A Behavioral Response Study with an Operational Marine Vibrator and Very Low Frequency Whales

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Contents

Abstract

Marine geophysical surveys use high-powered acoustic sources to image subsurface features. Traditional compressed airgun sources produce intense impulsive

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broadband noise, though only frequencies below ~200 Hz are of practical use. Given demand for reduced-impact alternative imaging sources, offshore energy industry partners launched efforts to operationalize marine vibrators (MV) that concentrate output energy at these low frequencies and have lower rise time and peak pressures. These parameters likely reduce or eliminate potential impacts on marine species that hear and/or utilize higher frequencies. However, key questions remain for species that make and rely on low frequency sounds, notably large baleen whales. We conducted controlled exposure experiments to obtain novel baseline behavior and behavioral response data for ESA-listed, very low frequency whales to a full-scale operational MV source in realistic field conditions. The study occurred in the Southern California Bight and focused on blue (*Balaenoptera musculus*) and fin (*Balaenoptera physalus*) whales. A strategic multi-scale tagging approach utilized both longer duration (weeks) dart-attached depth and movement sensing and shorter-term (days) suction-cup attached high-resolution depth, movement, and acoustic tags. Tag data was augmented with passive acoustic monitoring of MV exposure and calling behavior, individual focal follows, photo identification, and body condition measurements made from uncrewed aerial systems. The MV source was an operational, full-scale prototype that produced repeated signals during 30-minute exposure periods with the following source parameters: 5–100 Hz linear FM sweeps, 5-second signal duration, 50% duty cycle, and up to 190 dB re: 1μPa RMS sound pressure level across the band. Two pilot studies using lower power sound sources simulating operational MV signals were conducted in 2022 and 2023. During the primary effort in 2024 with the operational MV source, a total of 33 tags were deployed (32 blue whales and 1 fin whale), yielding nearly 2500 hours of behavioral data. Eight 90-minute experiments (30-min phases before, during, post-exposure) were conducted (six with operational MV signals and two no-noise "control"). Results from pilot studies with simulated MV playbacks indicated mild and temporary avoidance responses by blue whales that were either traveling or feeding in areas of lower prey density. Field observations and initial analyses of the tests with the operational MV source, however, did not indicate broadscale avoidances or strong changes for whales feeding intensely in locations of concentrated prey.

Keywords

Behavioral response · Whales · Marine vibroseis · Controlled exposure experiment · Very low frequency

Introduction

Given the essential importance of the production, reception, and use of sound to marine mammals, there has been both concern and increasingly extensive investigation into the varied effects of anthropogenic noise on biological functions and vital rates (e.g., Southall et al., 2019a, 2021; Duarte et al., 2021; Erbe et al., 2025). Considerable scientific research, technology development, and regulatory assessment have been focused on the potential and measured effects of active sonars on various marine mammal species (e.g., Miller et al., 2012; Southall et al., 2016, 2019b). Certain mid-frequency (1–10 kHz) military sonars have been associated with clear behavioral responses and even mortality of certain species in certain context. However, there are a relatively few of the most powerful systems involved in these events in contrast to other human noise sources.

Additional attention has been focused on low frequency (< 1 kHz) aspects of large industrial noise sources, given the particularly effective, long-range propagation of these frequencies. This has included both research and noise mitigation efforts to understand and reduce the prevalence of radiated low frequency noise from large commercial vessels (e.g., McKenna et al., 2024; Darias-Ohara et al., 2025). Much of the concern and challenges associated with vessel noise are the vast number and wide geographic spread of many commercial shipping routes. Commercial vessel noise is relatively intense—source levels are variable, but some have broadband levels that exceed 190 dB re: 1μPa root-mean-square (RMS) sound pressure level (SPL)—and predominately low frequency, but it is the preponderance in number and continuous presence in many areas that elevate low frequency background noise (Erbe et al., 2025). This raises associated concerns, particularly regarding masking of important signals for species that primarily utilize such sounds for communication, notably baleen whales and phocid seals (e.g., Hatch et al., 2012; Sills et al., 2025).

