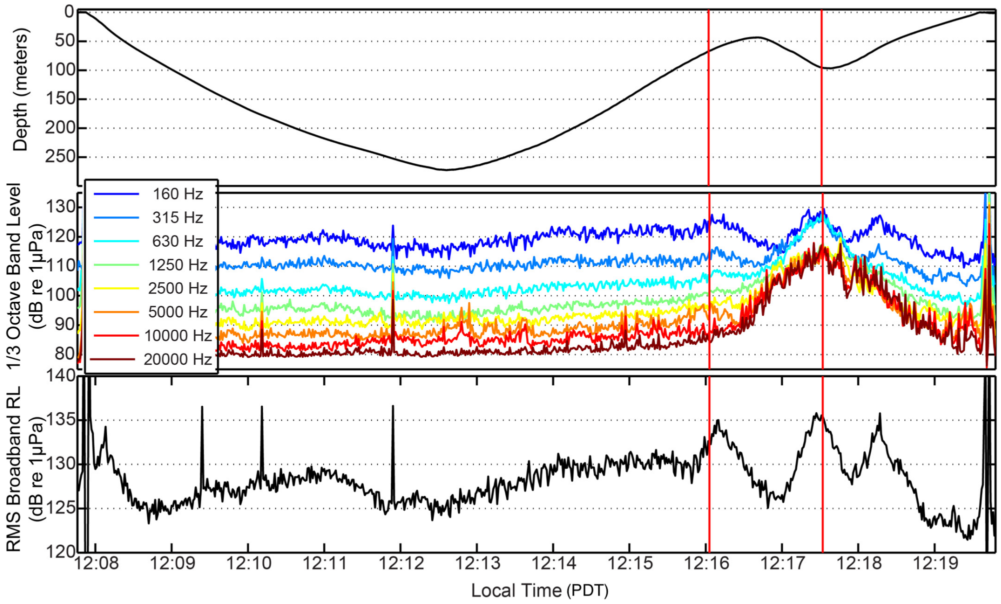

FIGURE 4 | Received levels (RLs) recorded on the DTAG-3 during the passage and CPA of Mokihana. Both 1/3-octave band sound levels **(middle panel)** and broadband (RMS) measurements **(bottom panel)** are shown. The **upper panel** shows the depth of the tagged whale during the same time period. The first red vertical line indicates the onset of a behavioral response by the whale. The second red vertical line indicates the CPA with the Mokihana.

DISCUSSION

The unique dataset from this case study provides a detailed account of the closest documented encounter between a large commercial vessel and a blue whale. The exact cues used to facilitate the successful avoidance in this close encounter case were unknown. However, contemporaneous data from multiple platforms (i.e., fine-scale kinematic, acoustic, movement, position, demographic, and long-term sighting history data) available in this study provided a comprehensive picture of the interaction, allowing us to explore the potential visual and acoustic cues available to the whale. It is likely that the observed behavioral response to the close ship passage resulted from some integration of these multi-modal indicators of close presence rather than any single parameter (e.g., maximum RL) driving the avoidance response.

The observed response behavior of the whale in this study occurred during an ascent from a deep non-lunge feeding dive when the whale aborted its ascent to the surface in order to descend back down to a deeper, and potentially safer depth, until the ship had passed overhead. There appeared to be no change in the direction of the whale as it traveled along the shelf edge perpendicular to the course of the ship. This mirrored the behavioral response previously described by a blue whale in McKenna et al. (2015). The whale also performed a 25-degree left-hand roll as the ship passed overhead.

The focal follow of the whale was a consistent part of the observation/tracking of this whale and lasted from 0736 (nearly 1 h prior to tagging) through 1436 (with a small number of follow-up observations through 1756). The only exceptions from this routine involving other types of approaches were well before or after the ship close approach and included approaches by the RHIB to deploy tags at 0848, an approach to conduct a unmanned aircraft system flight over the whale around 1000 (and ending by 1010), and two approaches to collect biopsy and fecal samples between 1340 and 1436. No obvious strong reactions were noted to these approaches (a potential acceleration was noted as a reaction to the biopsy collection at 1340). There were no sudden changes or close approaches to the tagged whale immediately before, during, and after the close approach with the Mokihana, allowing us to reliably detect changes during close encounters. Given that these approaches were not within an hour of the ship close approach and did not elicit a response, we are confident the specific and unusual observed response documented around the time of the ship CPA and described here is primarily related to the encounter with the Mokihana.

The cues whales use to detect the presence of a ship will likely influence how they respond and the amount of time they may have to react before a potential collision. Although cetacean vision is monochromatic, they do have adaptations for better underwater vision, including large, flattened eyeballs; enlarged pupils; and a tapetum lucidum, which translates to increased light intake and clearer images (Dawson, 1980; Mass and Supin, 2007). Deep-diving whales also have higher rhodopsin, a light-sensitive protein in the rod cells that confer greater sensitivity toward blue-shifted underwater light (Jacobs, 1993; Southall et al., 2002; Dungan et al., 2016). This suggests that in a clear ocean, whales could make use of any available light within the euphotic zone. In turbid waters, reduced visibility may increase the risk of ship strike; however, in our study, the Beaufort Sea State was reported as a 4, and the whale was 67.5 m from the surface. The whale may have been close enough to the surface to see the downwelling light blocked by the nearly 300-m cargo ship, similar to how they would assess prey distribution. Additionally, rolling 25 degrees, an uncommon response for blue whales near the surface (Segre et al., 2018), is suggestive of deliberate behavior, and would enhance panoramic vision (120–130° visual field) in multiple dimensions (Goldbogen et al., 2013a), allowing the whale to watch the ship pass overhead. Because cetacean vision functions in air and water (Supin et al., 2001), this whale also may have seen the ship approaching when the whale was at the surface.

At the time the whale initiated its response, there was only a minimal increase in the overall ship noise level above background levels (as detected on the tag) although there was a rapid increase in relative levels of high-frequency noise. This indicates that the whale may have reacted to the these changes in acoustic cues of the vessel's proximity soon after they were available. However, the ship was only audible on the tag above background levels once it was within extremely close range (∼300 m). Additionally, the main source of noise – the propeller – is located at the stern of the ship, so at the maximum received sound level, hundreds of meters of ship had already passed overhead. This suggests that a whale ahead of a ship may have very little acoustic information to indicate its approach and therefore only extremely limited time to initiate an appropriate behavioral response. Several factors can affect the ability of whales to detect and locate the sounds of approaching ships, including acoustical shadowing if the propellers are located shallower than keel depth, masking of ship noise by ambient sound from other ships, and the Lloyd's Mirror Effect whereby refraction of lower frequency sounds from the surface leads to extreme sound attenuation at shallow depths (Gerstein et al., 2005).

Additionally, the maximum RMS broadband received sound levels exceeded pre-ship sound levels by ∼10 dB, a value well below those associated with avoidance and diving behavioral responses of shallow-diving blue whales to active sonar sounds (see: Southall et al., 2019). While these have different contexts than continuous noise associated with vessels, the data are consistent with the observation that the response was not necessarily driven by an aversive reaction to a perceived loud sound. Rather, the increase in ship noise above ambient conditions, and other factors we were unable to measure (e.g., Doppler shifts indicating relative motion), were potentially integrated with visual information to indicate the close proximity of the ship to the whale that resulted in the observed response. However, as background ocean noise levels increase, particularly driven by greater shipping traffic (Ross, 1993; Andrew et al., 2002; Chapman and Price, 2011; Southall et al., 2018), it may prove to be even more difficult for a blue whale to detect acoustic cues in order to locate and avoid passing ships. If blue whales are not detecting acoustic cues, or the acoustic cues are below individual hearing thresholds, they must rely solely on visual detection, which greatly reduces the range that they can detect an oncoming ship.

The whale's behavioral state at the time of the close encounter may have played a role in its behavioral response. Lunge feeding was not detected in the dive recorded by the DTAG-3 during the CPA. However, lunges were detected in dives before and after the CPA. The dive occurring during the CPA may have been part of a larger foraging bout or constituted traveling in search of a new prey patch. Behavioral state has been shown to influence the context-dependent behavioral response of tagged blue whales, including during playback experiments with ship noises and navy sonar (Goldbogen et al., 2013b; Southall et al., 2018, 2019). Feeding whales may be distracted (Chatterton, 1926; Horwood, 1981; Watkins, 1986) and thus be less capable of detecting – and, therefore, avoiding – approaching vessels. They may also ignore ships in favor of their current behavior (e.g., feeding, socializing, migrating) or due to habituation (Laist et al., 2001; Nowacek et al., 2004; Silber et al., 2010).

The avoidance of a collision between the tagged whale and large vessel may not have been solely due to the animal's behavior. Specifically, the ship's speed may have played a role by giving the whale enough time to respond. At the time of the close passage and onset of the observed behavioral response by the whale, the ship was going 11.3 knots. This ship had recently left the Precautionary Area of the SBC Traffic Separation Scheme. Matson, Inc., which owns the Mokihana, was participating in a vessel speed reduction trial incentive program, which aimed to slow ships in the SBC from 14–18 knots to 12 knots. In addition to reducing air pollution, slowing ships to 12 knots has been shown to greatly reduce the chances of a lethal ship strike (Vanderlaan and Taggart, 2007; Gende et al., 2011; Wiley et al., 2011; Conn and Silber, 2013; McKenna et al., 2015). The Mokihana had not yet picked up speed, which may have allowed the additional reaction time for the animal to arrest its ascent and avoid a potential collision. The behavioral action may not have been as effective if the vessel was traveling at greater speeds (McKenna et al., 2015), and the whale could have been struck at the surface or gotten close enough to the ship's draft that the propeller suction effect created by the ship's hydrodynamic flow could pull the whale toward the hull (Silber et al., 2010) resulting in a ship strike.

One of the hypotheses to arise from the research of McKenna et al. (2015) is that because the evolutionary history of blue whales did not include threats at the surface, whales have not developed an effective behavioral response strategy for this surface hazard. Our study confirms that there are some sensory cues available to the whale, but only at relatively close ranges (<300 m) and under certain oceanographic conditions. This may mean that even experienced individuals cannot always effectively adapt to the threat of shipping traffic. However, this may be further compounded by potential habituation to the presence of ships in important habitats. We know from the long sighting history of the tagged whale that it spent large amounts of time in high ship traffic areas, was exposed to military sonar, and was even involved in the capsizing of a small boat. The whale in this study was able to make last minute behavioral changes in response to the ship when it was already extremely close. However, this response may not be effective in all situations, making blue whales particularly vulnerable to ship strikes. The two key data points from our study – distance and acoustic cues (including RLs and frequency content) – will aid future models in determining when animals would need to respond to avoid being hit by a ship.

The combination of the distinct methodologies and technologies presented in this case study allowed for the collection of high-resolution behavioral information to examine a blue whale's response during a close encounter with a large vessels. Not only has this filled in gaps in our current understanding of blue whale exposure to anthropogenic threats, which will contribute to more informed evaluation and mitigation strategies, but this study provides an example of how multiple methodologies can be combined to conduct behavioral studies in other highly mobile marine megafauna. Future work will examine close encounters from multiple whales to determine if certain contextual factors lead to a higher rate of behavioral response. This information can be used by managers to reduce the risk of exposure to ships or increase the chances of a successful evasion during a ship encounter.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of Institutional Animal Care and Use Committee protocols (#AUP-6) and National Marine Fisheries Service Authorizations and Permits for Protected Species (#14534-2). The protocol was approved by the Institutional Animal Care and Use Committee protocols (#AUP-6) and National Marine Fisheries Service Authorizations and Permits for Protected Species (#14534-2).

AUTHOR CONTRIBUTIONS

JC and BS conducted the field work and collected the data. AS and JC conceived of the presented idea. AS processed and analyzed the kinematic dive data, conducted the distance calculations, and wrote the draft manuscript. AA and BS conducted the acoustic analysis. JF created the whale pseudotrack track file. AS, AA, JC, JF, MM, and BS discussed the results and contributed to the final manuscript.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Manage vessels not whales: A rich data set reveals no detectable response of blue whales to approaching vessels

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Abstract

Members of at least 75 marine species have been injured or killed by vessels, including many whale species. By sharing habitat with dense vessel traffic on the U.S. West Coast, blue whales are at risk of injury or death due to vessel strikes. Models have allowed for estimations of risk and lethality; however, assumptions are made due to uncertainty about whale avoidance. We assessed vessel (type, length, width, draft, speed, encounter duration, heading variability, and heading relative to whale), environmental (month, hour, wind speed, Beaufort scale, and distance to shipping lanes, port, and coast), and whale (ID, exposure number, mean daily encounter rate, depth, dive portion, and behavior) variables associated with 216 close passages (<2 km) between 174 vessels and 24 tagged whales to determine if they influenced distance, and therefore risk during close passages. We also looked for differences and uniqueness in whale dive behavior (dive and surface duration, number of lunges per dive, maximum depth) and movement (speed and heading) during close passages. None of the contextual variables showed a relationship with distance and we found no evidence of behavioral response. The absence of avoidance behavior indicates a need to manage vessels, not whales to reduce collision risk.

Keywords

baleen whales, behavioral response, bio-logging, blue whales, endangered, human-wildlife conflict, marine megafauna, shipping lanes, ship strike, vessel strike

Introduction

As expanding human populations encroach upon natural habitats, humans and animals are increasingly coming into conflict over food and space (Zimmermann et al., 2010). Especially in the context of large-bodied carnivores—notably bears, wolves, and cats—these conflicts have received management attention. More complex, and less understood, human-wildlife conflicts also exist in marine ecosystems (Draheim et al., 2015). One significant example is a vessel physically striking a marine animal, which can be costly at a minimum, and deadly in the worst case. Members of at least 75 marine species are known to have been injured or killed by vessel collisions (Schoeman et al., 2020). These include manatees, sharks, seals, sea otters, turtles, fish, and whales. Nearly all whale species are vulnerable to vessel collisions, and this has been determined as the leading human-caused source of mortality for baleen whales on the U.S. West Coast (Carretta et al., 2020).

From 2018 to 2020, the National Oceanic and Atmospheric Administration (NOAA) National Stranding Database documented 27 whale-vessel collisions off California. The true number of fatal whale-vessel collisions is likely much greater (Rockwood et al., 2017; Pace et al., 2021). Whales in remote areas are unlikely to be documented, only a few species can wrap around a vessel's bow and be carried into port (Douglas et al., 2008), and an unknown fraction of carcasses strand or remain floating (Moore et al., 2020). Among the documented dead were the eastern North Pacific blue whales (*Balaenoptera musculus*), which share their coastal foraging habitat with high vessel traffic transiting to and from the major ports of Los Angeles/Long Beach and San Francisco/Oakland. Climate change may be driving blue whales to extend their stay off Southern California (Szesciorka et al., 2020), which could further increase vessel strike risk.

A growing body of research using stranding data, simulations, and models have focused on estimating the probability of encounter, strike, and lethality to inform management decisions that aim to reduce vessel strike-related mortality. These models include information on co-occurrence (e.g., Redfern et al., 2013; Nichol et al., 2017; Rockwood et al., 2017; Blondin et al., 2020); vessel size, speed, and draft (e.g., Laist et al., 2001; Vanderlaan & Taggart, 2007; Silber et al., 2010; Gende et al., 2011; Wiley et al., 2011; McKenna et al., 2012; Silber & Bettridge, 2012; Conn & Silber, 2013); and diel whale behavior and habitat use (e.g., Calambokidis et al., 2019; Keen et al., 2019; Caruso et al., 2020). Because of uncertainty about the nature of whale behavioral response, models must make assumptions, for example treating whale avoidance as a function of speed (e.g., Kite-Powell et al., 2007; Gende et al., 2011; Conn & Silber, 2013; Rockwood et al., 2020), including multiple behavior response parameters (Rockwood et al., 2017), or leaving whale behavior out of the models to avoid the uncertainty (e.g., Crum et al., 2019).

Until more recent advances in biotelemetry (Goldbogen et al., 2013, 2017; Szesciorka et al. 2016; Mate et al., 2016), it was difficult to collect the fine-scale behavior and movement data that would allow for studies of whale behavioral response — studies that would allow for behavioral response to be included in risk models. Additionally, behavioral response studies have tended to focus on the impacts of whale-watching vessels and cruise ships (e.g., Baker et al., 1989; Corkeron 1995; Williams et al., 2002; Lusseau et al., 2009; Stamation et al., 2010; Harris et al., 2012, Schuler et al., 2019). Given the significant overlap between important blue whale feeding hotspots and commercial shipping activity (Berman-Kowalewski et al., 2010; Redfern et al., 2013; Dransfield et al., 2014; Irvine et al., 2014; Calambokidis et al., 2015; Hazen et al., 2016) and previous unusual mortality events due to vessel strikes (Berman-Kowalewski et al. 2010), there is a strong need to understand blue whale behavioral response to a multitude of vessels under various contexts.

McKenna et al. (2015) found that nine tagged blue whales did not move horizontally but may have altered their diving behavior when vessels were within a few hundred meters of the whales, suggesting a limited response to very close passages. Lesage et al. (2017) observed that on average the surface times of blue whales were 40% shorter and dive times 36% shorter at vessel distances ≤400 m, but this study was not able to explore the impacts of depth, frequency of exposure, and contextual aspects of the close passages. Szesciorka et al. (2019) illustrated an example of an apparently strong avoidance response of a tagged blue whale to a vessel passing approximately 100 m away, and through fine-scale sampling data were able to determine the time the whale altered its diving behavior as well as investigate aspects of the context of the close passage.

Two major questions arose from these previous studies: What is the context under which vessels get close to whales, and are there generalizable behavioral responses to close vessel passages? Our goal for this paper was to expand on previous analyses using a large and rich dataset to quantitatively assess close passages with vessels. Here we combine six years of blue whale tag data to examine the context of close passages and ask (a) can we detect a systematic difference in behavior associated with a close passage with a vessel, and (b) is the behavior exhibited during a close passage a unique behavior that only occurred during the close passage with a vessel?

Materials and Methods

Tag deployments and data — Thirty-five blue whales were tagged from 2013 to 2018 off California, within the Santa Barbara Channel (n=28) and off northern California (n=7), in areas overlapping with busy traffic separation schemes (hereafter, "shipping lanes"; Supplementary Fig. 1). Tag deployments were conducted from 6-7 m rigid hull inflatable boats. The tagger stood on an elevated bow platform and used 3-4 m poles to attach tags. TDR10 (Wildlife Computers) and Acousonde (Greeneridge Sciences, Inc.) tags were attached with various configuration of suction cups or modified stainless steel darts as described by Szesciorka et al. (2016). Tags were placed roughly halfway along the back of blue whales near the dorsal fin. Most TDR10 tags sampled pressure at 1 Hz; however, newer tags sampled pressure at 32 Hz. The Acousonde tags sampled three-axis accelerometry at 100 Hz, pressure and three-axis magnetometry at 10 Hz, and acoustic data at 1,815 or 12,226 Hz (Supplementary Table 1). Satellite position snapshots were taken each time the whales surfaced by the TDR10's Fastloc GPS or Sirtrack FastGPS (Lotek); components which were attached to the Acousonde tags. Whale GPS locations were resolved from the position snapshots when >4 satellite signals were captured. Tags were recovered with the aid of Argos satellite transmitters (SPOT-258A, Wildlife Computers) and VHF transmitters (Series MM100, Advanced Telemetry Systems, Inc.) after they detached from the animal and floated to the surface.

Dive and kinematic analysis — Dive analysis was conducted using custom software in python (v2.7). Because surface readings do not always correspond to zero due to the placement of the tag on the whale, its movement while breathing at the surface, and zero offset drift, we defined a surface band for each whale (e.g., Supplementary Fig. 2). For most whales, the 1-m bin from 0 to10 m with the highest count was considered the surface band cutoff. A 10-m cutoff was based on the maximum zero offset drift identified from manual analysis of the full tag dataset. For a handful of whales with extremely inconsistent surface readings, we used the 1-m bin that contained 50% of the data. An extra 1-m buffer was added to all surface band cutoffs to account for noise due instrument resolution and accuracy.

To identify and analyze dives, we divided the dive data into chunks that began and ended at the surface band cutoffs with a minimum duration of 2 min (to ensure we had enough data to model). Due to instrument resolution and accuracy noise res, we decimated the data to 0.2 Hz, then fit a cubic polynomial equation to the decimated data using "scipy.interpolate.interp1d". We used a 3-sec moving window to determine slope for each smoothed point, then used the slopes to identify any inflection points that persisted for more than 2 sec, indicative of changes in vertical direction. Each change was classified as flat (±1.5°), descending (<-1.6°), or ascending (>1.6°).

Inflection points below the surface cutoff were used to investigated possible dives. Time between inflection surface points needed to be longer than 15 sec, and the whale needed to be ≥3.5 m below the surface cutoff for at least 6 sec to be considered a dive. These values were chosen from trial and error using the full tag dataset. If a dive was identified from these criteria, the two surface inflection points would represent the start and end of the dive. From there we calculated total dive duration (sec) and maximum dive depth (m).

The inflection points were then used to define descent, bottom, and ascent periods (Supplementary Fig. 2). Descent start was the first negative inflection point at the surface at the start of the dive. The end of descent was the next negative inflection point that occurred at depth. In some cases, inflection points can happen early in the descent due to fluking. Thus, we compared the ratio of the depth of each negative inflection point to the maximum depth. We considered the negative inflection point that occurred deeper than 20% of the maximum depth to be the end of descent. This cutoff was chosen from trial and error using the full tag dataset. Ascent was defined using the opposite of this method. Ascent end was the first positive inflection point at the surface at the end of the dive. As with descent, inflection points can happen later in the ascent due to fluking. We considered the start of ascent to be the first positive inflection point that occurred deeper than 20% of the maximum depth. The period between descent and ascent was considered the bottom of a dive. The time between dives was calculated to determine surface recovery time associated with previous dive. For each tagged whale's dive record, we calculated descent and ascent rate (m/s), descent and ascent time (s), bottom time (s), surface time (s), and maximum depth (m) for each dive. These characteristics were manually validated following automated dive analysis.

The presence of lunges, indicative of feeding, was detected using the expert scoring method outlined by Cade et al. (2016). Dives from TDR10s that could not be analyzed for lunges were manually inspected for the presence of vertical lunges as a coarse determination of presumed feeding. Where possible, georeferenced pseudotracks were generated at 1 Hz sampling rate using the depth, pitch, speed, and known geographic reference points of the tagged animal (GPS positions from the TDR10 and Sirtrack) (Wilson et al., 2007). The three-axis accelerometer and magnetometer data from the tags were corrected in MATLAB (Mathworks) so the axes aligned with the "whale frame" using periods of known orientation (Johnson and Tyack, 2003). Animal orientation (i.e., pitch, roll, and heading) was calculated using custom-written MATLAB scripts (Johnson & Tyack, 2003; Cade et al., 2016). For all Acousonde tags and TDR tags that were sampling at 32 Hz, whale speed was calculated using the jiggle method (Cade 2017). For TDR tags that were sampling at 1 Hz, speed could not be assessed.

Vessel data — Vessel activity data were obtained using Automated Identification System (AIS) data from the U.S. Coast Guard's Nationwide Automatic Identification System (NAIS), a national network of land-based stations that receive and transmit AIS data and whose primary function is to promote Maritime Domain Awareness (MDA) in the coastal and territorial waters of the U.S. AIS data contains both vessel position and vessel characteristics data, including, but not limited to, vessel length, beam, draft, heading, and speed. Vessel characteristics were added (when missing from the AIS signal) and validated using online vessel tracking services (marinetraffic.com). Six vessels whose information (i.e., Maritime Mobile Service Identity, length, width, and type) could not be verified were excluded from analyses. Data containing the reported positions of the AIS transmitter on each vessel relative to their bow and port were downloaded from a computer connected to an AIS receiver located on Santa Cruz Island (33.995°N, 119.632°W). The vessel activity data was stored and analyzed in PostgreSQL (PostgreSQL Global Development Group).

Position interpolation and distance calculations — To identify the closest point between each individual whale and vessel, the PostGIS "ST_Distance_Sphere" function was used to calculate distances between each whale and vessel AIS transmitter. Vessel and whale GPS positions within 2 km (defined for this study as a "close passage") were interpolated to 1-s intervals with the "ST_Line_Interpolate_Point" function in PostGIS, assuming a constant speed and course over ground. A two-dimensional polygon for each vessel was created using the length and width of the vessel provided in the AIS data. Closest horizontal distances between vessels and whales were estimated, accounting for the location of the AIS transmitter on the vessel and the vessel's heading relative to the whale. Distances were adjusted to account for the position of the tag on the whale. For the correction, we treated the whale as a circle and used a 10-m radius based on a 20.9 m mean blue whale length (Gilpatrick & Perryman, 2008). Three-dimensional straight-line distances were then calculated as the hypotenuse of the horizontal (described above) and vertical distance between the vessel and the whale, which was based on the whale's depth (determined from the tag's pressure sensor) and the vessel's reported draft. If a vessel's draft was not reported or if it was incorrect, mean draft was interpolated from times around the missing draft or based on the mean draft over that vessel's track. The close passages distances were classified as "near" (≤400 m) and "far" (>400 m) passages (Fig. 1). A 400-m cutoff was based on the findings of Lesage et al. (2017), the distance at which blue whale dive and surface times were thought to be impacted by vessels, and also the speed-dependent distances estimated by McKenna et al. (2015) required for a blue whale to initiate a behavioral response to an approaching vessel (e.g., 300 m for a vessel traveling at 30 kn).

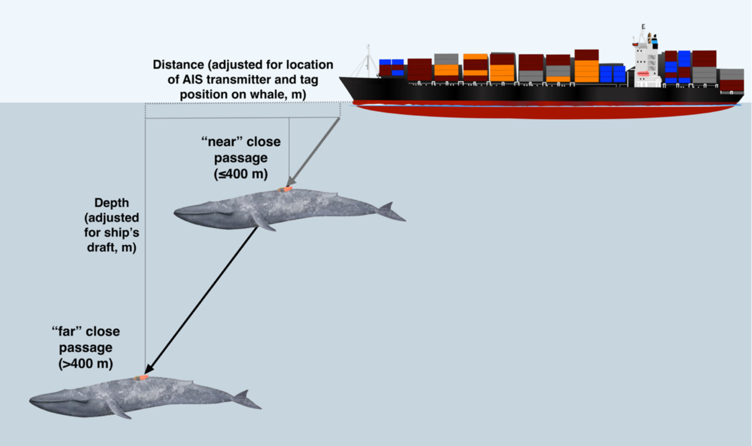

Figure 1. Schematic illustrating the calculation of the closest distance (m) between tagged whales and vessels, including corrections based on the location of the AIS transmitter on the vessel (m), the vessel's reported or estimated draft (m), and the whale's depth (m). Distances were classified as near close passages (≤400 m) or far close passages (>400 m).

Close-passage metrics — To constrain our analyses to periods when vessel presence would be more likely to be detected by a whale, we only investigated events with estimated distances between any vessel and a tagged whale of 2 km or closer. We compiled vessel, environmental, and whale contextual information based on the time of the closest distance within the close-passage period (Supplementary Table 2). A total of 21 close-passage metrics were collected or derived from the data (8 vessel, 7 environmental, and 6 whale).

The eight vessel variables included vessel type, length (m), width (m), depth (m), speed (kn), encounter duration, heading variability, and heading relative to the whale. Vessels were categorized as cargo/container, bulk/vehicle carrier, oil tanker, towing/tug/tender, passenger, whale watching, service/research (i.e., Navy, NOAA, Coast Guard), recreational/fishing (i.e., diving, commercial and recreational fishing, pleasure, sailing), and cruise ship. Length, width, and depth came from AIS data or obtained from vesselfinder.com using the vessel's Maritime Mobile Service Identity. If speed was not transmitted at the time of the closest passage, it was calculated as the change in position over the times before and after the time of the closest distance. Duration for each close passage was determined based on the amount of time the vessel was within 2 km of the whale. Heading variability was qualitatively assessed as constant or variable for the time the vessel was within 2 km of a whale. Vessel heading relative to the whale was qualitatively assessed as moving toward, parallel, or away from a whale for the duration the vessel was within 2 km of a whale.

The seven environmental variables included month, hour, wind speed (m/s), Beaufort scale, distance to shipping lanes (km), distance to port (km), and distance to coast (km). Wind speed was obtained from the National Oceanic and Atmospheric Administration's National Data Buoy Center (https://www.ndbc.noaa.gov/). The locations at the closest passages were matched to the closest buoy in date and time at a 10-min resolution. Wind speed was used to estimate sea state using the Beaufort scale. Distances to shore (km) at the time of the close passage was estimated from using the "marmap" package (v 1.0.4, Pante & Simon-Bouhet, 2013) in R. Distance to the closest port (km) and shipping lanes (km) was calculated with the "st_distance" function using the "sf" package (v 0.9-5, Pebesma, 2018) in R. Port shapefiles were downloaded from Natural Earth (v 4.0.0). Shipping lanes were downloaded from the National Oceanic and Atmospheric Administration's Office of Coast Survey (https://nauticalcharts.noaa.gov).

The six whale variables included whale ID, exposure number, mean daily encounter rate, whale depth (m), dive portion, and behavior. Whale ID was each whale's unique identification number. Exposure number was the number of the specific encounter relative to each whale's total number of close passages observed. Mean daily encounter rate was calculated as the number of close passages divided by the number of days the whale was tagged. Dive portion was classified as descending, bottom, ascending, and surface. We examined the individual whale's dives during the close passage, and neighboring dives, to assess the animal's behavioral state. We assigned four broad behavioral states for each dive depending on the presence or absence of lunges, time of day, and animals' lateral movement as: (a) feeding, if lunges were present and performed during a feeding bout (sequences lunge feeding dives with <30 min of consecutive non-lunge feeding dives); (b) search/travel mode, which included shallow and deep nonfeeding dives that were made during the day in between feeding bouts; (c) shallow surface behavior, which was only seen at night when animals were in the upper 50-m (often upper 20-m, of the water column); and (d) transition to/from feeding to shallow surface behavior, which showed when whale went from shallow surface behavior to feeding or vice versa (Supplementary Fig. 3).

Analyses — We compared the probability density functions of near (≤400 m) and far (>400 m) close passages under various vessel, environmental, or whale explanatory variables. Differences in the probability density functions would show which factors played a role in a whale's detection and avoidance of vessels (i.e., changes in whale dive behavior), prior to the vessel's closest distance to a whale (Supplementary Table 2). An exploratory approach was taken to understand if any conditions independently resulted in closer passages. Multivariate models could not explain closer passages with any more confidence than what the probability density functions revealed and were therefore not included. We acknowledge the limitations in drawing conclusions and possible interaction between variables that might reveal effects on behavior.

The explanatory variables are described in the Methods. Briefly, vessel explanatory variables (n=8) included vessel type, length, width, draft, speed, heading variability, and heading relative to the whale. Because whale-watching and personal vessels were actively pursuing whales, these encounters were excluded from this analysis. Environmental explanatory variables (n=7) included month, hour, wind speed, Beaufort scale, distance to the nearest port, distance to shore, and distance to the nearest shipping lanes. Month was adjusted to account for the uneven number of tagged whales per month; however, there was no difference in number of animals tagged per hour. Whale explanatory variables (n=6) included whale ID, exposure number, depth, per whale mean daily encounter rate, dive portion, and behavior. Differences between the empirical distributions of continuous variables were assessed using the bootstrap Kolmogorov-Smirnov (k-s) test (100,000 iterations) with the Matching package (v4.9-7, Sekhon, 2011), and differences between categorical variables were assessed with pairwise chi-square tests. For each whale ID, we calculated the difference in near (≤400 m) to far (>400 m) close passages and used a two-sided Wilcoxon test to compare the distribution of the differences between means (far minus near) to a null distribution with a zero mean. Differences would indicate if each whale had significantly more near (≤400 m) vs. far (>400 m) close passages. All analyses were done in R.

To examine potential behavioral response, specifically avoidance and/or immediate impacts resulting from close passages, we examined vertical and lateral movement during periods "before vs. after", "prior to", and "around" the time of the closest vessel passage (time 0) using a number of continuous and discrete methods (Table 1; definitions provided in Fig. 2).

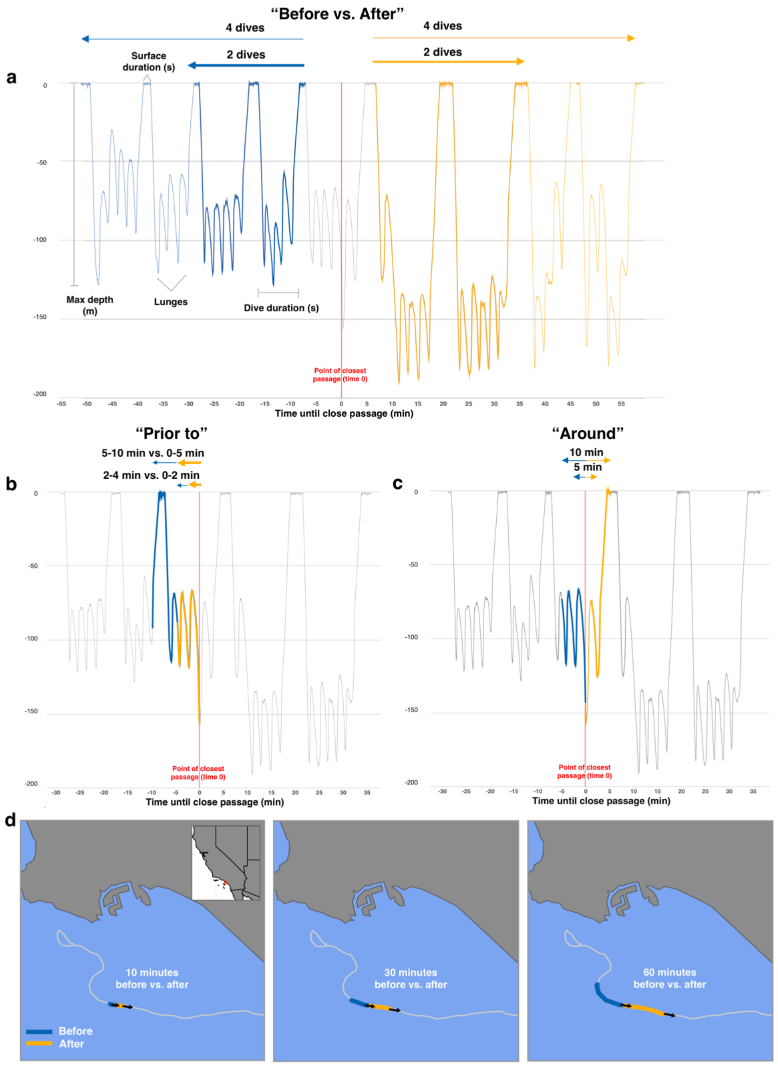

Figure 2. Schematic of periods used to explore behavioral response to vessels, including (a) discrete dive characteristics: dive duration (s), surface duration (m), maximum depth (m), and number of lunges per dive in comparing 2 dives before vs. 2 dives after and 4 dives before vs. 4 dives after close passages, (b) continuous depth over time for comparisons of 0-2 min vs. 2-4 min prior to close passages and 0-5 min vs. 5-10 min prior to close passages, (c) continuous depth over time for comparing 5 min around (2.5 min before vs. after), and 10 min around (5 min before vs. after) close passages, and (d) continuous lateral movement: speed and heading for comparisons of 10, 30, and 60 min before and after close passages.

Table 1. Summary of statistical tests examining differences and uniqueness in whale vertical and lateral movement and behavior before vs. after, prior to, and around the time (time 0) of the closest vessel passage (<2 km) with a vessel.

	Movement	Question	Variable	Metric(s)	Before vs After Close Passage	Number of Tests	Prior to Close Passage	Number of Tests	Contextual Variants	Close Approach Variants	Test Statistic
Difference	Vertical	Can we detect a difference in dive behavior as a result of a close passage with a vessel?	dive duration surface duration maximum dive depth # lunges per dive	distribution (after-before) compared to distribution with zero mean	2 dives 4 dives	146			all close approaches by behavior by vessel type	all close approaches passages <400 m passages <400 m whale depth <50 m	Wilcoxon test
		Are whales were putting themselves in more "at-risk" positions as vessels approach?	depth	distribution (after-before) compared to distribution with zero mean	-	-	0-2 min prior vs. 2-4 min prior 0-5 min prior vs. 5-10 min prior	18	all close approaches by behavior by vessel type		Wilcoxon test
	Lateral	Do whales change their speed or direction of travel as a result of a close passage?	speed heading	distribution (after-before) compared to distribution with zero mean	10 min 30 min 60 min	30			all close approaches by behavior by vessel type		Wilcoxon test
Uniqueness	Vertical	Are chages in dive behavior a unique behavior that only occurred during the close passage?	depth	cross correlation	2 min around 5 min around	42	0-2 min prior 0-5 min prior	38	excluded whale watch and personal vessels	<400m distance	> 0.85 corr

Difference in behavior — The first question we aimed to answer regarding behavioral response was: can we detect a difference in behavior associated with a close passage with a vessel? If an animal reacted to the vessel, we expected to see a change in the dive characteristics before vs. after the closest point during the vessel's passage (time 0; Fig. 2a). The discrete dive variables we assessed were dive duration, surface duration, maximum dive depth, and number of lunges per dive. A whale might dive deeper, as in Szesciorka et al. (2019) or reduce foraging, as in Lesage et al. (2017). We compared two dives before with two dives after a close passage, and four dives before with four dives after a close passage (Fig. 2a). These ranges were chosen because we had no knowledge of when whales might respond to an approaching vessel. Dives were assessed collectively, grouped by whale behavior, and grouped by vessel type. We also specifically examined vessel near close passages (≤400 m), and vessel far close passages (>400 m) when whales were shallower than 50 m depth, a depth range where a whale might come dangerously close to the effects of a vessel's draft (Silber et al. 2010). We used a two-sided Wilcoxon test to compare the distribution of the differences between means (after minus before) of each dive characteristic to a null distribution with a zero mean. Statistical analysis could not be completed for 58 of the 240 test variants due to low sample size (<6) and were not included in the total number of tests in Table 1. For tests assessing for number of lunges before and after close passages, 36 instances occurred during feeding bouts; dives that contained zero lunges before or after and were not included.

In addition to assessing the distribution of the differences of discrete dive characteristics before and after close passages, we wanted to know if whales were putting themselves in more "at-risk" positions as the vessel approached; that is, are whales ascending to shallower, dangerous waters in the minutes prior to the close passage (time 0; Fig. 2b)? For this, we compared changes in dive depth just prior to a close passage to a time just before that. As before, because we had no knowledge of the timeframe over this might occur, so we compared changes in depth 0-2 min prior to a close passage to changes in depth 2-4 min prior, and changes in depth 0-5 min prior to a close passage to changes in depth 5-10 min prior. The changes in depth over time were assessed collectively, grouped by whale behavior, and grouped by vessel type. We used a two-sided Wilcoxon test to compare the distribution of the differences between means (after minus before) to a null distribution with a zero mean. Differences that were significantly different from a mean of zero would tell us whether the whale had moved to shallower or deeper water prior to a close passage, whereas differences that were not significantly different from a mean of zero would indicate no change in depth prior to a close passage.

A difference in behavior as a result of a close passage with a vessel might also be evident in lateral movement, as quantified by changes in speed or heading before vs. after a close passage. To assess whale movement, we used tags with kinematic data (n=25), to examine differences in speed or heading 10, 30, and 60 min before vs. after a close passage (time 0; Fig. 2c). We chose these time ranges to account for potential of short- and long-term behavioral responses. Lateral movement was assessed collectively, grouped by whale behavior, and grouped by vessel type. We used a two-sided Wilcoxon test to compare the distribution of the differences between means (after minus before) of speed and heading 10, 30, and 60 min before and after close passage to a null distribution with a zero mean. Differences that were significantly different from a mean of zero would tell us whether the whale changed its speed or direction of travel as a result of a close passage. Statistical analysis could not be completed for 24 of the 54 test variants due to low sample size (<6) and were not included in the total number of tests in Table 1.

Uniqueness of behavior —The second question we aimed to answer regarding behavioral response was: is the behavior exhibited during a close passage a unique behavior that only occurred during the close passage with a vessel? If an animal was performing a last-minute avoidance response to an approaching vessel, the behavior should not look like any other behavior the whale made when vessels were not close. To determine whether an individual animal's vertical movement (i.e., change in depth over time) prior to and around close passages (time 0; Fig. 2b,c) with vessels was unique, we extracted data from periods prior to and around a close passage, and searched for statistically similar period(s) in the animal's dive record (cross-correlation R>0.85) using the "findsignal" and "xcorr" functions in MATLAB. In Szesciorka et al. (2019), the whale initiated a change in its depth ~1.5 min prior to the close passage with a large container vessel. However, because we had no knowledge of when other individual whales might respond to an approaching vessel, we examined a number of time ranges both prior to a close passage and around the close passage (Fig. 2b,c). We examined 2 min around a close passage (1 min on either side of time 0) and 2 min prior to a close passage. We also examined 5 min around a close passage (2.5 min on either side of time 0) and 5 min before a close passage. We excluded periods from analyses when the whale had other close passages to restrict our comparisons of close passages to periods with presumably normal vertical movement. We limited this analysis to close passages that were within 200 m and whales that were shallower than 50 m — conditions under which we might expect a behavioral response. This restriction resulted in 20 close passages with 10 whales and 15 vessels, but we also included the encounter from Szesciorka et al (2019) to assess the uniqueness of the whale's presumed avoidance behavior. Statistical analysis could not be completed for 4 of the 84 test variants due to surface offset issues with the tags and were not included in the total number of tests in Table 1.

Results

Data Summary

The 35 tag deployments resulted in 5,175 hr (215.6 days) of dive data (Supplementary Table 1). Tag attachment durations ranged from 2.8 to 768.5 hr. With a mean deployment duration of 6.2 days, 37% of the tags remained attached for less than 24 hours, 31.5% of the tags remained attached between 1 and 5 days, and 31.5% of the tags remained attached for more than one week. The longest deployment was 32 days on a whale that was tagged while foraging off Bodega Canyon and then transited to central Baja on a potential return migration to the breeding grounds before the tag detached (see Oestreich et al., 2020). GPS fixes per whale ranged from 4 to 3,697 with a mean of 139.3 (± 125.3 SD) resolved positions per day. One whale's GPS positions could not be resolved and could not be included in analyses. Of the 46,236,694 AIS positions collected from 9,037 vessels, we identified 237 vessels that were within 2 km of a tagged whale and interpolated 236,812 points from vessels that were within 2 km of a tagged whale. Close passages were excluded if the vessel's information could not be verified, or if the vessel was anchored (all speeds <0.1 kn), leaving us with a total of 216 close passages between vessels and tagged whales (Fig. 3, Supplementary Table 3).