Similar concerns regarding auditory masking over large areas as well as behavioral disruption of vital biological functions have driven additional investigation into the impacts of seismic surveys for oil and gas exploration and geophysical research (e.g., Dunlop et al., 2017; Kyhn et al., 2019; Gailey et al., 2022; Southall et al., 2023b). Marine geophysical surveys use intense acoustic sources to image subsurface features. Traditional compressed airgun sources are operated in arrays that produce intense (effective source levels can exceed 250 dB re: 1 μPa (peak pressure)), impulsive (tens of ms) signals typically repeated every ~10 s along intermittent survey lines that can run for weeks to months (Erbe et al., 2025). Given their rapid rise time and high peak pressure, these impulsive signals are broadband in nature with some radiated noise energy exceeding 20 kHz, although only frequencies below ~200 Hz are of practical use in geophysical imaging. The predominate radiated noise energy is below 1 kHz, particularly over appreciable propagation ranges. However, the higher frequency noise that is present could have unintended negative biological consequences, including for species that have more sensitive hearing or produce communication signals at higher frequencies.

Given the demonstrated and potential negative effects of marine seismic surveys, the offshore energy industry has launched efforts to develop reduced-impact alternative imaging sources. These have included both modifications of existing seismic airgun technologies as well as completely different technologies including marine vibrators (MV) that concentrate output energy at the low frequencies of the most use in seismic imaging and have reduced impulsive features, including lower rise times and output sound pressure (Alfaro et al., 2023). These signals have much longer duration (typically several seconds) and higher duty cycles (typically 50% or higher). Because MV sources can effectively eliminate radiated noise at frequencies above ~200 Hz, they likely reduce or eliminate potential impacts on marine species that hear and/or primarily utilize higher frequency bands (i.e., dolphins, porpoises, and many pinnipeds). While the goal is to reduce impacts, key questions of effectiveness remain and empirical measurements of response are needed for species that make and rely on low frequency sounds, in particular large baleen whales that have been characterized as very low frequency (VLF) cetaceans (Southall et al. 2019a).

The goal of this study was to experimentally investigate the potential behavioral responses of VLF whales, with a primary focus on blue whales (*Balaenoptera musculus*) and a secondary priority for fin whales (*Balaenoptera physalus*), to full-scale MV sources. Recent studies using controlled exposure experiments (CEEs) with both blue and fin whales provided well-established field methods for tracking, tagging, monitoring, and experimentally exposing whales in behavioral response studies (Southall et al., 2019b, 2023a) within the same study area used here. The overall objective was to apply similar methodological approaches with multi-scale animal-borne tags and systematic CEEs methods to obtain novel direct measurements of potential behavioral responses of endangered VLF whales to operational MVs in realistic free-field conditions.

Methods

The study involved locating, tagging, and tracking blue and fin whales and conducting CEEs. A strategic multi-scale tagging approach was employed utilizing both longer duration (weeks) dart-attached depth and movement sensing and shorter-term (days) suction-cup attached high-resolution depth, movement, and acoustic tags. Tag data was augmented with passive acoustic monitoring of MV exposure and calling behavior, individual focal follows, photo identification, and body condition measurements from uncrewed aerial systems. These complementary methods provided novel baseline behavior and behavioral response data for many individual VLF baleen whales to a full-scale operational MV source in realistic field conditions. The study occurred in various coastal regions of the Southern California Bight off the coast of California (USA), primarily areas within the Santa Barbara Channel near the northern Channel Islands and off San Diego. Field teams, tagging methods, and CEE conditions are described in detail below.

Field Teams, Tagging, and Monitoring Methods

Field effort occurred in early summer months (June–July) of 2022–2024. The first two field campaigns in 2022 and 2023 were week-long pilot efforts to test and evaluate multi-scale tagging approaches and to adapt CEE methods from earlier studies of responses of blue and fin whales to active military sonar systems at higher (3–4 kHz) frequencies (Southall et al., 2019b, 2023a) to exposures with very low frequency (<100 Hz) sounds at relatively lower source levels. The primary field effort in 2024 comprised two 2-week field phases and included the first-ever experimental exposures of VLF whales to very low frequency, high amplitude signals from a full-scale operational MV source.

Field teams included an adaptable configuration of research vessels and personnel. This included one (pilot efforts) or two (primary effort) ~7 m rigid-hull inflatable boat (RHIB) platforms with crews of 3–5 experienced personnel that conducted all research activities near focal whales. These included broadscale scouting to identify potential tagging candidates, animal-borne tag deployments, and photo-identification, visual focal follows, and uncrewed aerial system (UAS) imagery. The RHIB-teams strategically deployed multiple types of archival tag sensors on focal whales in a multi-scale design. Tags with three-dimensional accelerometers and fine-scale depth- and GPS-sensing capabilities were attached with small skin-piercing darts designed for large baleen whales (see Szesciorka et al., 2016). These tags were attached days to weeks ahead of CEEs. Animals were either resighted to serve as focal individuals or were remotely present in the study area during exposure, and behavior was quantified from data recorded days or weeks after initial deployment. Additionally, customized animal tracking solutions (CATS) tags that contain a three-dimensional accelerometer, magnetometer, gyroscope, acoustic recorder, depth sensor, and GPS sensor and attach with suction cups were deployed typically several hours prior to CEEs and remained attached for hours following (see Cade et al., 2021).