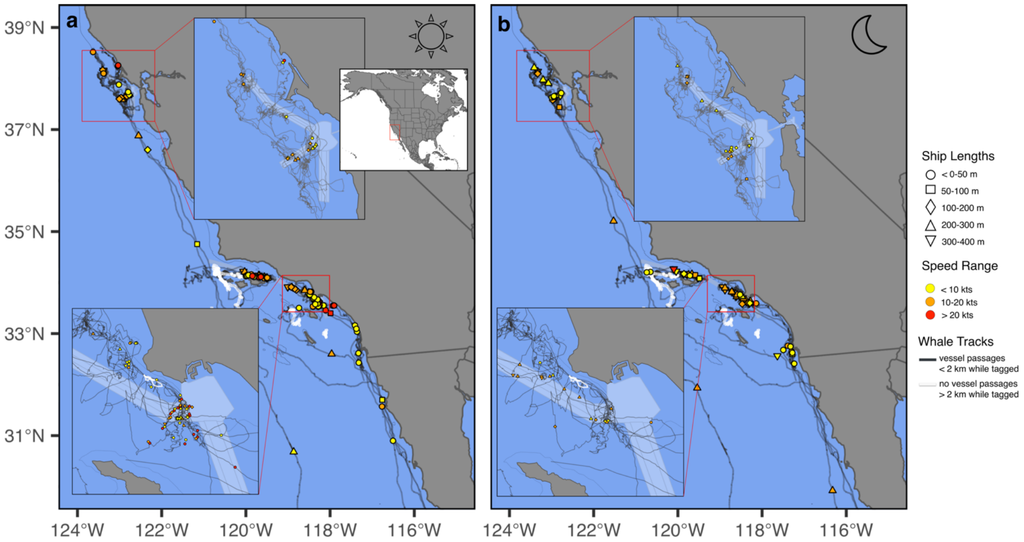

Figure 3. Map depicting locations of close passages between vessel and tagged whales (a) during the day and (b) night in northern California (n=35) and Southern California (n=181). Insets provide greater detail near shipping lanes in both regions (a and b) in light blue, and the larger geographic region of the study area (a). Shapes depict size of vessels in 50-m increments and colors depict speed range of vessels. Dark gray tracks indicate paths of whales that experienced vessel passages (n=24) within 2 km and white tracks indicate paths of whales that experienced no vessel passages (n=11) within 2 km.

Close Passage Metrics

There were 174 unique vessels involved in the 216 close passages involving 24 whales. These included cargo, container, and vehicle and bulk carriers, which comprised the majority of close passages (37%); followed by recreational/fishing vessels, which included fishing, diving, sailing, and pleasure craft (20%); tankers (15%); passenger vessels (11%); towing, tug, and tender (8%); whale-watching boats (6%); service and research (1%); and one cruise ship (Table 2). Vessel sizes involved in the close passages ranged 7 to 368 m. Cargo, container, and carriers were the largest types of vessels involved in the close passages. Some of the smaller vessels included recreational/fishing and whale-watching vessels. Cargo, container, carrier, and tankers were located within ~3.2 km of shipping lanes during close passages more often than recreational/fishing vessels and whale-watching boats.

Table 2. Summary characteristics of vessels involved in close passages with tagged whales.

Vessel type	Number of encounters	Percent of encounter	Mean length (range, m)	Mean speed (range, kts)	Percent >10 kts	Min distance (m)	Ecounters <400m	Percent <400 m	Percent <3.2 km shipping lanes
Cargo/Container/Carrier	80	37.0%	275.2 (171-368)	12.5 (5.9-20.9)	68.8%	15	15	18.8%	91%
Recreational/Fishing	44	20.4%	17.5 (7-65)	10.3 (1.1-27.8)	34.1%	180	8	18.2%	30%
Tanker	33	15.3%	224.4 (174-332)	10.8 (5.7-14.7)	66.7%	27	12	36.4%	82%
Passenger	24	11.1%	35.3 (15-64)	22.6 (11.5-30)	100.0%	93	3	12.5%	75%
Towing/Tug/Tender	18	8.3%	52.78 (18-180)	7.9 (4.3-16)	11.1%	38	2	11.1%	50%
Whale Watching	13	6.0%	23.2 (20-26)	6.8 (0.3-20.7)	15.4%	10	11	84.6%	38%
Service/Research	3	1.4%	56.67 (38-68)	12.7 (10.2-14.2)	100.0%	309	1	33.3%	33%
Cruise ship	1	0.5%	290	16.5	100.0%	1675	0	0.0%	0%

With the exception of the whale-watching boats and towing, tug, and tenders, all mean vessel speeds were greater than 10 kn, a speed at which vessel strikes have a higher probability of serious injury or mortality (Vanderlaan & Taggart, 2007; Conn & Silber, 2013). Every passenger vessel was traveling greater than 10 kn, with a mean of 22.6 kn and max of 30 kn. Recreational/fishing vessels had the second fastest speeds, ranging 1.1-27.8 kn, with 34% traveling greater than 10 kn. Cargo, container, and carriers ranged 5.9-20.9 kn with 69% traveling greater than 10 kn. Tankers ranged 5.7-14.7 kn with 68% traveling greater than 10 kn. Service and research vessels ranged 10.2-14.2 kn, all traveling greater than 10 kn. The cruise ship was traveling at 16.5 kn. More than 76% of the closest passages were more than 400 m away from the whale. Those closer than 400 m included 15 cargo, container, carriers; 12 tankers; 11 whale-watching boats; 8 recreational/fishing; 3 passenger; 2 towing vessel; and 1 service/research vessel. The closest distance estimated between a vessel and tagged whale was 10 m and involved a 23-m whale watching boat traveling at 7.3 kn.

Twenty-four of the 35 tagged whales (69%) came within 2 km of at least one vessel. Close passages with vessels ranged from 1 over 1.5 days to 55 over ~13 days (Table 3). Encounter rates were fewer than one per day for half of the whales. The minimum number of vessels a whale encountered in a 24-hour period was one vessel, while the maximum was 11 vessels. The mean daily close passage rate per whale ranged from 0.18 to 19.15, with a mean over all whales of 3.41 (± 4.5 SD) close passages per day. Despite being near high-traffic areas and other whales that encountered vessels, 11 whales did not have a <2 km encounter with a vessel, despite 0-to-4-day tag deployment durations (mean=0.18 days; see Fig. 3).

Table 3. Encounter summaries for each whale tagged including number of encounters, number of fractional days tagged, encounter rate (encounters/sample period), and closest distance to a passing vessel (m).

whale_id	encounters	days tagged	encounter rate	closest_distance (m)
20140829-1	0	0.6	0.0	n/a
20140901-2	0	0.2	0.0	n/a
20140901-3	0	0.4	0.0	n/a
20150819-5	0	2.2	0.0	n/a
20160815-B021	0	0.1	0.0	n/a
20160817-B021	0	1.9	0.0	n/a
20160918-B008	0	4.1	0.0	n/a
20170622-13	0	4.9	0.0	n/a
20170925-11	0	0.6	0.0	n/a
20170925-12	0	4.1	0.0	n/a
20170925-14	0	0.3	0.0	n/a
20151016-7	3	16.4	0.2	1105.9
20160717-B021	3	14.2	0.2	16.9
20170926-14	1	4.3	0.2	228.4
20160918-B021	1	4.3	0.2	1387.0
20181021-11	8	32.0	0.2	142.0
20150818-8	3	10.8	0.3	312.3
20181021-14	6	12.5	0.5	309.4
20151016-5	1	1.6	0.6	1752.3
20160523-6	6	8.1	0.7	144.2
20140827-4	14	16.4	0.9	230.7
20140719-5	3	3.1	1.0	541.8
20160716-B020	20	20.1	1.0	9.5
20160523-B020	10	9.8	1.0	47.7
20170622-12	31	17.8	1.7	96.7
20170706-11	5	2.8	1.8	191.5
20131005-4	2	1.0	2.0	631.4
20140825-5	16	4.8	3.3	75.7
20140825-6	55	12.9	4.3	15.1
20160926-07	5	0.9	5.3	37.9
20140827-1	3	0.4	8.5	298.5
20140904-2	3	0.3	9.5	436.0
20140904-1	7	0.7	10.6	97.8
20140913-1	7	0.6	11.2	87.5
20140901-1	9	0.5	16.6	256.7

Aside from eight animals that ceased foraging and transited south to Baja (presumably for additional foraging opportunities) or on their way to their breeding grounds in Costa Rica Dome (Supplementary Fig. 4a), no whales left the area — even those with chronic close passages (>5 per day based on the slope of the empirical density distribution) spanning days to weeks (e.g., Fig. 4; Supplementary Fig. 4b). Despite these chronic close passages, there were only five occasions when more than one vessel was within 2 km of a tagged whale at the same time. Two of those instances involved whale-watching boats, that despite their close physical proximity to the tagged whales, were all traveling less than 6 kn. The other three had at least one vessel that was more than 700 m away. Time between encounters of the remaining close passages ranged from 22 seconds to more than 11 days, with 56 (32%) of the subsequent close passages occurring within one hour of each other. Of those, 29 (17%) were within 30 mins of one another and 12 (7%) were within 10 min of one another.

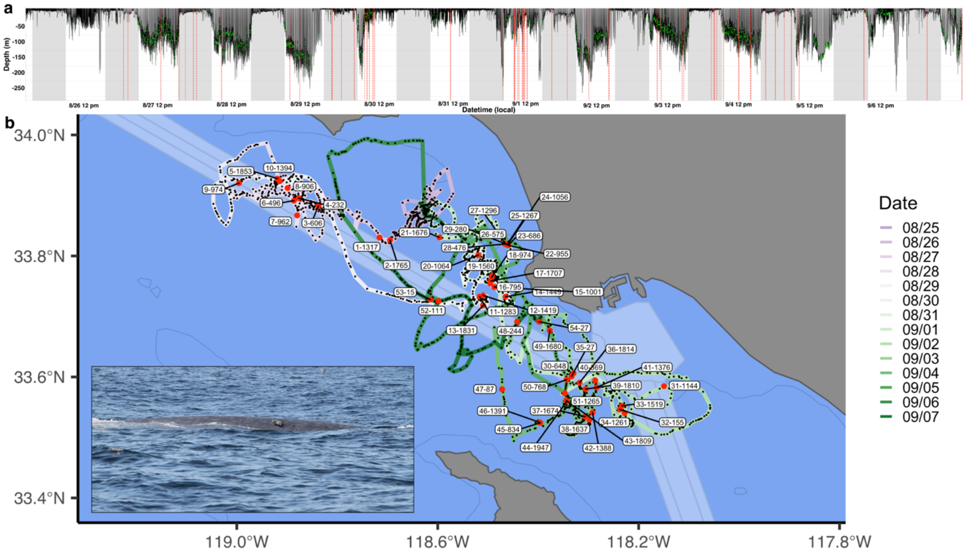

Figure 4. Example of whale with chronic exposure to vessels. The animals time-depth record (a) shows diving patterns across 14 days from Aug. to Sep. 2018. The green circles indicate where lunges were detected. The red lines indicate each close passage. The red rectangles around each red line indicate the duration that each vessel was within 2 km of the tagged whale. The gray bars indicate nighttime. The GPS locations (b) show the animal's horizontal movements in and around the shipping lanes (in light blue) between Catalina Island and Los Angeles spanning Santa Monica Basin and Canyon to San Gabriel Canyon. The 200-m isobath is in gray. The black dots represent the GPS positions. The path colors indicate the date of the positions. The red circles indicate the location of the 55 close passages less than 2 km, and the corresponding numbers are the encounter number followed by the closest passage (m). The photo shows the tag on the animals back. Photo by John Calambokidis/Cascadia Research.

Near vs. Far Close Passages

None of the contextual variables we assessed during close passages explained why some passages with vessels were near (≤400 m) or far (>400 m) (Figs. 5-7). The only significant difference among the vessel characteristics (Fig. 5) we explored were encounter duration (k-s, D=0.36, p=0.004) and vessel heading relative to the whale's position (Chi-square <0.01). The ship characteristics of the close passages suggest that whales have a higher probability of near (≤400 m) close passages when vessels are heading toward them, which resulted in longer encounter durations. The only significant difference among the distributions of the environmental characteristics (Fig. 6) we explored was the distance to the shipping lanes (k-s, D=0.37, p=0.002). A majority of all the close passages (~70%) occurred in or within ~3.2 km of the shipping lanes (roughly the width between the incoming and outgoing lanes); however, more near (≤400 m) close passages were in or near the shipping lanes. There were also more near (≤400 m) close passages midday (between 11:00 and 14:00 local time). The environmental characteristics of the close passages suggest whales have a higher probability of near (≤400 m) close passages during midday when they are in the shipping lanes. Of the whale characteristics (Fig. 7) we explored, the only significant difference was in near (≤400 m) vs. far (>400 m) close passages per whale (Wilcoxon, V=165, $p<0.05$): most whales have a higher probability of far (>400 m) passages than near (≤400 m) close passages.

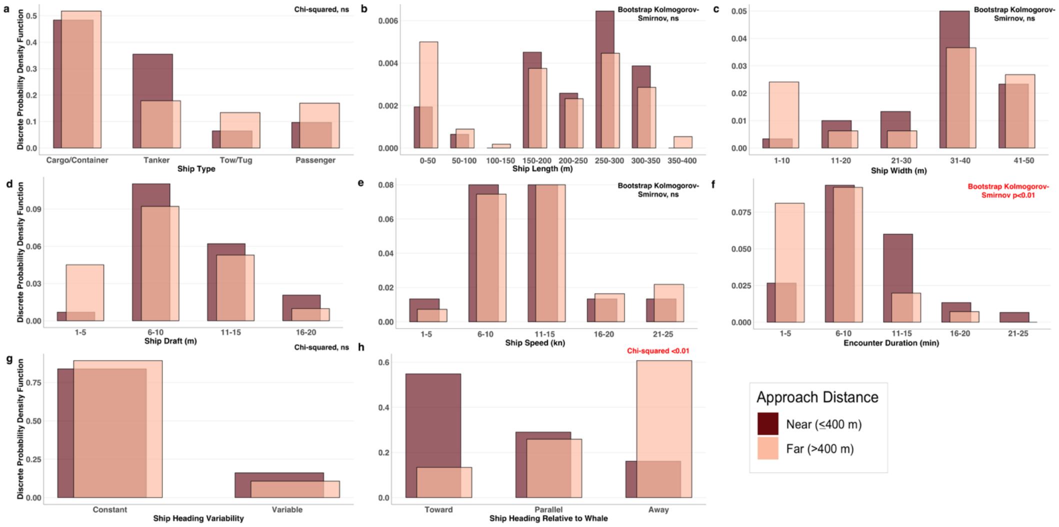

Figure 5. Discrete probability density functions (bars offset horizontally as a visual aid) of vessel characteristic variables, represented by each panel, associated with near (≤400 m, dark red) and far (>400 m, light red) passages to tagged whales, including (a) vessel type, (b) length (m), (c) width (m), (d) draft (m), (e) speed (kn), (f) encounter duration (min), and (g) vessel heading. The only variables that showed significant differences between the empirical cumulative distributions were encounter duration (k-s, D=0.36, p=0.004) and vessel heading relative to the whale's position (Chi-square <0.01, red text).

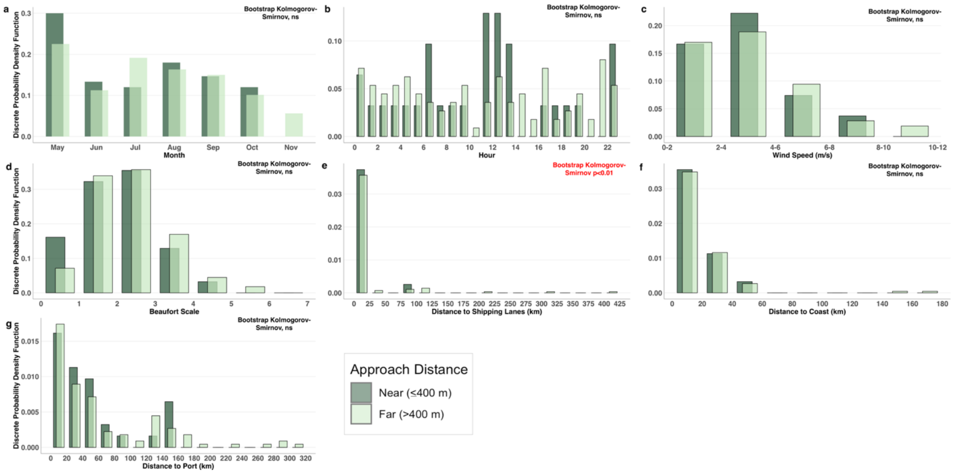

Figure 6. Discrete probability density functions (bars offset horizontally as a visual aid) of environmental variables associated with near (≤400 m, dark green) and far (>400 m, light green) passages to tagged whales, including (a) month, (b) hour, (c) wind speed (m/s), (d) Beaufort scale, (e) distance to the nearest shipping lane (km), (f) distance to the nearest port (km), and (g) distance to coast (km). The only variable that showed a significant difference between the empirical cumulative distributions was distance to the shipping lanes (k-s, D=0.37, p=0.002, red text).

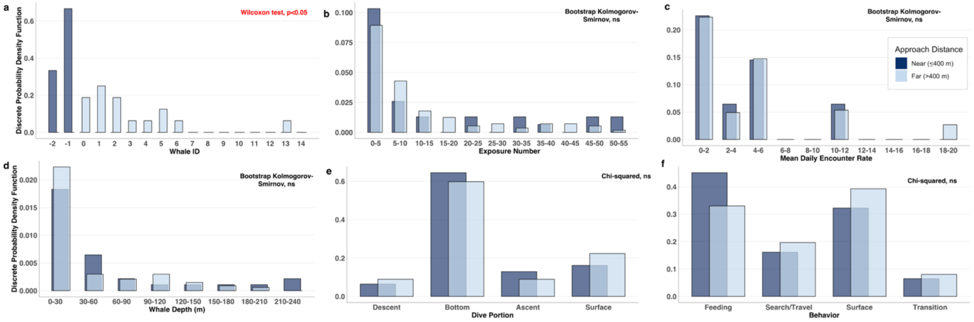

Figure 7. Discrete probability density functions (bars offset horizontally as a visual aid) of whale variables associated with near (≤400 m, dark blue) and far (>400 m, light blue) passages to tagged whales, including (a) the difference in near (≤400 m) vs. far (>400 m) close passages per whale, (b) sequential exposure number, (c) mean daily encounter rate, (d) whale depth (m), (e) dive portion, and (f) behavior. The only variable that showed a significant different between the empirical cumulative distributions was the difference in near (≤400 m) vs. far (>400 m) close passages per whale (Wilcoxon, V=165, p<0.05, red text), suggesting more whales had far (>400 m) close passages.

Difference in behavior

The probability density functions of the after minus before differences of the discrete dive characteristics (dive duration, surface duration, maximum dive depth, and number of lunges) showed that 129 of the 146 (88.4%) tests were not significant (e.g., Fig. 8; Supplementary Table 4). The 17 significant tests were explored in more detail and described below. However, the differences could be explained by the onset of foraging or transition from day/night and were not related to close passages. From this analysis, we can conclude that there is no difference in behavior as a result of a close passage with a vessel. Whales are not changing their behavior before a close passage in order to avoid vessels nor are they impacted after the close passage. Four of the significant tests involved the assessment of the number of lunges before vs. after a close passage (Supplementary Table 4). Of those, two tests involved all dives assessed collectively, and two involved lunge feeding dives. An increase in lunges appeared to be an artifact of the start of foraging bouts, which are typified by increased numbers of lunges per dive. The effect disappeared when feeding dives were removed from the two tests involving all dives assessed collectively. The 13 remaining significant tests involved changes in maximum depth (Supplementary Table 4). Of those, six involved whale watch boats and five involved lunge feeding dives. The active approach of feeding whales is an artifact of the whale-watching boats' close passages, and whale feeding onsets, which are typified by increased maximum dive depth. One test involved all dives assessed collectively. The effect disappeared when feeding dives were removed. The onset of foraging is usually excluded in behavioral response studies (e.g., Southall et al. 2019). The final significant test involved transition dives, that is a change in behavioral state from day to night or from night to day, during which there is a drastic change in dive depth. Analysis of feeding dives suggested an increase in maximum dive after near close passages ($n=22$, $p<0.01$) coincident with an increase in lunges per dive ($n=13$, $p=0.02$).