The 18.9 m, fast catamaran, research vessel *Shearwater* (operated by the Channel Islands National Marine Sanctuary; National Oceanic and Atmospheric Administration) served as a central research platform in all field efforts, supporting an additional 5–7 research personnel. The *Shearwater* crew conducted visual observations, photo identification, and focal animal tracking in support of RHIB operations and research permit compliance requirements, deployed and recovered passive acoustic recording arrays, and served as a base of operations for simulated MV source experimental sources in the 2022–23 pilot CEEs (additional details below). Passive acoustic monitoring (PAM) of ambient noise, MV exposure signals, and group-level whale calling behavior was conducted from the recording array. It included up to five archival recorders in a vertical line array (VLA) on shock-mounted bungee lines at depths of 10–100 m from drifting GPS-location-sensing surface buoys. SoundTrap ST300 (Ocean Instruments) recorders were used in all years. In 2024, two additional autonomous multichannel acoustic recorders (AMARs; JASCO Applied Sciences) equipped with enhanced low frequency sensitivity hydrophones (M14-V35-301; GeoSpectrum Technologies, Inc.) were added to the PAM VLA.

For the primary field effort in 2024, a larger vessel was added to the research configuration. The 39.6 m M/V *Clean Ocean* based in Long Beach, California, USA, served primarily to safely deploy, operate, and recover the full-scale MV source during CEE trials, but also provided an additional elevated platform for visual observers to support RHIB operations and permit compliance during experiments.

CEE Methods

The experimental approaches to measuring behavior and behavioral responses to MV signal exposures were closely based on well-established methods used in a variety of marine mammal species exposed to simulated and actual military sonars (e.g., Miller et al., 2012; Southall et al., 2016), specifically focal blue (Southall et al., 2019b) and fin whales (Southall et al., 2023a) in the Southern California Bight. Similar vessel positioning to obtain target received levels based on animal movement and in situ noise propagation modeling, baseline and experimental exposure periods, and behavioral measurement approaches were deliberately applied here to enable comparisons between studies.

As many as nine whales were tagged hours to weeks prior to experimental periods, providing baseline data during periods when no MV exposure or dedicated small boat focal follows occurred. One or two individuals were identified from the constellation of tagged whales being monitored as "focal" whales for which the experimental parameters (target exposure received level with associated distance and direction of travel considerations) were selected. Opportunistically, non-focal whales were monitored via the long-duration archival tags or through additional focal follow or compliance related monitoring.

Three experimental phases (each 30 min) were distinguished: *pre-exposure*, *exposure*, and *post-exposure*. Tag-based monitoring with archival sensors, RHIB-based visual follows of focal whales, and PAM using the VLA were maintained throughout the 90-minute CEE. During the *pre-exposure* phase, no MV or any other known anthropogenic noise exposures (other than nearby vessels) occurred. During this phase, the noise source vessel moved slowly and maintained a range of 1 km or greater relative to focal animals to reach target received levels (up to ~130 dB SPL per MV transmission for focal whales, which would nominally yield cumulative sound exposure levels (hereafter cSEL) of ~160 dB re: 1 μPa^2-s for focal whales). The source vessel did not deliberately position directly ahead of the whale's track to minimize contextual aspects of response (Southall et al., 2016, 2019a, 2021). During the *exposure* phase, the sound source vessel was stationary with the sound source deployed and either transmitted MV signals (5-second duration signals at 50% duty cycle; additional parameters specified below) during "MV playback" sessions or deliberately withheld MV exposure during "control" CEEs. During the *post-exposure* phase, no MV or any other known noise was presented, the MV source was recovered, and the sound source vessel resumed transit in a similar manner as in the pre-exposure.

For CEEs with active MV playbacks, different sources with different signal parameters were used in an adaptive manner with escalating output power. Simulated MV sources were used in the two pilot efforts. In 2022, the MV source was a J-11 transducer (Naval Undersea Warfare Center (NUWC)) with a flat frequency response down to ~40 Hz, based on which a 5-second frequency modulated (FM) linear upsweep signal from 40 to 100 Hz (repeated every 10 s = 50% duty cycle) at a measured across-band source level of 163 dB SPL. In 2023, a substantially larger J-15-3 transducer (NUWC) with a flat frequency response down to

~40 Hz was used. The same 40–100 Hz linear upsweep signal and 50% duty cycle was used, but the measured across-band source level was 176 dB SPL. Finally, for the primary research effort in 2024, a full-scale (5-ton dry weight) operational MV source was used, specifically an integrated projector node (IPN) custom source (General Dynamics, Applied Physical Sciences; Alfaro et al., 2023). Signal duration was maintained as 5 s at 50% duty cycle, but the bandwidth was extended, given the very low frequency capability of the IPN, to 5–100 Hz. This linear FM sweep was representative of operational MV signal parameters, with consistently measured source levels for this band of 190 dB SPL.