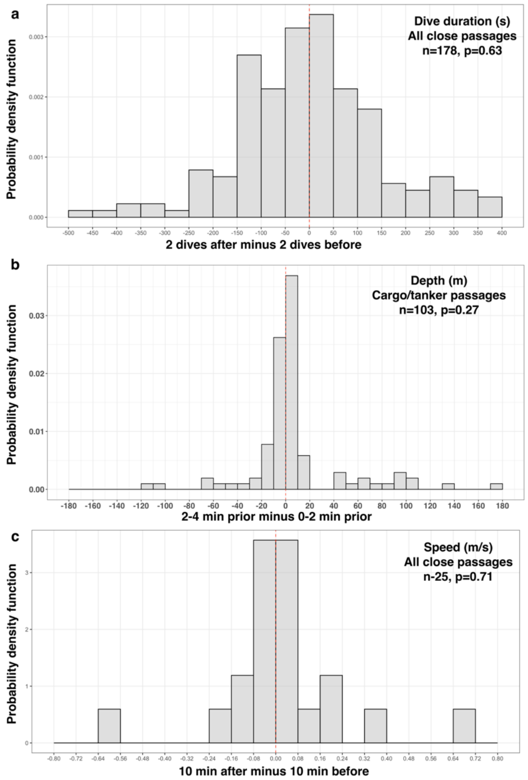

Figure 8. (a) Representative result examining (a) the probability density function of dive duration (s) 2 dives after a close passage (time 0) minus 2 dives before a close passage for all close passages. (b) the probability density function of depth (m) 2-4 min prior to a close passage (time 0) minus 0-2 min prior to a close passage for close passages with cargo and tanker ships. (c) the probability density function of speed (m/s) 10 min after minus 10 min before a close passage (time 0) for all close passages. The vertical red lines indicate how well the distribution is centered around a mean of zero.

Of the 18 tests examining whether a whale would be closer to the surface prior to a close passage (i.e., comparing 0-2 min prior to a close passage (time 0) to changes in depth 2-4 min prior, or 0-5 min prior to a close passage (time 0) to changes in depth 5-10 min prior), only four suggested a shift from deeper to shallower depths (Supplementary Table 5). However, the four significant tests match the trends of our previous results because they included an active approach and the onset of foraging. The effects were not significant when whale-watching boats were removed from the analyses. Whales encountering large cargo, container, tankers, passenger, and personal vessels did not shift to shallower or deeper waters as the vessels passed (e.g., Fig. 8b). From this analysis, we can conclude that whales do not move to shallower, dangerous waters in the minutes prior to the close passage (time 0). Whales are not putting themselves in more "at-risk" positions as vessels approach. Finally, for the 30 tests examining lateral changes (Table 1) in speed and heading 10, 30, and 60 min before vs. after close passages, there were zero occasions where the after minus before difference probability density functions had a mean different than zero (Fig. 8c; Supplementary Table 6). From this analysis, we can conclude that whales are not changing their speed or direction of travel before or after a close passage.

Uniqueness of behavior

The cross-correlation analyses to determine whether an individual animal's vertical movement prior to or around a close passage was unique relative to periods when there was no vessel nearby found one or more similar dive periods for all 20 close passages (<200 m) when whales were at >50 m depth (e.g., Fig. 9; Supplementary Table 7). In most cases, there were tens to hundreds of dive periods similar to those both prior to a close passage (e.g., 2 and 5 min prior) and around a close passage (e.g., 2 and 5 min to include periods before and after). There was a decrease in the number of similar dives identified when going from 2 to 5 min for analyses prior to and around the close passage; however, there were no significant differences in the number of similar dives among the groups determined by one-way ANOVA (F(3,79)=0.51, p =0.68).

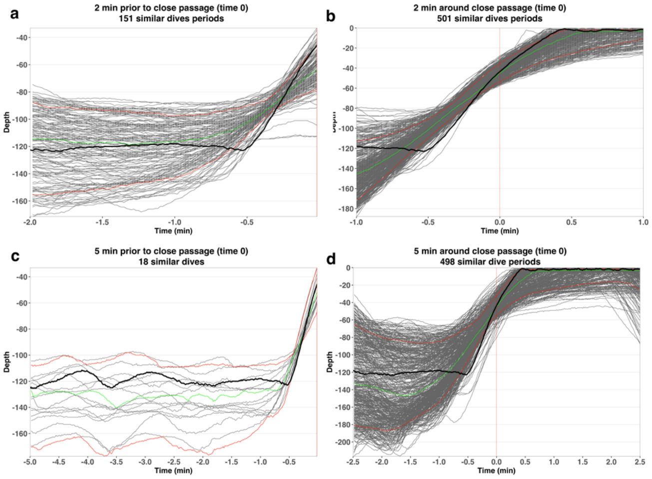

Figure 9. Statistically similar depth signals identified in the dive record for a close passage <400 m at <50 m depth, (a) two min (120 s) before the close passage, (b) two min (120 s) around the close passage, (c) five min (300 s) before the close passage, and (d) five min (300 s) around the close passage. The thicker black lines indicate the dive during the close passage. Thinner black lines indicated the highly correlated (>= 0.85) signals identified in the dive record. Green line indicates the median of all the dive periods, and the red lines indicate the 10th and 90th percentiles. The vertical red lines indicate the moment of the close passage.

Discussion

Our study pooled six years of blue whale behavioral data from archival tags to investigate 216 close passages between 174 vessels and 35 tagged whales. The close passages we documented covered a breadth of real-world conditions — nearly every type and size of vessel passing at various speeds and distances, while the whales engaged in a variety of behaviors. This allowed us to explore factors that might increase vessel strike risk and provide insight into potential general behavioral responses across these variety of conditions. We did not detect any difference in dive duration, surface duration, maximum depth, or number of lunges per dive as a result of close passages. Whales also did not alter their speed or direction of travel in response to close passages. Whales also did not display behaviors that would increase the distance between the vessels and themselves. Even during the closest passages (<200 m when whales were in <50 m depth), behaviors exhibited by whales were not unique behaviors that only occurred during the close passage. However, there was no indication that whales were putting themselves in more harm's way, for example by ascending into shallower, dangerous waters or freezing at the surface as vessels passed at their closest distance. On the other hand, there was no indication that the whales were moving deeper, out of harm's way.

Vessel strike research is growing as conservationists and managers work to reduce the co-occurrence of vessels and marine mammals and lethality of vessel strikes — especially for critically endangered species (e.g., North Atlantic right whale (*Eubalaena glacialis*)) and in regions where little is known about risk and lethality (e.g., the Arctic). Despite the increase in research, risk assessments have made assumptions about which contextual factors increase the probability of a vessel strike and the role of animal behavioral response. With respect to behavioral response, our findings confirmed that whales do not react to ships, which suggests that risk models that assumed no behavioral response are an appropriate approximation of risk. With respect to risk and lethality, important factors typically include proximity to shipping lanes, size of vessels, speed of vessels, time of day, and whale depth in the water column. Our findings confirmed some of these factors, but also illuminated risk tradeoffs that should be considered in future risk assessments and mitigation strategies.

Although risk may vary with the spatiotemporal variability of vessel traffic distribution (Blondin et al. 2020), almost all close passages occurred in and near the shipping lanes, supporting studies that suggest risk is concentrated along the major shipping lanes (Rockwood et al. 2017, Redfern et al., 2019). Most close passages occurred with larger vessel types (cargo, container, vehicle/bulk carriers, and tankers), which are often involved in severe and lethal whale injuries (Laist et al. 2001). However, the remainder of the close passages came from smaller vessels, many of which were moving at high speeds. Passenger vessels were the fastest, traveling at an average of 23 kn — double the speed of the large vessels. The role of speed in lethality has been well studied, with more than 50% lethality resulting from vessels traveling greater than 10 kn (Laist et al. 2001, Vanderlaan & Taggart 2007, Wiley et al. 2011). Biophysical models suggest that, despite their smaller size, fast-moving passenger vessels might be just as dangerous as a slower-moving larger vessel (Kelley et al. 2021).

Finally, while these whales spent more time at the surface at night (see Calambokidis et al. 2019), more near (≤400 m) close passages occurred during the daytime. Whales that had close passages at night were in proportionately shallower depths, which would put them at greater risk; however, most nighttime passages in this study were more than 400 m away. They were also less concentrated in the shipping lanes at night. And although whales spent more time at greater depths during the day, the risk associated with close passages involving high-speed passenger vessels (that are only out during the day) may equal that of the risk associated with slower, large vessels at night.

Despite the breadth of data, smaller vessels and our vessels are not accounted for in this study. Smaller vessels are not required to transmit positions via AIS, so we do not know how many additional small vessels may have had close passages with the tagged whales. While it is possible that our research vessels affected the behavior of blue whales, all vessels followed the methodology developed for the SOCAL-BRS experiment to minimize the impact the presence small boats would have on behavior (see Southall et al., 2012, 2016). Our vessels remained on average more than 460 m from the whale and at average speeds of 5.6 kn. Any subsequent approach was made slowly to record the exact dive position from the whale's footprint or to take photographs of the tag, fluke or dorsal.

Our findings showed that chronic passages between vessels and whales were common, mostly in and near shipping lanes off Northern and Southern California. Repeated close passages, as many as 11 per day, reveal that vessels are in close proximity to blue whales on a daily basis. Despite the constant ship traffic, whales remained in the area, foraging in what is essentially a highway. In the absence of being struck and killed by a vessel, exposure to constant vessel traffic could lead to long-term, non-lethal effects (Gill et al., 2001; Lusseau & Bejder 2007). Although we did not find any immediate changes in the number of lunges per dive before and after close passages, we do not know whether whales failed to initiate foraging or had shorter foraging bouts and net energy gain compared to whales that feed in areas free from vessels. Simulations of foraging blue whales in the Gulf of St. Lawrence suggested a loss of as much as 25% of net energy gain in the presence of vessels (Gulpin et al., 2020). Thus, even in the absence of acute responses to vessels, there could be effects on the population.

Whales did not display behaviors that would increase the distance between the vessels and themselves during close passages. This was evident in the contextual variables we assessed during close passages. For example, encounter duration was greater for near close passages (<400 m). While encounter duration is a function of speed, heading, and distance, this observation suggests whales did not move away from the vessels, which would have decreased the encounter duration. Vessel speeds during near (≤400 m) and far (>400 m) close passages were nearly identical, suggesting that whales did not distance themselves from faster moving vessels. We also expected that whale depth would increase just before the time of the closest passage: for example, the response dives documented by McKenna et al (2015) and Szesciorka et al. (2019). However, this expectation was rejected by the statistical analyses of our large data set.

That being said, ship strikes can only occur when a whale is within near-surface waters, where they are not only physically close to ships, but potentially subject to a propeller suction effect as deep as two times the draft vertically (Silber et al. 2010). Only 79 encounters had depth differences less than 13.6 m (two times the average draft from our data). And of those, only 18 were within 400 m, of which half were slow-moving whale-watching and small personal vessels. We could not detect a statistically significant change in depth of the whales in any of the nine remaining potentially dangerous encounters. Though this is a small sample size, it did include one close passage studied by Szesciorka et al. (2019). In an examination of the longer time series from this whale, the response dive during the close passage — a presumed avoidance behavior — was similar to movements by the whale at other times when no vessel was present.

We have never tagged a whale that was subsequently struck by a vessel, so we must interpret the behavior of whales that have not, to our knowledge, been struck by vessels, but have had high-risk, close passages. And while individual animals may display a high degree of among-individual behavioral variation (Hertel et al. 2020), given the breadth of our analyses, the lack of behavioral response (dive behavior or lateral movement), and lack of uniqueness in behavior prior to or around a close passage, the findings suggest that whales do not react to vessels. The question is why.

One hypothesis for the absence of avoidance responses is that blue whales do not have a behavioral repertoire that includes response to approaching vessels (McKenna et al., 2015). While it would seem simple to move away from an approaching vessel, this threat is recent in the context of evolutionary time. Similar, seemingly paradoxical, situations that result in death of an individual because of lack of behavioral response are common in vertebrate animals. Breeding seabirds of many species do nothing as their eggs and chicks are eaten alive by introduced rats on their island colonies, even as the parent bird incubates or broods (e.g., Jones et al. 2008). Killer whale ecotypes are known to be so specialized in terms of prey that individual animals starve, and their populations decline as their preferred prey becomes scarce, even as alternative prey are seemingly readily available (e.g., Hanson et al. 2021). More than 6 million dolphins in the eastern tropical Pacific have been killed due to incidental entanglement and drowning in nets intended to capture co-schooling tuna (National Research Council 1992), even though escape for dolphins is as simple as jumping over the net corkline at the surface.

As second potential hypothesis is that whales cannot afford to respond in the exaggerated manner that we would expect. The ability of a whale to respond to an approaching vessel may depend on their individual state and state of the environment. For example, birds with better body conditions and in rich feeding areas were found to respond sooner to disturbance, whereas those with the most to lose from a reduction in feeding time showed the least behavioral response (Beale & Monaghan 2004). With required threshold of krill densities greater than 100 krill m^{-3} for optimal blue whale foraging (Hazen et al. 2015), perhaps whales cannot afford to respond in ways we would expect.

Conclusion

We did not detect differences in blue whale behavior associated with close passages with vessels. Dive duration, surface duration, maximum depth, and number of lunges per dive did not change before vs. after, prior to, or around close passages. Whales did not alter their speed or direction of travel, nor did they leave the area due to chronic close passages (>5/day). Even during ≤200 m close passages when whales were in ≤50 m depth, the behaviors exhibited by whales were not unique behaviors that only occurred during the close passage. These findings highlight the need for any new management decisions to account for a lack of whale behavioral response in future approaches. This study has also highlighted gaps in our understanding of blue whale ecology. Not only do we need more information on the sensory system of whales, but we need to develop a better understanding of blue whale movement, habitat use, and persistence in high-risk areas. High risk areas could be identified based on habitat quality, foraging opportunities, and migration timing. Understanding why whales do not respond to approaching vessels is vital for conservation and management decisions that may reduce lethal vessel strikes. Measures already include adding and adjusting shipping routes, expanding existing areas to be avoided, voluntary speed reductions (Redfern et al., 2019, 2020), tools providing near-real-time data to detect endangered whales; and dynamic area management for vessel speeds (Becker et al. 2016). However, with no evidence of behavioral responses to close vessel passages, we need to continue managing vessel traffic and operations under the assumption that baleen whales generally will not avoid vessels.

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Conflict of Interest

The authors declare no competing interests.

Data Availability

The datasets generated for this study are available on request to the corresponding author.

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Manage vessels not whales: A rich data set reveals no detectable response of blue whales to approaching vessels

Supplemental Materials

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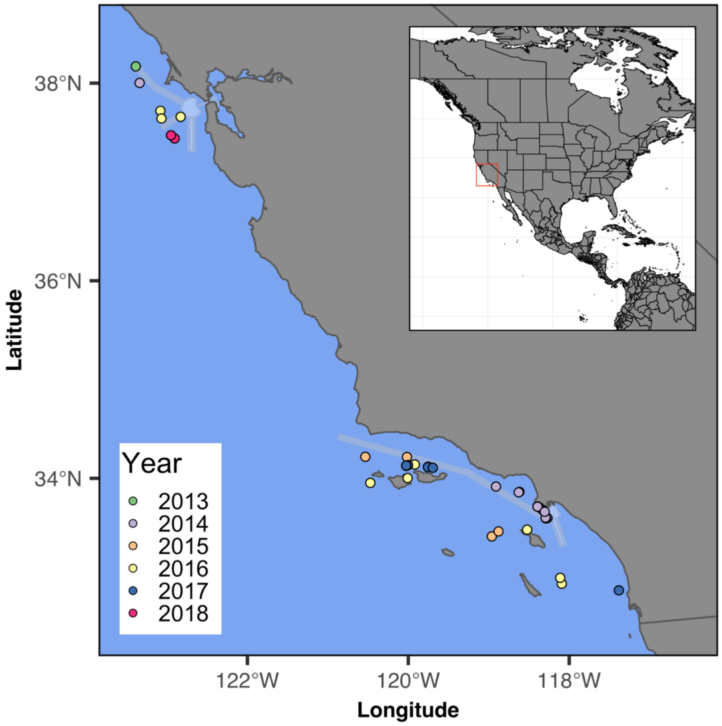
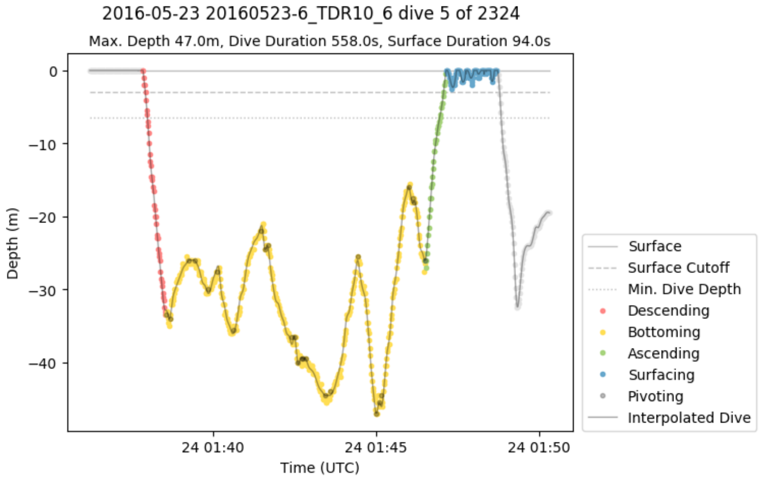
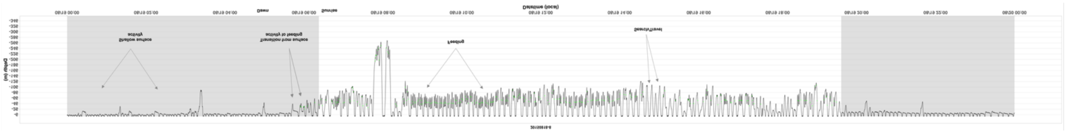


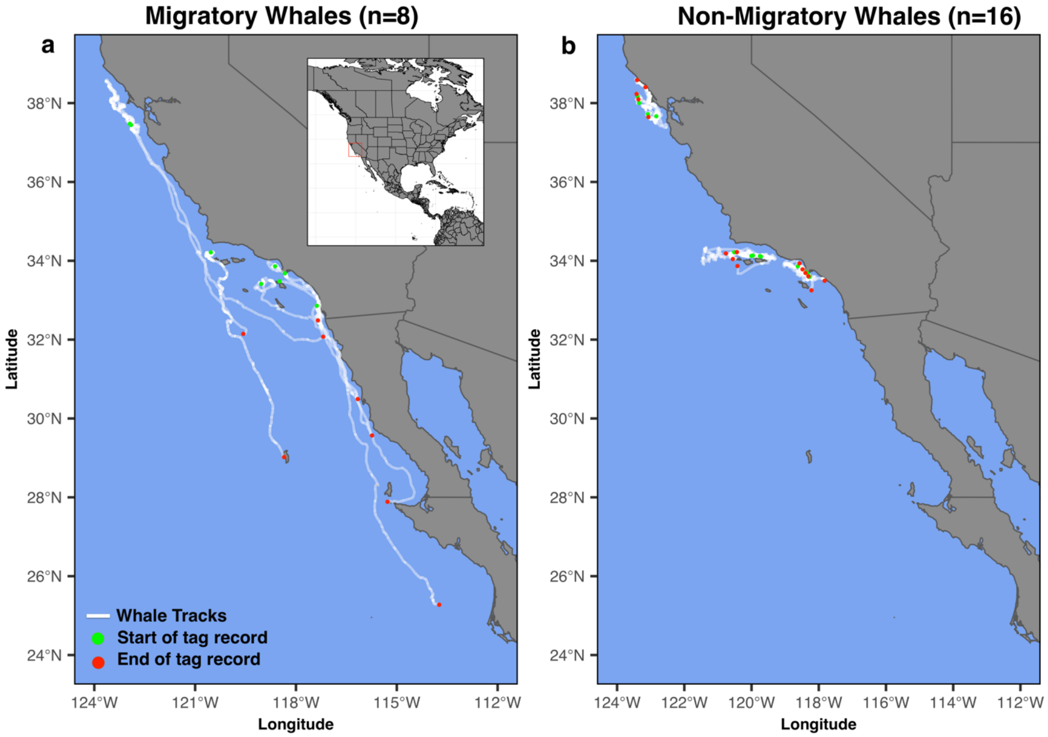
Supplementary Figure 1. Location of 35 blue whale tagging events in Northern California (n=7) and Southern California (n=28). Tag locations colored by year. Major shipping lanes shaded in light gray.



Supplementary Figure 2. Example of output from dive analysis. The points represent real depths from the tag's pressure sensor. The interpolated dive fit using a cubic polynomial equation is indicated as a gray line below the depth points. Red points indicated descent period. Yellow points indicate the bottom of the dive. Green points indicate the ascent period. Blue points indicate the surface period within the surface band, including the surface (gray line) and surface cutoff period (dashed gray line). The minimum dive depth (3.5 m from the surface cutoff) is also indicated as a dotted gray line.



Supplementary Figure 3. Examples of the four broad behaviors assigned to each whale per dive, specifically feeding (if lunges were present and performed during feeding bouts), search/travel (nonfeeding dives that were made during the day in between feeding bouts), shallow surface activity (only seen at night when animals were in the upper 50-m, and often upper 20-m, of the water column), and transition to/from day feeding to night shallow surface behavior, which showed went from shallow surface behavior to feeding or vice versa. Dive record from individual whale across a 24-hour period (y-axis). Depth (x-axis) is in meters. The green circles indicate lunge detections. They gray periods indicate nighttime but include dawn/dusk.



Supplementary Figure 4. Maps depicting (2) whales that left the region and transited south to Baja (presumably for additional foraging opportunities) or on their way to their breeding grounds in Costa Rica Dome and (b) whales that stayed in the same region (n=16) until the tags detached. The tracks are denoted in white. Green circles indicate the start of the location data collected on each tag's GPS and red indicated the time the tag detached from the animal.

Supplementary Table 1. Tag deployment and data summary, including tag attachment and detachment datetimes, type of tag and attachment type, location of tagging, sensor sample rates, number of hours the tag was attached, hours of data and acoustic recording (if the memory card became full), and sex of the whale (if determined from previous genetic analysis from blubber samples).

whale ID	tag datetime	tag type	attachment	location	pressure rate (Hz)	accelerometry rate (Hz)	magnetometry rate (Hz)	acoustic rate (Hz)	gps_fixes	A calls	B calls	D calls	ship_noise	military_sonar	tag_off_animal	data_end	acoustics_end	H-on	H-data	H-Acoustics	known_sex
20131005-4	2013-10-05 16:56:00	TDR10	1 large suction cup	GF/Bodega Canyon	1	-	-	-	77	-	-	-	-	-	2013-10-06 17:11:10	n/a	n/a	24.25	24.25	n/a	unknown
20140719-5	2014-07-19 17:10:19	TDR10	4 titanium darts	GF/Bodega Canyon	1	-	-	-	623	-	-	-	-	-	2014-07-22 20:33:00	n/a	n/a	75.38	75.38	n/a	unknown
20140825-5	2014-08-25 15:23:03	TDR10	4 titanium darts	Southern CA	1	-	-	-	954	-	-	-	-	-	2014-08-30 10:36:00	n/a	n/a	115.22	115.22	n/a	unknown
20140825-6	2014-08-25 17:08:00	TDR10	4 titanium darts	Southern CA	1	-	-	-	1929	-	-	-	-	-	2014-09-07 13:36:00	n/a	n/a	308.47	308.47	n/a	unknown
20140827-1	2014-08-27 12:47:00	TDR10	1 large suction cup	Southern CA	1	-	-	-	89	-	-	-	-	-	2014-08-27 21:13:00	n/a	n/a	8.43	8.43	n/a	unknown
20140827-4	2014-08-27 09:33:40	TDR10	4 titanium darts	Southern CA	1	-	-	-	1113	-	-	-	-	-	Unknown	2014-09-12 19:10:00	n/a	Unknown	393.60	n/a	unknown
20140829-1	2014-08-29 13:30:00	TDR10	1 large suction cup	Southern CA	1	-	-	-	66	-	-	-	-	-	2014-08-30 03:31:00	n/a	n/a	14.02	14.02	n/a	unknown
20140901-1	2014-09-01 12:20:00	TDR10	1 large suction cup	Southern CA	1	-	-	-	71	-	-	-	-	-	2014-09-02 01:19:49	n/a	n/a	13.00	13.00	n/a	unknown
20140901-2	2014-09-01 12:52:43	TDR10	1 large suction cup	Southern CA	1	-	-	-	35	-	-	-	-	-	2014-09-01 18:44:00	n/a	n/a	5.85	5.85	n/a	Female
20140901-3	2014-09-01 12:55:00	TDR10	1 large suction cup	Southern CA	1	-	-	-	4	-	-	-	-	-	2014-09-01 21:38:00	n/a	n/a	8.72	8.72	n/a	Male
20140904-1	2014-09-04 12:16:41	TDR10	1 large suction cup	Southern CA	1	-	-	-	53	-	-	-	-	-	2014-09-05 04:11:00	n/a	n/a	15.91	15.91	n/a	unknown
20140904-2	2014-09-04 13:05:30	TDR10	1 large suction cup	Southern CA	1	-	-	-	40	-	-	-	-	-	2014-09-04 20:39:00	n/a	n/a	7.56	7.56	n/a	unknown
20140913-1	2014-09-13 08:47:00	TDR10	1 large suction cup	Southern CA	1	-	-	-	122	-	-	-	-	-	2014-09-13 23:46:15	n/a	n/a	14.99	14.99	n/a	Female
20150818-8	2015-08-18 11:54:50	TDR10	4 stainless steel darts	Southern CA	1	-	-	-	634	-	-	-	-	-	2015-08-29 07:08:01	n/a	n/a	259.22	259.22	n/a	Male
20150819-5	2015-08-19 11:30:00	TDR10	4 stainless steel darts	Southern CA	1	-	-	-	103	-	-	-	-	-	2015-08-21 15:06:05	n/a	n/a	51.60	51.60	n/a	unknown
20151016-5	2015-10-16 09:46:00	TDR10	4 stainless steel darts	Southern CA	8	-	-	-	283	-	-	-	-	-	2015-10-17 23:54:00	n/a	n/a	38.13	38.13	n/a	unknown
20151016-7	2015-10-16 12:25:00	TDR10	4 stainless steel darts	Southern CA	32	-	-	-	3412	-	-	-	-	-	2015-11-01 20:49:20	n/a	n/a	392.41	392.41	n/a	unknown
20160523-6	2016-05-23 11:09:00	Acousonde	4 stainless steel darts	GF/Coastal Bodega	32	-	-	-	1415	-	-	-	-	-	2016-05-31 12:39:00	n/a	n/a	193.50	193.50	n/a	unknown
20160523-B020	2016-05-23 11:37:00	Acousonde	3 stainless steel darts	GF/Continental shelf	10	100	10	1815	1756	0	0	228	15	0	2016-06-02 07:58:57	2016-05-27 13:17:41	2016-06-06 04:43:01	236.37	236.37	236.37	unknown
20160716-B020	2016-07-16 12:12:33	Acousonde	3 stainless steel darts	Southern CA	10	100	10	1815	1369	0	0	0	1	0	2016-08-05 14:06:05	2016-07-20 08:45:21	2016-07-20 07:24:24	481.89	481.89	67.19	unknown
20160717-B021	2016-07-17 09:27:53	Acousonde	3 stainless steel darts	Southern CA	10	100	10	1815	442	0	0	0	0	0	2016-07-31 15:17:00	2016-07-21 16:00:38	2016-07-31 18:02:48	341.82	341.82	341.80	unknown
20160815-B021	2016-08-15 11:16:06	Acousonde	3 stainless steel darts	Southern CA	10	100	10	12226	20	0	0	0	0	0	2016-08-15 14:04:07	2016-08-15 16:17:01	2016-08-15 16:17:01	2.80	2.8003	3.8917	unknown
20160817-B021	2016-08-17 13:54:30	TDR10	3 stainless steel darts	Southern CA	10	100	10	12226	27	0	0	1	0	0	2016-08-19 11:44:31	2016-08-19 19:58:46	2016-08-19 11:44:47	45.83	45.8336	45.8331	unknown
20160918-B008	2016-09-18 13:15:00	TDR10	3 stainless steel darts	Southern CA	10	100	10	12226	3023	28	63	7	0	0	Unknown	2016-09-22 16:01:24	2016-09-22 16:02:50	Unknown	98.93	96.80	unknown
20160918-B021	2016-09-18 11:56:32	TDR10	4 stainless steel darts	Southern CA	10	100	10	12226	65	1596	2860	723	0	1	Unknown	2016-09-23 01:29:47	2016-10-01 05:52:45	Unknown	102.55	298.91	Male
20160926-07	2016-09-26 16:57:30	TDR10	4 stainless steel darts	Farallones	32	-	-	-	193	-	-	-	-	-	2016-09-27 15:26:00	n/a	n/a	22.48	22.48	n/a	unknown
20170622-12	2017-06-22 10:44:00	TDR10	4 stainless steel darts	Southern CA	32	32	-	-	3697	-	-	-	-	-	2017-07-10 05:10:00	n/a	n/a	426.43	426.43	n/a	unknown
20170622-13	2017-06-22 10:17:40	TDR10	4 stainless steel darts	Southern CA	32	32	-	-	24	-	-	-	-	-	2017-06-27 08:15:00	n/a	n/a	117.96	117.96	n/a	unknown
20170706-11	2017-07-06 12:30:00	TDR10	4 small suction cups	Southern CA	32	32	-	-	541	-	-	-	-	-	2017-07-09 07:10:50	n/a	n/a	66.68	66.68	n/a	unknown
20170925-11	2017-09-25 12:09:00	TDR10	4 small suction cups	Southern CA	32	32	-	-	38	-	-	-	-	-	2017-09-26 03:37:34	n/a	n/a	15.48	15.48	n/a	unknown
20170925-12	2017-09-25 10:34:00	TDR10	4 stainless steel darts	Southern CA	32	32	-	-	592	-	-	-	-	-	2017-09-29 12:31:00	2017-09-29 13:03:46	n/a	97.95	97.95	n/a	unknown
20170925-14	2017-09-25 11:16:50	TDR10	4 small suction cups	Southern CA	32	32	-	-	9	-	-	-	-	-	2017-09-25 18:38:15	n/a	n/a	7.36	7.36	n/a	unknown
20170926-14	2017-09-26 10:55:40	TDR10	4 small suction cups	Southern CA	32	32	-	-	345	-	-	-	-	-	2017-09-30 18:24:30	2017-09-30 19:22:44	n/a	103.48	103.48	n/a	unknown
20181021-11	2018-10-21 10:23:33	TDR10	4 stainless steel darts	Farallones	32	32	-	-	2394	-	-	-	-	-	2018-11-22 10:57:00	2018-11-22 10:57:00	n/a	768.56	768.56	n/a	unknown
20181021-14	2018-10-21 13:31:39	TDR10	4 stainless steel darts	Farallones	32	32	-	-	1430	-	-	-	-	-	2018-11-03 00:31:22	2018-11-03 03:22:27	n/a	299.00	299.00	n/a	unknown

Supplementary Table 2. Contextual variables used to assess near close passages (<400m) and far close passages (>400m) between vessels and tagged whales.

category	variable_name	data_type	unit	source	details
vessel	vessel type	categorical	-	AIS	cargo/container, bulk/vehicle carrier, oil tanker, tow/tug/tender, passenger, whale watching, service/research (Navy, NOAA, Coast Guard), recreational (diving, fishing, pleasure, sailing), cruise ship
vessel	length	continuous	m	AIS	
vessel	width	continuous	m	AIS	
vessel	draft	continuous	m	AIS	
vessel	speed	continuous	kn	AIS or estimated	
vessel	heading variability	categorical	-	inferred based on movement of vessel during close passage	constant or variable
vessel	heading relative to the whale	categorical	-	inferred based on movement of vessel during close passage	toward, away, parallel
environment	month	discrete	-	-	
environment	hour	discrete	-	-	
environment	wind speed	continuous	m/s	NOAA National Data Buoy Center (https://www.ndbc.noaa.gov)	based on closest buoy dat and time
environment	Beaufort scale	discrete		calculated	
environment	distance to shipping lanes	continuous	km	calculated	marmap in R
environment	distance to port	continuous	km	calculated	st_distance in R
environment	distance to coast	continuous	km	calculated	st_distance in R
whale	whale ID	categorical	-	assigned	whale’s unique identification number
whale	exposure number	discrete		estimated	number of the specific encounter relative to each whale’s total number of close passages observed
whale	mean daily encounter rate	continuous		estimated	number of close passages divided by the number of days the whale was tagged
whale	whale depth	continuous		time-depth record	
whale	dive portion	categorical		time-depth record	descending, bottom, ascending, and surface
whale	behavior	categorical		inferred by lunges, time of day, and movement	feeding, search/travel, shallow surface behavior, transition

Supplementary Table 3. Summary of close passages between tagged whales and vessels, including ship type, ship dimensions, ship speed and heading, ais position, tag position, closest triangulated distance, and encounter duration.

whale	datetime_local	mmsi	ship_name	ship_type	length (m)	beam (m)	draft (m)	heading (°)	speed (kn)	ais_lat	ais_lon	tag_lat	tag_lon	closest_distance (	duration (s)
20160716-B020	2016-07-18 15:02:33	367568350	Condor Express	Whale watching	23	7	2	275.8	7.3	34.14127	-119.976499	34.141101	-119.976352	9.49	4688
20140825-6	2014-09-07 01:59:46	352058000	Hanjin China	Cargo	349	45	15.6	118.4	11	33.728811	-118.617424	33.727935	-118.614885	15.06	740
20160717-B021	2016-07-17 13:29:56	367565750	Island Explorer	Whale watching	22	8	3	39.7	3.1	34.132566	-119.9701	34.132278	-119.970034	16.91	4249
20160716-B020	2016-07-17 14:30:10	367565750	Island Explorer	Whale watching	22	8	3	195.5	2.6	34.133167	-119.971	34.132996	-119.970684	24.49	4261
20140825-6	2014-09-03 09:10:05	366948190	Alaskan Frontier	Tanker	294	50	18.9	90	11.6	33.6007	-118.336183	33.60103	-118.333472	26.5	602
20140825-6	2014-09-07 13:26:46	367580930	Triumphant	Whale watching	26	10	2.5	293.9	6.7	33.691665	-118.398199	33.691344	-118.398187	26.71	788
20160926-7	2016-09-27 02:42:02	369567000	Sea Reliance	Towing	180	23	7.5	238.9	8.8	37.62987	-122.941439	37.6287	-122.9427	37.91	805
20160717-B021	2016-07-17 13:06:10	367568350	Condor Express	Whale watching	23	7	2	78.7	4.1	34.133281	-119.97297	34.133076	-119.972506	40.95	2218
20160523-B020	2016-05-26 08:06:03	565343000	Maersk Borneo	Oil Tanker	175	29	8.2	52.9	9	37.680017	-122.77175	37.681197	-122.770854	47.68	1008
20160717-B021	2016-07-18 15:35:20	367568350	Condor Express	Whale watching	23	7	2	242.1	5.1	34.143301	-119.978817	34.1429	-119.978944	47.93	4752
20140825-5	2014-08-27 23:01:51	477203800	Great Ocean	Cargo	229	32	7.3	300.2	11.6	33.758339	-118.594225	33.758459	-118.596694	75.71	500
20140825-6	2014-09-04 20:50:16	311012800	Gulf Jumeirah	Tanker	183	32	8.3	271.4	13.3	33.580452	-118.472445	33.579636	-118.471916	86.52	618
20140913-1	2014-09-13 12:17:14	367196000	Mokihana	Cargo	262	32	10	258.7	11.4	33.579739	-118.283901	33.580563	-118.283176	87.45	569
20160716-B020	2016-07-17 13:20:06	367568350	Condor Express	Whale watching	23	7	2	184.6	5.7	34.133093	-119.967824	34.133098	-119.968904	90.5	2381
20140825-5	2014-08-28 17:05:55	367001740	Catalina Flyer	Passenger	38	12	0	62.6	24.7	33.4583	-118.105217	33.457518	-118.104429	92.66	338
20170622-12	2017-06-23 12:27:14	367568350	Condor Express	Whale watching	23	7	2	99.7	4.2	34.110634	-119.707377	34.109729	-119.707789	96.65	3897
20140904-1	2014-09-04 13:58:52	477222600	Oocl Memphis	Cargo	335	43	12.3	86.1	9.2	33.600417	-118.297242	33.60152	-118.294725	97.76	823
20140825-6	2014-09-06 05:11:39	538003858	Eser K	Tanker	251	44	9	119.5	10.6	33.72513	-118.60142	33.725205	-118.598521	110.75	725
20140825-5	2014-08-28 12:48:17	566747000	Oocl Kuala Lumpur	Cargo	280	40	12.1	87.8	7.9	33.60081	-118.308549	33.602086	-118.309475	126.34	760
20140913-1	2014-09-13 14:11:21	367580930	Triumphant	Whale watching	26	10	2.5	68.2	5.6	33.55125	-118.15405	33.551792	-118.152585	133.73	1229
20181021-11	2018-10-28 12:07:01	374217000	Iris Leader	Vehicle carrier	199	34	8.8	145.7	11.8	38.165532	-123.400401	38.16512	-123.402297	141.96	544
20160523-6	2016-05-24 13:33:37	338134000	Nancy Peterkin	Tanker	205	24	7	57.5	11.1	37.588012	-122.939435	37.588877	-122.940934	144.22	638
20140825-6	2014-09-02 10:38:48	367008510	Catalina Jet	Passenger	42	12	3.7	194	29.3	33.54583	-118.236802	33.546295	-118.237691	154.86	260
20140904-1	2014-09-04 13:11:25	371961000	Greenwich Bridge	Cargo	284	40	12.4	102.5	8.8	33.59835	-118.301417	33.599541	-118.299432	159.29	847
20181021-11	2018-10-29 10:54:54	538070502	Elisa	Pleasure	47	10	2.6	154.2	13	38.520404	-123.63004	38.520796	-123.627879	180	616
20170706-11	2017-07-07 19:28:10	368453000	Shogun	Fishing	24	8	2	169.6	10.8	31.570845	-116.766303	31.571708	-116.764488	191.49	1086
20170622-12	2017-06-29 13:24:03	366899260	Island Adventure	Whale watching	20	7	2.4	264	4.4	34.11268	-119.81141	34.114087	-119.812339	204.59	1876
20160523-B020	2016-05-30 01:33:56	215193000	Gold Point	Oil Tanker	183	32	9.5	56	14.7	37.5933	-122.946659	37.592329	-122.943761	211.41	502
20160716-B020	2016-07-16 13:09:10	367568350	Condor Express	Whale watching	23	7	2	188.1	0.3	34.12277	-119.999918	34.124683	-119.99888	215.7	1854
20140825-5	2014-08-28 12:14:36	367349430	Pacific Falcon	Towing	72	20	8.2	96.4	4.3	33.600247	-118.305607	33.601955	-118.303788	221.18	1570
20170622-12	2017-07-01 12:05:16	338200977	Fluid	Pleasure	12	4	1	230.9	6.9	34.146453	-119.93862	34.147158	-119.940159	224.62	934
20170926-14	2017-09-26 14:09:46	338140283	Fish One	Diving	7	2	0.9	30	23.9	34.128595	-119.844024	34.129314	-119.845507	228.37	285
20140827-4	2014-08-27 14:47:29	366943940	Super Express	Passenger	45	7	0	37.2	25.8	33.636798	-118.29607	33.63568	-118.294582	230.74	301
20140825-6	2014-08-27 19:45:50	538004470	Grand Pioneer	Cargo	190	32	6.9	301.4	11.8	33.893501	-118.878307	33.895334	-118.876642	232.45	390
20170622-12	2017-07-03 07:04:41	372340000	Hyundai Bangkok	Container	303	40	10.6	106.3	16.7	34.141387	-119.697998	34.139946	-119.697628	235.71	403
20170622-12	2017-06-23 06:14:42	477117900	Cscl Autumn	Cargo	335	49	16.8	105.8	13.9	34.141693	-119.707651	34.138788	-119.705492	237.9	538
20160523-6	2016-05-24 14:19:05	538006773	Pacific Treasures	Tanker	256	44	10.7	57.8	10.4	37.598121	-122.916549	37.596944	-122.913152	243.41	1009
20140825-6	2014-09-05 00:01:01	419555000	Jag Lalit	Tanker	274	48	14.6	300.6	12.1	33.688204	-118.440714	33.691488	-118.441823	244.46	673
20140901-1	2014-09-01 12:31:59	367574410	Pakala	Sailing	11	3	1	56.2	5.8	33.71275	-118.379142	33.710507	-118.378189	256.66	1050
20140825-6	2014-09-01 14:19:21	338143435	V Tack	Sailing	12	5	1	3.2	7.8	33.820778	-118.469778	33.820542	-118.466697	280.44	994
20170622-12	2017-06-24 23:37:25	538005988	STI Executive	Oil tanker	219	38	9.9	105.3	14	34.15047	-119.75073	34.147475	-119.74995	281.09	623
20140827-1	2014-08-27 13:41:35	371836000	Mol Endowment	Cargo	294	32	11.3	91.2	10.9	33.599847	-118.290409	33.602096	-118.287082	298.48	527
20170622-12	2017-07-04 03:17:53	319363000	Polar Star	Pleasure	65	13	3.9	285.3	14.1	34.148137	-119.58586	34.145549	-119.587309	301.04	547
20181021-14	2018-10-24 19:27:09	303865000	USCGC Aspen	US Coast Guard	68	14	3.5	141.4	10.2	37.439029	-122.813799	37.43778	-122.817131	309.4	783
20160716-B020	2016-07-20 07:53:22	477462400	Mol Gratitude	Cargo	275	40	11.4	105.2	11.3	34.091799	-119.497082	34.088805	-119.49764	309.73	626
20150818-8	2015-08-26 04:45:05	249159000	Marbat	Tanker	332	60	18.3	158.3	8.2	32.56432	-117.6375	32.559147	-117.635733	312.3	350
20160523-6	2016-05-30 12:13:34	367637040	Finely Finished	Sailing	11	4	1	192	4.1	38.245017	-123.044861	38.246039	-123.04862	340.62	2378
20181021-11	2018-10-31 23:50:05	477133700	Halifax Express	Cargo	294	32	13.9	139	9.1	37.972202	-123.201056	37.972614	-123.19612	341.82	754
20170622-12	2017-07-03 07:52:51	372025000	Sm Yantian	Cargo	304	40	11.2	105.8	17.2	34.139171	-119.713513	34.14126	-119.71016	346.63	424
20181021-14	2018-10-22 18:25:29	538005345	Glovis Superior	Vehicle carrier	199	35	8.6	239.6	9.9	37.604652	-123.000467	37.607871	-123.002093	361	819
20140825-6	2014-09-04 03:55:46	357258000	Silver Stacie	Tanker	183	32	8.6	88.5	5.7	33.597671	-118.288998	33.594373	-118.286387	368.94	1389
20150818-8	2015-08-25 14:13:41	303849000	Kaiser	Tanker	207	30	8.5	269.2	12.6	32.599961	-117.963227	32.5963	-117.964817	384.04	410
20160523-B020	2016-05-24 04:08:45	477407900	Hanjin Jungil	Cargo	337	48	12.2	55.6	8.8	37.665978	-122.791436	37.662042	-122.789838	420.18	659
20140825-5	2014-08-28 08:34:06	367192940	Avalon Express	Passenger	33	7	3	184.5	24.4	33.608597	-118.263085	33.608092	-118.267849	434.4	239
20140904-2	2014-09-04 13:12:00	371961000	Greenwich Bridge	Cargo	284	40	12.4	94.9	8.4	33.59812	-118.29978	33.601973	-118.296773	436.02	762
20140827-4	2014-09-02 20:18:45	367198110	Vigilance	Offshore Supply S	60	6	4	45	8.3	32.595845	-117.282458	32.599426	-117.285606	440.03	719
20140825-5	2014-08-28 07:01:27	371821000	MV Vinca	Cargo	190	32	12	91.5	8.1	33.603467	-118.271095	33.59935	-118.272013	444.33	900
20140825-5	2014-08-28 18:22:04	366943960	Catalina Express	Passenger	64	6	4	74.7	28.2	33.398872	-117.98757	33.395067	-117.985302	458.56	292
20140901-1	2014-09-01 20:29:01	248671000	Avor	Tanker	249	44	9.7	279.3	12	33.631901	-118.278489	33.636611	-118.27997	460.81	578
20160926-7	2016-09-27 02:02:35	636017034	Trammo Independent	Bulk carrier	179	32	8.6	238.4	12.9	37.62509	-122.960303	37.629285	-122.962107	461.73	548
20140825-6	2014-09-01 13:24:52	338076841	Artemus	Sailing	12	3	1	0.8	6.4	33.820116	-118.470308	33.819908	-118.465111	476.42	1124
20140825-6	2014-08-28 00:26:21	477203800	Great Ocean	Cargo	229	32	7.3	300.9	12.2	33.894412	-118.881314	33.891456	-118.886393	495.64	509
20181021-11	2018-11-04 04:02:22	636092872	Anl Warrnambool	Container	262	32	9.9	146.6	18.7	35.205892	-121.527031	35.209652	-121.523111	506	467
20140827-4	2014-09-06 23:06:33	477165000	Isla De Cedros	Cargo	223	32	12.6	145.2	13.3	29.922324	-116.325216	29.925641	-116.32108	514.18	631
20140913-1	2014-09-13 19:05:07	367632310	Seaviche	Pleasure	8	4	0.9	27.8	25.7	33.549841	-117.904198	33.547726	-117.89898	531.22	180
20170622-12	2017-07-03 09:03:25	477071300	High Mars	Tanker	182	32	9.3	105.4	12.8	34.137619	-119.692887	34.141988	-119.689382	533.34	616
20160523-6	2016-05-30 05:41:07	338159978	Tunacan	Fishing	11	4	1	184.7	22.2	38.258265	-123.033284	38.258801	-123.039478	538.23	192
20140827-4	2014-09-02 22:06:38	367435980	Killeen	Towing	18	6	2.2	71	5.7	32.62361	-117.28143	32.628703	-117.28164	554.57	449
20140827-4	2014-08-29 14:24:20	338166043	Saiorse	Sailing	9	3	0.9	346.9	5.4	33.094424	-117.375209	33.095749	-117.369392	555.41	809
20140904-2	2014-09-04 13:55:37	477222600	Oocl Memphis	Cargo	335	43	12.3	88.7	9.3	33.600147	-118.307227	33.595023	-118.30531	558.12	761
20140825-6	2014-09-01 12:44:08	367021380	Echo One	Pleasure	15	4	1.3	3.2	15.9	33.819855	-118.470185	33.819434	-118.463925	574.5	563
20160523-B020	2016-05-24 10:09:53	366962000	Mississippi Voyager	Tanker	190	32	9.3	236.9	10.8	37.70004	-122.812005	37.703024	-122.81849	584.44	584
20170622-12	2017-07-03 05:49:02	373500000	Santa Graciela	Bulk carrier	229	32	9.9	93.2	13	34.14233	-119.689427	34.147598	-119.686028	586.02	515
20170622-12	2017-07-09 08:57:04	338104149	Bonza	Pleasure	13	5	1	246.8	19.4	34.1073	-119.67599	34.112501	-119.677741	592.03	399
20140825-6	2014-08-27 13:45:26	636091434	Cap Patton	Cargo	186	28	9.2	302	11	33.877022	-118.839428	33.882638	-118.837609	606.42	613
20170622-12	2017-06-23 05:07:55	353408000	Bulk Pods	Bulk carrier	225	32	12	104.1	11.5	34.13797	-119.695267	34.143614	-119.69418	611.22	555
20131005-4	2013-10-06 08:20:05	235009850	Ever Sigma	Cargo	300	43	10	281.2	16.3	38.161417	-123.3831	38.167604	-123.385521	631.44	475
20181021-11	2018-10-29 23:28:47	309822000	HON Henry Jackman	Oil tanker	245	32	10.5	313.6	9	38.211862	-123.411787	38.215406	-123.405742	633.6	724
20160716-B020	2016-07-21 22:10:16	228338600	Cma Cgm Nabucco	Container	335	42	12.6	106	11.7	34.088389	-119.52087	34.081992	-119.520166	638.65	352
20140825-5	2014-08-29 13:43:39	338166043	Saiorse	Sailing	9	3	0.9	355.7	4.7	33.038043	-117.361719	33.039292	-117.368319	643.49	780
20160523-B020	2016-05-26 18:14:11	259953000	Champion Cornelia	Tanker	182	32	19.3	57.5	12.6	37.655823	-122.828639	37.650207	-122.825706	647.46	596
20140825-6	2014-09-01 22:27:11	477973000	Saga Voyager	Cargo	199	30	11	90.5	10.9	33.599867	-118.3318	33.605905	-118.329785	647.57	740

Supplementary Table 3, Continued

whale	datetime_local	mmsi	ship_name	ship_type	length (m)	beam (m)	draft (m)	heading (°)	speed (kn)	ais_lat	ais_lon	tag_lat	tag_lon	closest_distance	duration (s)
20140825-6	2014-09-01 10:13:43	367574410	Pakala	Sailing	11	3	1	171.3	5.5	33.818803	-118.452199	33.817684	-118.459547	685.78	1171
20140904-1	2014-09-04 21:38:57	338126671	Alls Well Tio	Sailing	12	4	1	297.7	5.1	33.764468	-118.524373	33.758673	-118.527914	714.59	2402
20160523-6	2016-05-28 01:32:31	636016423	Msc Bhavya	Cargo	294	32	10.6	121.2	9.5	37.90603	-123.075557	37.899211	-123.077488	720.52	863
20170622-12	2017-07-09 06:31:31	477056400	Cosco Oceania	Cargo	349	46	10.8	105.7	17.7	34.120181	-119.599609	34.112624	-119.597582	745.92	407
20140827-4	2014-09-02 15:09:54	366951730	Jeffrey M	Tug	26	8	3	259.4	6.6	32.616522	-117.326287	32.623368	-117.326749	751.82	1230
20140825-6	2014-09-05 05:19:25	636016200	Hyundai Long Beach	Cargo	293	40	12.5	109.7	5.9	33.602859	-118.348431	33.595513	-118.343478	768.04	1006
20170622-12	2017-07-04 06:11:26	368684000	Apl Philippines	Cargo	276	40	10.8	104.9	16.5	34.132527	-119.676609	34.13846	-119.671081	775.93	408
20140825-5	2014-08-28 05:33:39	367457000	Oregon Voyager	Tanker	189	32	9.8	271.4	11.6	33.637409	-118.295679	33.644408	-118.293623	779.64	406
20160716-B020	2016-07-21 16:29:00	366813530	Islander	Passenger	20	7	2.1	49.9	19.7	34.095636	-119.493911	34.090273	-119.488149	786.84	370
20140825-6	2014-08-30 09:37:24	338146516	Freedom	Sailing	14	3	1	186.3	7	33.753779	-118.486884	33.754678	-118.49547	794.62	901
20160716-B020	2016-07-20 16:22:03	366813530	Islander	Passenger	20	7	2.1	49	19.2	34.088038	-119.505105	34.083028	-119.498675	801.5	380
20170706-11	2017-07-07 06:02:50	367631360	Embajador	Sailing	26	7	2.5	2.6	9	32.429097	-117.319088	32.427842	-117.327742	813.98	585
20140904-1	2014-09-04 12:31:44	566748000	Oocl Italy	Cargo	280	40	12	92	9	33.6032	-118.29483	33.595438	-118.292786	830.6	543
20140825-6	2014-09-04 15:48:40	367192940	Avalon Express	Passenger	33	7	0	215.8	24.5	33.528318	-118.403341	33.524134	-118.395971	834.33	287
20170622-12	2017-07-01 22:43:22	235010450	Ever Smart	Cargo	300	43	12.2	287.3	20.9	34.264063	-120.097383	34.257206	-120.102933	853.63	351
20160716-B020	2016-07-21 09:28:11	367265000	Coast Guard 623	US Coast Guard	64	9	4.3	105.4	14.2	34.088268	-119.462685	34.080799	-119.46607	874.81	573
20140904-1	2014-09-04 15:33:12	367192940	Avalon Express	Passenger	33	7	0	215.4	24.1	33.61319	-118.331017	33.609169	-118.322584	891.05	271
20160523-B020	2016-05-26 12:50:03	367503140	Mystique	Sailing	13	4	1	259.8	7.2	37.735625	-122.795458	37.743783	-122.796469	903.32	836
20160716-B020	2016-07-20 07:03:00	371752000	Msc Rania	Cargo	332	42	13.1	107	11.2	34.090508	-119.505213	34.082859	-119.5095	905.23	731
20140825-6	2014-08-28 09:43:26	563754000	Apl Holland	Cargo	277	40	11.3	301.7	12.1	33.905716	-118.905194	33.912317	-118.898958	906.06	550
20140719-5	2014-07-22 00:42:41	636015771	Carnation Ace	Cargo	199	32	8.6	139.7	12.8	38.095672	-123.329817	38.102738	-123.323175	923.97	566
20140904-2	2014-09-04 14:16:37	367353070	Evergreen State	Oil Tanker	188	32	10	72.5	8.6	33.599067	-118.298867	33.60808	-118.296032	926.04	886
20160523-6	2016-05-24 10:58:51	366962000	Mississippi Voyager	Tanker	190	32	9.3	239.9	10.5	37.625042	-122.963431	37.616608	-122.960341	931.51	624
20170622-12	2017-06-30 05:54:49	367098480	Conception	Diving	24	8	2	214.7	10.5	34.161153	-119.871498	34.157363	-119.862267	938.9	752
20140825-6	2014-09-01 10:05:03	367615030	Reflections	Sailing	11	4	1	169.8	6.4	33.819399	-118.449167	33.817583	-118.459295	955.06	1018
20140825-6	2014-08-28 01:30:59	352804000	Nyk Athena	Cargo	300	40	10.9	120.3	14.2	33.857743	-118.881676	33.867098	-118.879818	962.46	360
20140913-1	2014-09-13 12:51:19	367008510	Catalina Jet	Passenger	42	12	3.7	195.5	30	33.565067	-118.236365	33.56836	-118.246246	963.02	212
20140825-6	2014-08-30 11:31:57	338020915	Harbinger	Pleasure	11	4	1	184.4	7.3	33.763809	-118.482079	33.764554	-118.492634	974.23	809
20140825-6	2014-08-29 08:13:17	413165000	Xin Mei Zhou	Cargo	335	43	12.2	119.4	11.3	33.914244	-119.004538	33.92034	-118.995608	974.24	561
20140825-5	2014-08-29 22:52:32	367006770	Robyn J	Towing	36	8	3	145.8	11	32.761607	-117.389854	32.767878	-117.382339	977.99	579
20140825-6	2014-08-30 08:50:14	338122002	Tucana	Pleasure	17	6	1.6	184.1	19.7	33.748427	-118.476586	33.74863	-118.487479	1001.45	240
20140901-1	2014-09-01 20:11:56	367304990	Cochise	Towing	60	10	12	27.5	8.3	33.627546	-118.274461	33.632886	-118.283462	1011.86	1081
20170622-12	2017-06-23 01:30:33	310765000	London Express	Container	295	32	10.4	103.6	12.6	34.147604	-119.739718	34.13869	-119.74426	1039.59	573
20160926-7	2016-09-27 02:35:42	367008020	Arthur Brusco	Tug	35	10	4.2	244.9	8	37.638871	-122.949182	37.629874	-122.945539	1040.17	668
20170622-12	2017-06-26 03:33:33	256871000	MSC Athos	Container	300	48	8.7	107.6	10.2	34.171612	-119.866092	34.161831	-119.867699	1047.4	563
20140825-6	2014-09-01 11:11:13	338020915	Harbinger	Pleasure	11	4	1	5.1	15.7	33.819211	-118.472644	33.818353	-118.461221	1056.19	330
20140825-6	2014-08-31 13:05:53	308927000	Sirius Voyager	Tanker	275	50	15.1	39.9	6.7	33.801524	-118.507143	33.801301	-118.519266	1064.47	1025
20140825-5	2014-08-28 06:16:34	311000111	Pegasus Voyager	Oil Tanker	276	48	13.2	70.3	9.3	33.605887	-118.273444	33.613541	-118.281332	1074.77	440
20140827-4	2014-08-27 16:23:34	367311590	Miss Christi	Passenger	15	4	1.5	45.5	16.7	33.618313	-118.325917	33.625911	-118.333322	1081.48	392
20151016-7	2015-10-30 12:13:09	477044300	Zhenhua24	Cargo	244	40	8.2	65.1	8.7	30.681021	-118.864026	30.673906	-118.854668	1105.87	609
20181021-14	2018-10-22 14:27:39	367455580	Florida Voyager	Tanker	183	32	22.3	238.4	10	37.598239	-123.004631	37.606086	-123.013132	1108.75	595
20170622-12	2017-07-03 15:08:24	367749230	Worldcat	Pleasure	9	8	0.9	81.3	27.8	34.111463	-119.645459	34.121336	-119.6471	1119.05	225
20170622-12	2017-07-03 21:03:34	354839000	Hammersmith Bridge	Cargo	336	46	11.3	103.3	12	34.123964	-119.656145	34.114164	-119.660899	1142.32	636
20140827-1	2014-08-27 13:57:47	636013457	Apl Austria	Cargo	295	40	12.3	89.8	11.4	33.60003	-118.304859	33.610577	-118.301315	1143.38	340
20140825-6	2014-09-02 03:31:38	367393270	Nicholas L	Tender	31	7	2.4	141	16	33.592581	-118.141164	33.584837	-118.1495	1143.78	329
20170622-12	2017-07-03 04:13:41	353408000	Bulk Pods	Bulk carrier	225	32	12	283.7	12.6	34.164852	-119.666582	34.155105	-119.672105	1151.07	456
20160716-B020	2016-07-20 20:48:17	220379000	Gudrun Maersk	Cargo	368	42	12.3	107.3	17.8	34.092011	-119.492962	34.08142	-119.494975	1151.07	326
20151016-7	2015-10-17 23:27:50	367531260	Southeast	Fishing	20	8	3	174.8	7.8	34.208829	-120.651682	34.210073	-120.664213	1152.62	591
20140827-4	2014-09-02 05:11:04	123412112	Rsc-3	Navy	38	10	2.5	296.8	13.7	32.647628	-117.299854	32.656574	-117.293331	1153.89	199
20160716-B020	2016-07-20 07:20:27	636015019	Express Rome	Container	349	46	10.6	105.7	13.8	34.095041	-119.496384	34.085179	-119.501314	1155.89	494
20140901-1	2014-09-01 16:11:02	338077467	Mintaka	Sailing	12	4	1	44.8	6.3	33.667621	-118.296639	33.673254	-118.307626	1191.62	841
20160716-B020	2016-07-20 20:15:52	477878000	Saga Monal	Cargo	199	32	7.6	106.6	11.3	34.0909	-119.488294	34.079921	-119.49005	1192.87	544
20131005-4	2013-10-05 23:13:37	477685300	Cosco Korea	Cargo	334	43	12	319.8	15.2	38.139785	-123.325336	38.145033	-123.312241	1230.79	308
20160716-B020	2016-07-20 10:21:10	367565750	Island Explorer	Whale watching	22	8	3	238.6	18.5	34.082921	-119.561598	34.092222	-119.569105	1233.51	329
20170622-12	2017-06-24 04:07:35	232006508	CMA CGM G.Washington	Cargo	366	48	17.6	105.2	14.9	34.156375	-119.78238	34.144768	-119.783952	1255.85	471
20181021-11	2018-11-02 17:37:09	369322000	Cape Ann	Tug	132	21	6.6	340.4	8.2	36.602358	-122.331464	36.597366	-122.344328	1255.9	477
20140913-1	2014-09-13 17:35:28	367001740	Catalina Flyer	Passenger	38	12	2.5	60.4	22.9	33.546773	-117.933651	33.555818	-117.942118	1260.56	188
20140825-6	2014-09-02 17:20:50	367006280	Catalina King	Passenger	39	11	3.3	14.3	12.1	33.541712	-118.241509	33.540442	-118.227933	1260.75	411
20140825-6	2014-09-05 07:52:49	370930000	Msc Ivana	Cargo	363	46	10.7	272.8	11.8	33.584539	-118.350484	33.573154	-118.347016	1264.51	642
20140825-6	2014-09-01 11:37:55	338045235	Genesis	Pleasure	24	6	2	354.9	11.7	33.819498	-118.448259	33.818663	-118.461998	1266.89	486
20170622-12	2017-07-09 05:40:03	319112500	Stolt Tenacity	Oil Tanker	185	32	9.6	104	14.1	34.119172	-119.618288	34.107293	-119.618546	1275.62	360
20140825-6	2014-08-29 22:00:24	565570000	Maersk Altair	Cargo	338	44	11.4	299.1	10.9	33.720185	-118.518328	33.732713	-118.51655	1282.59	467
20181021-14	2018-10-21 23:44:14	367098550	Heidi L Brusco	Tug	35	10	3.6	60.2	9	37.653896	-122.944529	37.66482	-122.949796	1288.15	552
20150818-8	2015-08-22 09:07:11	338045235	Genesis	Pleasure	24	6	2	193.3	7.7	33.50256	-118.73749	33.509014	-118.74923	1294.83	1000
20140825-6	2014-09-01 13:03:08	366829990	Fast Reorrg	Sailing	15	3	1.3	354.6	5.4	33.82044	-118.450437	33.819655	-118.464478	1295.72	1020
20160716-B020	2016-07-20 08:46:13	477443000	Black Forest	Cargo	177	28	7.9	106.5	11	34.098754	-119.528745	34.086867	-119.530579	1298.84	439
20140904-1	2014-09-04 14:13:57	367353070	Evergreen State	Oil Tanker	188	32	10	86.6	9.4	33.597567	-118.306533	33.609762	-118.303479	1307.59	623
20140825-6	2014-08-27 01:25:51	303316000	Sea-Land Lightning	Cargo	292	32	10.4	294.2	12.5	33.818667	-118.720167	33.830501	-118.716006	1316.62	427
20140913-1	2014-09-13 10:58:22	367192970	Cat Express	Passenger	30	12	0	33	25.9	33.655993	-118.292508	33.649994	-118.279957	1325.88	214
20170622-12	2017-07-01 20:49:47	256808000	Oregon	Bulk carrier	225	32	11.8	105.5	11.4	34.20934	-120.028091	34.198825	-120.0356	1327.91	441
20160523-B020	2016-05-24 09:36:46	240275000	Finesse	Tanker	274	48	10.3	56.7	9.1	37.666368	-122.791704	37.679414	-122.794005	1346.86	425
20160716-B020	2016-07-21 06:39:11	477135600	Cosco Excellence	Cargo	366	48	11.6	104.7	11.6	34.093955	-119.496643	34.081324	-119.498676	1364.36	333
20140825-6	2014-09-04 04:43:38	366791000	Horizon Reliance	Cargo	274	30	7.8	35.3	11.9	33.592712	-118.293462	33.582716	-118.283574	1376.38	269
20160918-B021	2016-09-19 23:22:36	367169560	Outer Limits	Fishing	15	6	1	257.9	7.1	32.747043	-117.325761	32.75919	-117.321764	1387.04	710
20140825-6	2014-09-04 06:58:16	367004930	Tuffy2	Towing	24	11	2.3	5.4	7.7	33.538193	-118.277244	33.540934	-118.291888	1387.68	520
20140825-6	2014-09-04 15:59:40	367311590	Miss Christi	Passenger	15	4	1.5	38.1	15.8	33.532641	-118.408343	33.524771	-118.396664	1391.05	240
20140825-6	2014-08-29 11:27:10	311056100	Pgs Apollo	Towing	107	19	6.5	299.8	13.5	33.913003	-118.922609	33.923572	-118.914494	1393.72	422
20181021-14	2018-10-21 23:08:17	366855000	Florida	Oil tanker	183	32	10.1	236.2	9.9	37.652056	-122.903158	37.659556	-122.916829	1397.99	619
20170622-12	2017-06-26 03:56:17	220413000	Gunvor Maersk	Cargo	367	42	12.6	104.2	10.4	34.17609	-119.87427	34.162954	-119.874729	1398.41	486
20170622-12	2017-07-02 04:43:35	431296000	Mol Courage	Cargo	316	45	12.8	104.7	9.7	34.221664	-120.039952	34.210305	-120.047489	1400.02	487

Supplementary Table 3, Continued

whale	datetime_local	mmsi	ship_name	ship_type	length (m)	beam (m)	draft (m)	heading (°)	speed (kn)	ais_lat	ais_lon	tag_lat	tag_lon	closest_distance	duration (s)
20140825-6	2014-08-29 22:10:27	566410000	Apl Salalah	Cargo	347	45	11.5	300.5	14.9	33.7244	-118.519406	33.734854	-118.509793	1418.97	319
20160523-B020	2016-05-24 02:56:48	367008020	Arthur Brusco	Tug	35	10	4.2	247.3	7.3	37.715338	-122.769724	37.702299	-122.76773	1447.32	850
20140825-6	2014-08-30 05:25:42	311007500	Oracle	Tanker	229	42	8.2	325.2	7.6	33.728117	-118.479967	33.732609	-118.464927	1448.59	586
20140825-5	2014-08-27 19:23:01	538004470	Grand Pioneer	Cargo	190	32	6.9	300	11.8	33.855252	-118.801627	33.865582	-118.791477	1451.36	301
20140827-4	2014-08-27 15:32:07	367192940	Avalon Express	Passenger	33	7	0	202.7	25.6	33.6355	-118.297	33.631453	-118.281835	1469.06	229
20140901-1	2014-09-01 19:29:57	367192970	Cat Express	Passenger	30	12	0.5	12.2	23.9	33.613266	-118.26521	33.615968	-118.281392	1519.12	140
20140825-6	2014-09-02 17:07:49	367580930	Triumphant	Whale watching	26	10	2.5	12.2	20.7	33.553951	-118.249697	33.552289	-118.23337	1519.18	195
20170622-12	2017-07-01 22:52:24	354886000	Cosco Europe	Cargo	349	46	11.4	284.7	17.2	34.26912	-120.100622	34.2561	-120.108209	1550.64	311
20170706-11	2017-07-07 17:49:43	235739000	La Masquerade	Pleasure	60	10	3.1	171.9	9.5	31.701074	-116.761454	31.70253	-116.777938	1552.51	1004
20140825-6	2014-08-30 12:04:29	338143435	V Tack	Sailing	12	5	1	184	7.2	33.766222	-118.474958	33.767359	-118.491828	1560.18	645
20151016-7	2015-10-29 03:35:27	636091403	Hs Bach	Cargo	245	32	10.1	151.9	17.2	31.933878	-119.539741	31.925203	-119.553255	1561.23	246
20181021-14	2018-10-30 14:14:14	367133160	Tecumseh	Tug	90	15	4.9	356.5	7.7	34.754292	-121.157614	34.751879	-121.175117	1605.97	454
20160523-B020	2016-05-25 17:26:46	636015659	Kota Ekspres	Container	228	37	10.8	55	9.6	37.692404	-122.763885	37.685226	-122.746661	1617.88	393
20170622-12	2017-07-02 05:23:37	477136800	Cosco Kaohsiung	Cargo	349	46	11.6	104.4	17.5	34.219205	-120.058567	34.232715	-120.049868	1629.3	211
20140901-1	2014-09-01 17:48:01	366943960	Catalina Express	Passenger	64	6	4	39.9	12.2	33.651713	-118.298287	33.641374	-118.285599	1635.18	250
20140825-6	2014-09-03 17:50:08	367192940	Avalon Express	Passenger	33	7	0	10.4	25	33.526313	-118.280625	33.529168	-118.297956	1637.07	172
20160716-B020	2016-07-20 10:16:21	538003490	Mindoro Star	Tanker	238	32	10.3	100.8	13.9	34.105723	-119.564189	34.091277	-119.568723	1639	321
20140904-1	2014-09-04 14:25:57	367000160	Yellowfin	Fishing	25	8	2.5	37.2	9.4	33.627978	-118.315272	33.617396	-118.30241	1661.81	466
20140827-4	2014-08-27 10:55:15	636091434	Cap Patton	Cargo	186	28	9.2	280.1	10.6	33.633162	-118.296767	33.647551	-118.290687	1673.18	286
20140825-6	2014-09-03 17:19:55	367004930	Tuffy2	Towing	24	11	2.2	49	7.5	33.544306	-118.320217	33.534321	-118.30651	1673.62	425
20160926-7	2016-09-26 22:48:28	538006575	Chembulk New Orleans	Tanker	174	28	8.9	56.1	12.2	37.577714	-122.972916	37.591156	-122.982032	1674.12	263
20181021-11	2018-11-07 08:26:04	310327000	Grand Princess	Cruise ship	290	36	8.7	300	16.5	33.018777	-120.089733	33.032478	-120.081576	1675.13	221
20140825-6	2014-09-01 06:24:02	308927000	Sirius Voyager	Tanker	275	50	13	239.1	10.5	33.846025	-118.601117	33.830586	-118.596617	1675.88	250
20140825-6	2014-09-05 02:59:40	368686000	Apl Thailand	Cargo	276	40	10	300.4	10.7	33.664685	-118.388418	33.676755	-118.376847	1679.53	321
20140825-5	2014-08-28 09:37:01	366629000	Horizon Spirit	Cargo	272	30	8.9	31.7	11.8	33.630381	-118.270259	33.641305	-118.283305	1681.39	280
20170622-12	2017-07-09 09:25:24	338131069	Fantome	Pleasure	9	3	0.9	246.3	20.8	34.100665	-119.679815	34.114385	-119.687846	1685.7	195
20170622-12	2017-06-26 03:07:32	371073000	Blue Ocean	Cargo	171	27	8.5	96.2	9.3	34.172224	-119.85598	34.157103	-119.860088	1698.89	420
20140825-6	2014-08-30 10:24:05	338076841	Artemus	Sailing	12	3	1	182.4	5.9	33.75769	-118.47585	33.758703	-118.494314	1707.18	571
20140825-5	2014-08-27 20:44:40	477117900	Cscl Autumn	Cargo	335	49	16.8	299.1	11.8	33.816009	-118.713639	33.803423	-118.725621	1720.45	189
20140827-1	2014-08-27 16:48:05	538004470	Grand Pioneer	Cargo	190	32	6.8	275	11.5	33.633062	-118.255348	33.618987	-118.265324	1735.68	261
20140825-5	2014-08-28 10:58:39	367192940	Avalon Express	Passenger	33	7	3	31.4	25.7	33.630686	-118.304923	33.623021	-118.28846	1744.22	72
20160716-B020	2016-07-21 22:09:05	477738500	Oocl London	Cargo	323	43	12.3	106.1	9.8	34.098096	-119.517786	34.081961	-119.519686	1746.19	305
20140827-4	2014-08-27 13:04:10	366943940	Super Express	Passenger	45	7	0	218.3	24.7	33.622828	-118.318063	33.613332	-118.302853	1748.44	140
20151016-5	2015-10-17 23:03:02	367197230	Buck & Ann	Fishing	17	5	1.6	170.6	8.7	34.2	-120.738948	34.204803	-120.720732	1752.34	211
20181021-11	2018-11-02 13:02:41	353156000	Atlantic Highway	Cargo	200	32	8.7	347.1	11.5	36.877673	-122.548709	36.882726	-122.52962	1763.8	224
20140825-6	2014-08-27 02:54:52	564245000	Apl Turquoise	Cargo	294	32	10.3	297.4	13.3	33.812304	-118.704859	33.826167	-118.695	1764.61	251
20170622-12	2017-06-23 02:30:27	367170920	Angelette	Fishing	18	6	1.6	89.4	7.9	34.135887	-119.714538	34.151758	-119.711969	1767.21	654
20160926-7	2016-09-26 22:16:06	367098550	Heidi L Brusco	Tug	35	10	3.6	88.6	8	37.629116	-122.992842	37.614734	-122.983003	1802.85	195
20140825-6	2014-09-04 11:59:26	367345120	Escapade	Sailing	11	2	1	223.6	5.7	33.576043	-118.351311	33.560959	-118.343814	1809.26	600
20140825-6	2014-09-04 02:59:03	371969000	Hanjin Long Beach	Cargo	336	43	10.9	88.8	5.9	33.595844	-118.299165	33.579918	-118.305495	1809.57	240
20140901-1	2014-09-01 17:36:24	367192970	Cat Express	Passenger	30	12	0.5	197.3	24.4	33.635898	-118.264679	33.640377	-118.283593	1813.48	62
20140825-6	2014-09-03 10:25:55	367006280	Catalina King	Passenger	39	11	3.3	224.6	11.5	33.60324	-118.33017	33.590521	-118.31763	1814.13	241
20140825-6	2014-08-30 01:11:18	419555000	Jag Lalit	Tanker	274	48	16.2	319	11.6	33.724876	-118.490391	33.718197	-118.509602	1831.41	120
20140827-4	2014-08-29 12:25:25	367481150	Freebird	Sailing	13	4	1	174.1	6.6	33.159536	-117.40915	33.16295	-117.428422	1835.79	511
20140901-1	2014-09-01 19:13:20	357777000	Buena Ventura	Cargo	209	32	8.4	269.8	11.2	33.636397	-118.280793	33.619785	-118.286418	1848.27	240
20140825-6	2014-08-27 21:48:03	477117900	Cscl Autumn	Cargo	335	49	16.8	299.2	11.8	33.914628	-118.93196	33.927772	-118.919018	1853.13	70
20140913-1	2014-09-13 11:27:00	311000111	Pegasus Voyager	Oil Tanker	276	48	9.8	73.2	12.1	33.607528	-118.268432	33.623301	-118.276154	1857.34	157
20140825-5	2014-08-28 13:27:12	338097391	Mia Tai	Sailing	12	8	1	219.1	6.4	33.58701	-118.2983	33.599871	-118.311658	1882.03	298
20140719-5	2014-07-21 23:48:25	211262460	Kobe Express	Cargo	294	32	10.2	318.7	12.9	38.1368	-123.33015	38.124325	-123.345316	1894.5	151
20160716-B020	2016-07-20 10:28:40	636091307	Noro	Cargo	216	32	9.8	105.3	11.9	34.107103	-119.56383	34.089538	-119.565501	1911.81	171
20170706-11	2017-07-07 01:06:09	367116840	Northern Mariner	Towing	22	8	3.1	108.8	4.8	32.678948	-117.496274	32.694981	-117.504284	1913.6	335
20170706-11	2017-07-08 06:50:41	367130150	Searcher	Fishing	28	8	2.5	315.8	1.1	30.899157	-116.505499	30.915257	-116.49714	1941.63	272
20140827-4	2014-08-27 11:39:46	338122792	As Good as it Gets	Pleasure	19	6	1.6	114.7	10.8	33.63862	-118.29632	33.62133	-118.29979	1942.64	61
20140825-6	2014-09-04 12:02:17	367192940	Avalon Express	Passenger	33	7	0	44.9	25.5	33.571333	-118.358667	33.559233	-118.343253	1947.24	47

Supplementary Table 4. Results of tests of difference that compared differences in vertical dive behavior (dive duration, surface duration, maximum depth, and number of lunges (for feeding dives)) two and four dives before vs. after closest passages (time 0).

Test	Movement	Movement detail	Variable	Encounter category	Encounter subcategory	Number of dives	N dives	N encounters	Method 2 - PDF	Test 2	Result 2
difference	vertical	Dive behavior	dive duration	all	all encounters	2 before/after	723	178	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.632
difference	vertical	Dive behavior	dive duration	all	<400m distance	2 before/after	179	44	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.952
difference	vertical	Dive behavior	dive duration	all	<400m distance & <50 depth	2 before/after	123	30	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.812
difference	vertical	Dive behavior	dive duration	cargo/tanker	all encounters	2 before/after	369	90	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.331
difference	vertical	Dive behavior	dive duration	cargo/tanker	<400m distance	2 before/after	93	23	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.964
difference	vertical	Dive behavior	dive duration	cargo/tanker	<400m distance & <50 depth	2 before/after	57	14	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.808
difference	vertical	Dive behavior	dive duration	passenger	all encounters	2 before/after	88	22	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.702
difference	vertical	Dive behavior	dive duration	passenger	<400m distance	2 before/after	12	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	passenger	<400m distance & <50 depth	2 before/after	4	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	personal	all encounters	2 before/after	162	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.952
difference	vertical	Dive behavior	dive duration	personal	<400m distance	2 before/after	22	5	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	personal	<400m distance & <50 depth	2 before/after	14	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	towing/tug	all encounters	2 before/after	52	13	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.273
difference	vertical	Dive behavior	dive duration	towing/tug	<400m distance	2 before/after	8	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	towing/tug	<400m distance & <50 depth	2 before/after	8	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	whale-watching	all encounters	2 before/after	48	12	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.850
difference	vertical	Dive behavior	dive duration	whale-watching	<400m distance	2 before/after	44	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.700
difference	vertical	Dive behavior	dive duration	whale-watching	<400m distance & <50 depth	2 before/after	40	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	1.000
difference	vertical	Dive behavior	dive duration	feeding	all encounters	2 before/after	305	75	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.655
difference	vertical	Dive behavior	dive duration	feeding	<400m distance	2 before/after	100	25	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.797
difference	vertical	Dive behavior	dive duration	feeding	<400m distance & <50 depth	2 before/after	64	16	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.280
difference	vertical	Dive behavior	dive duration	night surface	all encounters	2 before/after	207	51	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.140
difference	vertical	Dive behavior	dive duration	night surface	<400m distance	2 before/after	41	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.432
difference	vertical	Dive behavior	dive duration	night surface	<400m distance & <50 depth	2 before/after	37	9	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.734
difference	vertical	Dive behavior	dive duration	search/travel	all encounters	2 before/after	163	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.778
difference	vertical	Dive behavior	dive duration	search/travel	<400m distance	2 before/after	30	7	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.688
difference	vertical	Dive behavior	dive duration	search/travel	<400m distance & <50 depth	2 before/after	18	4	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	transition	all encounters	2 before/after	44	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.898
difference	vertical	Dive behavior	dive duration	transition	<400m distance	2 before/after	8	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	transition	<400m distance & <50 depth	2 before/after	4	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	all	all encounters	2 before/after	723	178	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.136
difference	vertical	Dive behavior	surface duration	all	<400m distance	2 before/after	179	44	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.597
difference	vertical	Dive behavior	surface duration	all	<400m distance & <50 depth	2 before/after	123	30	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.196
difference	vertical	Dive behavior	surface duration	cargo/tanker	all encounters	2 before/after	369	90	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.505
difference	vertical	Dive behavior	surface duration	cargo/tanker	<400m distance	2 before/after	93	23	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.156
difference	vertical	Dive behavior	surface duration	cargo/tanker	<400m distance & <50 depth	2 before/after	57	14	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.340
difference	vertical	Dive behavior	surface duration	passenger	all encounters	2 before/after	88	22	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.246
difference	vertical	Dive behavior	surface duration	passenger	<400m distance	2 before/after	12	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	passenger	<400m distance & <50 depth	2 before/after	4	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	personal	all encounters	2 before/after	162	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.284
difference	vertical	Dive behavior	surface duration	personal	<400m distance	2 before/after	22	5	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	personal	<400m distance & <50 depth	2 before/after	14	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	towing/tug	all encounters	2 before/after	52	13	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.685
difference	vertical	Dive behavior	surface duration	towing/tug	<400m distance	2 before/after	8	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	towing/tug	<400m distance & <50 depth	2 before/after	8	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	whale-watching	all encounters	2 before/after	48	12	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.481
difference	vertical	Dive behavior	surface duration	whale-watching	<400m distance	2 before/after	44	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.520
difference	vertical	Dive behavior	surface duration	whale-watching	<400m distance & <50 depth	2 before/after	40	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.625
difference	vertical	Dive behavior	surface duration	feeding	all encounters	2 before/after	305	75	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.729
difference	vertical	Dive behavior	surface duration	feeding	<400m distance	2 before/after	100	25	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.942
difference	vertical	Dive behavior	surface duration	feeding	<400m distance & <50 depth	2 before/after	64	16	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.495
difference	vertical	Dive behavior	surface duration	night surface	all encounters	2 before/after	207	51	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.393
difference	vertical	Dive behavior	surface duration	night surface	<400m distance	2 before/after	41	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.432
difference	vertical	Dive behavior	surface duration	night surface	<400m distance & <50 depth	2 before/after	37	9	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.570
difference	vertical	Dive behavior	surface duration	search/travel	all encounters	2 before/after	163	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.109
difference	vertical	Dive behavior	surface duration	search/travel	<400m distance	2 before/after	30	7	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.688
difference	vertical	Dive behavior	surface duration	search/travel	<400m distance & <50 depth	2 before/after	18	4	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	transition	all encounters	2 before/after	44	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.898
difference	vertical	Dive behavior	surface duration	transition	<400m distance	2 before/after	8	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	transition	<400m distance & <50 depth	2 before/after	4	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	all	all encounters	2 before/after	723	178	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.834
difference	vertical	Dive behavior	max depth	all	<400m distance	2 before/after	179	44	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.021
difference	vertical	Dive behavior	max depth	all	<400m distance & <50 depth	2 before/after	123	30	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.064
difference	vertical	Dive behavior	max depth	cargo/tanker	all encounters	2 before/after	369	90	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.143
difference	vertical	Dive behavior	max depth	cargo/tanker	<400m distance	2 before/after	93	23	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.432
difference	vertical	Dive behavior	max depth	cargo/tanker	<400m distance & <50 depth	2 before/after	57	14	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.194
difference	vertical	Dive behavior	max depth	passenger	all encounters	2 before/after	88	22	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.793
difference	vertical	Dive behavior	max depth	passenger	<400m distance	2 before/after	12	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	passenger	<400m distance & <50 depth	2 before/after	4	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	personal	all encounters	2 before/after	162	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.588
difference	vertical	Dive behavior	max depth	personal	<400m distance	2 before/after	22	5	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	personal	<400m distance & <50 depth	2 before/after	14	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	towing/tug	all encounters	2 before/after	52	13	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.787
difference	vertical	Dive behavior	max depth	towing/tug	<400m distance	2 before/after	8	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	towing/tug	<400m distance & <50 depth	2 before/after	8	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	whale-watching	all encounters	2 before/after	48	12	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.002
difference	vertical	Dive behavior	max depth	whale-watching	<400m distance	2 before/after	44	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.001
difference	vertical	Dive behavior	max depth	whale-watching	<400m distance & <50 depth	2 before/after	40	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.002
difference	vertical	Dive behavior	max depth	feeding	all encounters	2 before/after	305	75	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.007
difference	vertical	Dive behavior	max depth	feeding	<400m distance	2 before/after	100	25	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.001
difference	vertical	Dive behavior	max depth	feeding	<400m distance & <50 depth	2 before/after	64	16	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.016
difference	vertical	Dive behavior	max depth	night surface	all encounters	2 before/after	207	51	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.120
difference	vertical	Dive behavior	max depth	night surface	<400m distance	2 before/after	41	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	1.000
difference	vertical	Dive behavior	max depth	night surface	<400m distance & <50 depth	2 before/after	37	9	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.734
difference	vertical	Dive behavior	max depth	search/travel	all encounters	2 before/after	163	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.356
difference	vertical	Dive behavior	max depth	search/travel	<400m distance	2 before/after	30	7	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.813
difference	vertical	Dive behavior	max depth	search/travel	<400m distance & <50 depth	2 before/after	18	4	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	transition	all encounters	2 before/after	44	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.024

Supplementary Table 4, Continued

Test	Movement	Movement detail	Variable	Encounter category	Encounter subcategory	Number of dives	N dives	N encounters	Method 2 - PDF	Test 2	Result 2
difference	vertical	Dive behavior	max depth	transition	<400m distance	2 before/after	8	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	transition	<400m distance & <50 depth	2 before/after	4	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	lunges	all	all encounters	2 before/after	590	72	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.020
difference	vertical	Dive behavior	lunges	all	<400m distance	2 before/after	183	22	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.500
difference	vertical	Dive behavior	lunges	all	<400m distance & <50 depth	2 before/after	120	14	Compare after-before PDF from mu=0	Wilcox.test 2-sided	1.000
difference	vertical	Dive behavior	lunges	cargo/tanker	all encounters	2 before/after	230	28	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.188
difference	vertical	Dive behavior	lunges	cargo/tanker	<400m distance	2 before/after	63	8	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.500
difference	vertical	Dive behavior	lunges	cargo/tanker	<400m distance & <50 depth	2 before/after	24	24	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	passenger	all encounters	2 before/after	104	13	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.500
difference	vertical	Dive behavior	lunges	passenger	<400m distance	2 before/after	16	16	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	passenger	<400m distance & <50 depth	2 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	personal	all encounters	2 before/after	156	19	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.500
difference	vertical	Dive behavior	lunges	personal	<400m distance	2 before/after	28	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	lunges	personal	<400m distance & <50 depth	2 before/after	20	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	lunges	towing/tug	all encounters	2 before/after	24	24	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	towing/tug	<400m distance	2 before/after	8	8	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	towing/tug	<400m distance & <50 depth	2 before/after	8	8	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	whale-watching	all encounters	2 before/after	68	68	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	whale-watching	<400m distance	2 before/after	68	68	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	whale-watching	<400m distance & <50 depth	2 before/after	68	68	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	feeding	all encounters	2 before/after	590	72	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.020
difference	vertical	Dive behavior	lunges	feeding	<400m distance	2 before/after	183	22	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.500
difference	vertical	Dive behavior	lunges	feeding	<400m distance & <50 depth	2 before/after	120	14	Compare after-before PDF from mu=0	Wilcox.test 2-sided	1.000
difference	vertical	Dive behavior	lunges	night surface	all encounters	2 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	night surface	<400m distance	2 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	night surface	<400m distance & <50 depth	2 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	search/travel	all encounters	2 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	search/travel	<400m distance	2 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	search/travel	<400m distance & <50 depth	2 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	transition	all encounters	2 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	transition	<400m distance	2 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	transition	<400m distance & <50 depth	2 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	dive duration	all	all encounters	4 before/after	1080	178	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.628
difference	vertical	Dive behavior	dive duration	all	<400m distance	4 before/after	267	44	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.885
difference	vertical	Dive behavior	dive duration	all	<400m distance & <50 depth	4 before/after	183	30	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.919
difference	vertical	Dive behavior	dive duration	cargo/tanker	all encounters	4 before/after	549	90	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.373
difference	vertical	Dive behavior	dive duration	cargo/tanker	<400m distance	4 before/after	138	23	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.893
difference	vertical	Dive behavior	dive duration	cargo/tanker	<400m distance & <50 depth	4 before/after	84	14	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.626
difference	vertical	Dive behavior	dive duration	passenger	all encounters	4 before/after	132	22	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.633
difference	vertical	Dive behavior	dive duration	passenger	<400m distance	4 before/after	18	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	passenger	<400m distance & <50 depth	4 before/after	6	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	personal	all encounters	4 before/after	243	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.966
difference	vertical	Dive behavior	dive duration	personal	<400m distance	4 before/after	33	5	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	personal	<400m distance & <50 depth	4 before/after	21	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	towing/tug	all encounters	4 before/after	78	13	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.542
difference	vertical	Dive behavior	dive duration	towing/tug	<400m distance	4 before/after	12	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	towing/tug	<400m distance & <50 depth	4 before/after	12	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	whale-watching	all encounters	4 before/after	72	12	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.677
difference	vertical	Dive behavior	dive duration	whale-watching	<400m distance	4 before/after	66	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.520
difference	vertical	Dive behavior	dive duration	whale-watching	<400m distance & <50 depth	4 before/after	60	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.846
difference	vertical	Dive behavior	dive duration	feeding	all encounters	4 before/after	456	75	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.165
difference	vertical	Dive behavior	dive duration	feeding	<400m distance	4 before/after	150	25	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.442
difference	vertical	Dive behavior	dive duration	feeding	<400m distance & <50 depth	4 before/after	96	16	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.821
difference	vertical	Dive behavior	dive duration	night surface	all encounters	4 before/after	309	51	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.273
difference	vertical	Dive behavior	dive duration	night surface	<400m distance	4 before/after	60	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.322
difference	vertical	Dive behavior	dive duration	night surface	<400m distance & <50 depth	4 before/after	54	9	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.570
difference	vertical	Dive behavior	dive duration	search/travel	all encounters	4 before/after	243	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.588
difference	vertical	Dive behavior	dive duration	search/travel	<400m distance	4 before/after	45	7	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.578
difference	vertical	Dive behavior	dive duration	search/travel	<400m distance & <50 depth	4 before/after	27	4	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	transition	all encounters	4 before/after	66	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.638
difference	vertical	Dive behavior	dive duration	transition	<400m distance	4 before/after	12	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	dive duration	transition	<400m distance & <50 depth	4 before/after	6	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	all	all encounters	4 before/after	1080	178	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.069
difference	vertical	Dive behavior	surface duration	all	<400m distance	4 before/after	267	44	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.724
difference	vertical	Dive behavior	surface duration	all	<400m distance & <50 depth	4 before/after	183	30	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.481
difference	vertical	Dive behavior	surface duration	cargo/tanker	all encounters	4 before/after	549	90	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.395
difference	vertical	Dive behavior	surface duration	cargo/tanker	<400m distance	4 before/after	138	23	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.121
difference	vertical	Dive behavior	surface duration	cargo/tanker	<400m distance & <50 depth	4 before/after	84	14	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.414
difference	vertical	Dive behavior	surface duration	passenger	all encounters	4 before/after	132	22	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.184
difference	vertical	Dive behavior	surface duration	passenger	<400m distance	4 before/after	18	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	passenger	<400m distance & <50 depth	4 before/after	6	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	personal	all encounters	4 before/after	243	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.293
difference	vertical	Dive behavior	surface duration	personal	<400m distance	4 before/after	33	5	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	personal	<400m distance & <50 depth	4 before/after	21	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	towing/tug	all encounters	4 before/after	78	13	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.569
difference	vertical	Dive behavior	surface duration	towing/tug	<400m distance	4 before/after	12	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	towing/tug	<400m distance & <50 depth	4 before/after	12	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	whale-watching	all encounters	4 before/after	72	12	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.233
difference	vertical	Dive behavior	surface duration	whale-watching	<400m distance	4 before/after	66	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.320
difference	vertical	Dive behavior	surface duration	whale-watching	<400m distance & <50 depth	4 before/after	60	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.432
difference	vertical	Dive behavior	surface duration	feeding	all encounters	4 before/after	456	75	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.344
difference	vertical	Dive behavior	surface duration	feeding	<400m distance	4 before/after	150	25	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.653
difference	vertical	Dive behavior	surface duration	feeding	<400m distance & <50 depth	4 before/after	96	16	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.900
difference	vertical	Dive behavior	surface duration	night surface	all encounters	4 before/after	309	51	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.347
difference	vertical	Dive behavior	surface duration	night surface	<400m distance	4 before/after	60	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.375
difference	vertical	Dive behavior	surface duration	night surface	<400m distance & <50 depth	4 before/after	54	9	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.496
difference	vertical	Dive behavior	surface duration	search/travel	all encounters	4 before/after	243	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.140
difference	vertical	Dive behavior	surface duration	search/travel	<400m distance	4 before/after	45	7	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.688
difference	vertical	Dive behavior	surface duration	search/travel	<400m distance & <50 depth	4 before/after	27	4	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	transition	all encounters	4 before/after	66	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.922
difference	vertical	Dive behavior	surface duration	transition	<400m distance	4 before/after	12	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	surface duration	transition	<400m distance & <50 depth	4 before/after	6	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	all	all encounters	4 before/after	1080	178	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.530
difference	vertical	Dive behavior	max depth	all	<400m distance	4 before/after	267	44	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.128
difference	vertical	Dive behavior	max depth	all	<400m distance & <50 depth	4 before/after	183	30	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.145
difference	vertical	Dive behavior	max depth	cargo/tanker	all encounters	4 before/after	549	90	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.223
difference	vertical	Dive behavior	max depth	cargo/tanker	<400m distance	4 before/after	138	23	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.520
difference	vertical	Dive behavior	max depth	cargo/tanker	<400m distance & <50 depth	4 before/after	84	14	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.173
difference	vertical	Dive behavior	max depth	passenger	all encounters	4 before/after	132	22	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.248
difference	vertical	Dive behavior	max depth	passenger	<400m distance	4 before/after	18	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	passenger	<400m distance & <50 depth	4 before/after	6	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small

Supplementary Table 4, Continued

Test	Movement	Movement detail	Variable	Encounter category	Encounter subcategory	Number of dives	N dives	N encounters	Method 2 - PDF	Test 2	Result 2
difference	vertical	Dive behavior	max depth	personal	all encounters	4 before/after	243	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.742
difference	vertical	Dive behavior	max depth	personal	<400m distance	4 before/after	33	5	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	personal	<400m distance & <50 depth	4 before/after	21	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	towing/tug	all encounters	4 before/after	78	13	Compare after-before PDF from mu=0	Wilcox.test 2-sided	1.000
difference	vertical	Dive behavior	max depth	towing/tug	<400m distance	4 before/after	12	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	towing/tug	<400m distance & <50 depth	4 before/after	12	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	whale-watching	all encounters	4 before/after	72	12	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.012
difference	vertical	Dive behavior	max depth	whale-watching	<400m distance	4 before/after	66	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.019
difference	vertical	Dive behavior	max depth	whale-watching	<400m distance & <50 depth	4 before/after	60	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.037
difference	vertical	Dive behavior	max depth	feeding	all encounters	4 before/after	456	75	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.014
difference	vertical	Dive behavior	max depth	feeding	<400m distance	4 before/after	150	25	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.027
difference	vertical	Dive behavior	max depth	feeding	<400m distance & <50 depth	4 before/after	96	16	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.130
difference	vertical	Dive behavior	max depth	night surface	all encounters	4 before/after	309	51	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.146
difference	vertical	Dive behavior	max depth	night surface	<400m distance	4 before/after	60	10	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.922
difference	vertical	Dive behavior	max depth	night surface	<400m distance & <50 depth	4 before/after	54	9	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.820
difference	vertical	Dive behavior	max depth	search/travel	all encounters	4 before/after	243	40	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.102
difference	vertical	Dive behavior	max depth	search/travel	<400m distance	4 before/after	45	7	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.578
difference	vertical	Dive behavior	max depth	search/travel	<400m distance & <50 depth	4 before/after	27	4	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	transition	all encounters	4 before/after	66	11	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.102
difference	vertical	Dive behavior	max depth	transition	<400m distance	4 before/after	12	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	max depth	transition	<400m distance & <50 depth	4 before/after	6	1	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	lunges	all	all encounters	4 before/after	590	72	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.020
difference	vertical	Dive behavior	lunges	all	<400m distance	4 before/after	183	22	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.500
difference	vertical	Dive behavior	lunges	all	<400m distance & <50 depth	4 before/after	120	14	Compare after-before PDF from mu=0	Wilcox.test 2-sided	1.000
difference	vertical	Dive behavior	lunges	cargo/tanker	all encounters	4 before/after	230	28	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.188
difference	vertical	Dive behavior	lunges	cargo/tanker	<400m distance	4 before/after	63	8	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.500
difference	vertical	Dive behavior	lunges	cargo/tanker	<400m distance & <50 depth	4 before/after	24	24	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	passenger	all encounters	4 before/after	104	13	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.500
difference	vertical	Dive behavior	lunges	passenger	<400m distance	4 before/after	16	16	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	passenger	<400m distance & <50 depth	4 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	personal	all encounters	4 before/after	156	19	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.500
difference	vertical	Dive behavior	lunges	personal	<400m distance	4 before/after	28	3	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	lunges	personal	<400m distance & <50 depth	4 before/after	20	2	Compare after-before PDF from mu=0	Wilcox.test 2-sided	n too small
difference	vertical	Dive behavior	lunges	towing/tug	all encounters	4 before/after	24	24	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	towing/tug	<400m distance	4 before/after	8	8	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	towing/tug	<400m distance & <50 depth	4 before/after	8	8	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	whale-watching	all encounters	4 before/after	68	68	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	whale-watching	<400m distance	4 before/after	68	68	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	whale-watching	<400m distance & <50 depth	4 before/after	68	68	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	feeding	all encounters	4 before/after	590	72	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.020
difference	vertical	Dive behavior	lunges	feeding	<400m distance	4 before/after	183	22	Compare after-before PDF from mu=0	Wilcox.test 2-sided	0.500
difference	vertical	Dive behavior	lunges	feeding	<400m distance & <50 depth	4 before/after	120	14	Compare after-before PDF from mu=0	Wilcox.test 2-sided	1.000
difference	vertical	Dive behavior	lunges	night surface	all encounters	4 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	night surface	<400m distance	4 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	night surface	<400m distance & <50 depth	4 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	search/travel	all encounters	4 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	search/travel	<400m distance	4 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	search/travel	<400m distance & <50 depth	4 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	transition	all encounters	4 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	transition	<400m distance	4 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges
difference	vertical	Dive behavior	lunges	transition	<400m distance & <50 depth	4 before/after	0	0	Compare after-before PDF from mu=0	Wilcox.test 2-sided	no lunges

Supplementary Table 5. Results of tests of difference that compared the vertical change in depth 0-2 min vs. 2-4 min prior to the closest passage (time 0) and 0-5 min vs. 5-10 min prior to the closest passage.

Test	Movement	Movement detail	Variable	Encounter category	Encounter subcategory	N whales	N encounters	Method 2	Test	Result
difference	vertical	Dive behavior	depth	all	0-2 min prior vs 2-4 min prior	24	201	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.01
difference	vertical	Dive behavior	depth	feeding	0-2 min prior vs 2-4 min prior	18	83	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.04
difference	vertical	Dive behavior	depth	night/surface	0-2 min prior vs 2-4 min prior	16	62	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.99
difference	vertical	Dive behavior	depth	search/travel	0-2 min prior vs 2-4 min prior	11	45	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.18
difference	vertical	Dive behavior	depth	cargo/tanker	0-2 min prior vs 2-4 min prior	19	103	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.27
difference	vertical	Dive behavior	depth	passenger	0-2 min prior vs 2-4 min prior	6	22	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.77
difference	vertical	Dive behavior	depth	personal	0-2 min prior vs 2-4 min prior	16	44	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.07
difference	vertical	Dive behavior	depth	towing/tug	0-2 min prior vs 2-4 min prior	9	17	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.68
difference	vertical	Dive behavior	depth	whale watching	0-2 min prior vs 2-4 min prior	5	12	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.20
difference	vertical	Dive behavior	depth	all	0-5 min prior vs 5-10 min prior	24	201	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.11
difference	vertical	Dive behavior	depth	feeding	0-5 min prior vs 5-10 min prior	18	83	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.04
difference	vertical	Dive behavior	depth	night/surface	0-5 min prior vs 5-10 min prior	16	62	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.09
difference	vertical	Dive behavior	depth	search/travel	0-5 min prior vs 5-10 min prior	11	45	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.31
difference	vertical	Dive behavior	depth	cargo/tanker	0-5 min prior vs 5-10 min prior	19	103	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.92
difference	vertical	Dive behavior	depth	passenger	0-5 min prior vs 5-10 min prior	6	22	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.50
difference	vertical	Dive behavior	depth	personal	0-5 min prior vs 5-10 min prior	16	44	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.54
difference	vertical	Dive behavior	depth	towing/tug	0-5 min prior vs 5-10 min prior	9	17	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.68
difference	vertical	Dive behavior	depth	whale watching	0-5 min prior vs 5-10 min prior	5	12	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.0005

Supplementary Table 6. Results of tests of difference that compared lateral movement (i.e., speed and heading) 10, 30, and 60 min before vs. after a close vessel passage (time 0).

Test	Movement	Movement detail	Variable	Encounter category	Encounter subcategory	N whales	N encounters	Method 2	Test	Result
difference	lateral	Kinematics	Heading	all	10	5	23	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.5392
difference	lateral	Kinematics	Heading	all	30	5	23	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.3377
difference	lateral	Kinematics	Heading	all	60	5	23	Compare after-before PDF from mu=0	wilcox.test 2-sided	6794
difference	lateral	Kinematics	Heading	cargo/container	10	3	12	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.25
difference	lateral	Kinematics	Heading	cargo/container	30	3	12	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.09766
difference	lateral	Kinematics	Heading	cargo/container	60	3	12	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.3125
difference	lateral	Kinematics	Heading	feeding	10	3	11	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.5771
difference	lateral	Kinematics	Heading	feeding	30	3	11	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.5771
difference	lateral	Kinematics	Heading	feeding	60	3	11	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.8203
difference	lateral	Kinematics	Heading	night/surface	10	1	2	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	night/surface	30	1	2	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	night/surface	60	1	2	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	passenger	10	2	3	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	passenger	30	2	3	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	passenger	60	2	3	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	personal	10	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	personal	30	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	personal	60	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	search/travel	10	3	10	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.9453
difference	lateral	Kinematics	Heading	search/travel	30	3	10	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.1094
difference	lateral	Kinematics	Heading	search/travel	60	3	10	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.1953
difference	lateral	Kinematics	Heading	towing	10	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	towing	30	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	towing	60	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Heading	whale watching	10	3	8	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.8125
difference	lateral	Kinematics	Heading	whale watching	30	3	8	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.4688
difference	lateral	Kinematics	Heading	whale watching	60	3	8	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.09375
difference	lateral	Kinematics	Speed	all	10	5	25	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.7079
difference	lateral	Kinematics	Speed	all	30	5	25	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.6091
difference	lateral	Kinematics	Speed	all	60	5	25	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.5621
difference	lateral	Kinematics	Speed	cargo/container	10	3	12	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.6523
difference	lateral	Kinematics	Speed	cargo/container	30	3	12	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.6523
difference	lateral	Kinematics	Speed	cargo/container	60	3	12	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.5703
difference	lateral	Kinematics	Speed	feeding	10	3	11	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.2402
difference	lateral	Kinematics	Speed	feeding	30	3	11	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.9658
difference	lateral	Kinematics	Speed	feeding	60	3	11	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.5195
difference	lateral	Kinematics	Speed	night/surface	10	1	2	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	night/surface	30	1	2	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	night/surface	60	1	2	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	passenger	10	2	3	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	passenger	30	2	3	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	passenger	60	2	3	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	personal	10	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	personal	30	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	personal	60	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	search/travel	10	3	10	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.5469
difference	lateral	Kinematics	Speed	search/travel	30	3	10	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.6406
difference	lateral	Kinematics	Speed	search/travel	60	3	10	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.7422
difference	lateral	Kinematics	Speed	towing	10	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	towing	30	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	towing	60	0	0	Compare after-before PDF from mu=0	wilcox.test 2-sided	n/a
difference	lateral	Kinematics	Speed	whale watching	10	3	8	Compare after-before PDF from mu=0	wilcox.test 2-sided	9375
difference	lateral	Kinematics	Speed	whale watching	30	3	8	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.5781
difference	lateral	Kinematics	Speed	whale watching	60	3	8	Compare after-before PDF from mu=0	wilcox.test 2-sided	0.2969

Supplementary Table 7. Results of tests of uniqueness that looked for statistically similar dive behavior in other time periods in the dive record compared against dive behavior 2 min around a close passage (time 0), 5 min around a close passage, 0-2 min prior to a close passage, and 0-5 min prior to a close passage.

whale	Distance (m)	Vessel Type	Method	Test	Duration (b/a)	Similar Dives	Duration (b/a)	Similar Dives	Duration (b/a)	Similar Dives	Duration (b/a)	Similar Dives
20140825-5	75.71	Cargo	squared Euclidean distance	xcorr	2 min around	59	2 min prior	22	5 min around	2	5 min prior	3
20140825-5	126.34	Cargo	squared Euclidean distance	xcorr	2 min around	414	2 min prior	237	5 min around	335	5 min prior	8
20140825-5	92.66	Passenger	squared Euclidean distance	xcorr	2 min around	389	2 min prior	n/a	5 min around	56	5 min prior	n/a
20140825-6	26.5	Tanker	squared Euclidean distance	xcorr	2 min around	492	2 min prior	501	5 min around	316	5 min prior	295
20140825-6	86.52	Tanker	squared Euclidean distance	xcorr	2 min around	358	2 min prior	108	5 min around	173	5 min prior	119
20140825-6	110.75	Tanker	squared Euclidean distance	xcorr	2 min around	28	2 min prior	8	5 min around	3	5 min prior	419
20140825-6	15.06	Cargo	squared Euclidean distance	xcorr	2 min around	14	2 min prior	329	5 min around	139	5 min prior	7
20140825-6	26.71	Whale watching	squared Euclidean distance	xcorr	2 min around	177	2 min prior	308	5 min around	25	5 min prior	34
20160523-B020	47.68	Oil Tanker	squared Euclidean distance	xcorr	2 min around	144	2 min prior	90	5 min around	16	5 min prior	16
20160716-B020	90.5	Whale watching	squared Euclidean distance	xcorr	2 min around	372	2 min prior	n/a	5 min around	321	5 min prior	358
20160716-B020	24.49	Whale watching	squared Euclidean distance	xcorr	2 min around	368	2 min prior	30	5 min around	314	5 min prior	357
20160716-B020	9.49	Whale watching	squared Euclidean distance	xcorr	2 min around	365	2 min prior	9	5 min around	329	5 min prior	310
20160717-B021	40.95	Whale watching	squared Euclidean distance	xcorr	2 min around	453	2 min prior	244	5 min around	373	5 min prior	358
20160717-B021	16.91	Whale watching	squared Euclidean distance	xcorr	2 min around	318	2 min prior	n/a	5 min around	377	5 min prior	373
20160717-B021	47.93	Whale watching	squared Euclidean distance	xcorr	2 min around	441	2 min prior	344	5 min around	317	5 min prior	38
20160926-7	37.91	Towing	squared Euclidean distance	xcorr	2 min around	29	2 min prior	25	5 min around	3	5 min prior	2
20170622-12	96.65	Whale watching	squared Euclidean distance	xcorr	2 min around	501	2 min prior	501	5 min around	501	5 min prior	501
20181021-11	141.96	Vehicle carrier	squared Euclidean distance	xcorr	2 min around	103	2 min prior	501	5 min around	116	5 min prior	460
20181021-11	180	Pleasure	squared Euclidean distance	xcorr	2 min around	304	2 min prior	501	5 min around	304	5 min prior	42
20140913-1	87.45	Cargo	squared Euclidean distance	xcorr	2 min around	45	2 min prior	62	5 min around	8	5 min prior	56
20140913-1	133.73	Whale watching	squared Euclidean distance	xcorr	2 min around	99	2 min prior	2	5 min around	62	5 min prior	41

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