Results

Successful MV CEEs were completed across three field seasons with increasing intensity and resulting accomplishments (Table 1). Effort in 2022 resulted in 120 hours of tag data from three tagged blue whales, two CEEs at relatively close (0.5–1 km) source to focal whale ranges, and four total MV exposure events. In 2023, 420 hours of tag data were collected from five tagged blue whales, and three MV playback CEEs were conducted at ~1 km ranges, resulting in seven total exposure events. During the primary effort in 2024 with the operational MV source, a total of 33 tags were deployed (32 blue whales, 1 fin whale), yielding nearly 2500 hours of behavioral data with extensive baseline and post-exposure measured behavior. Eight CEEs were conducted (6 MV playbacks, 2 no-noise "control").

Experiments and tag deployments across years took place throughout the Southern California Bight but primarily in coastal areas around San Diego and the northern Channel Islands in the Santa Barbara Channel (Fig. 1).

An example of spatial distribution of whales illustrating the multi-scale design and approach with several focal and many non-focal whales is given in Fig. 2. Two focal whales (Bm240627-T3 and Bm240627-T5) were tagged ~3 hours prior to this CEE and followed accordingly. An additional six whales had been tagged with archival dart-attached tags 2–4 days prior, remained in the broader study area, and were simultaneously exposed during this CEE (#24_01) on 27 June 2024.

For each whale exposure event in all MV playback and control sessions, spatial movement, three-dimensional movement parameters, derived aspects of behavior (e.g., feeding lunge events and rates), and statistical metrics of possible behavioral changes (e.g., Mahalanobis distance) (see DeRuiter et al. 2013; Southall et al.,

Table 1 Field accomplishments by CEE type and resulting whale exposure events

Field season (field days)	CEE Type	Total CEEs	Whale MV exposure events
2022 (5) pilot study	MV playback	2	4 blue whales
2023 (5) pilot study	MV playback	3	7 blue whales
2024 (28)	MV playback	6	31 blue whales; 1 fin whale
	Control	2	11 blue whales
Totals			53 blue whales; 1 fin whale

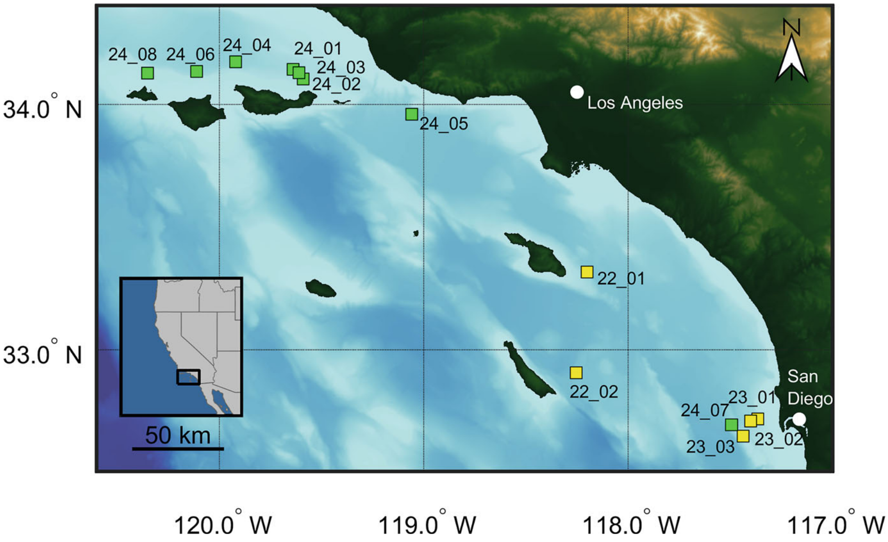

Fig. 1 CEE locations across years in the southern California Bight indicated by year and sequential experimental ID. Yellow squares show the location of CEEs during 2022 and 2023 pilot years. Green squares show the locations of CEEs during the primary effort in 2024 with a full-scale MV source. Bathymetry data is from ETOPO 2022

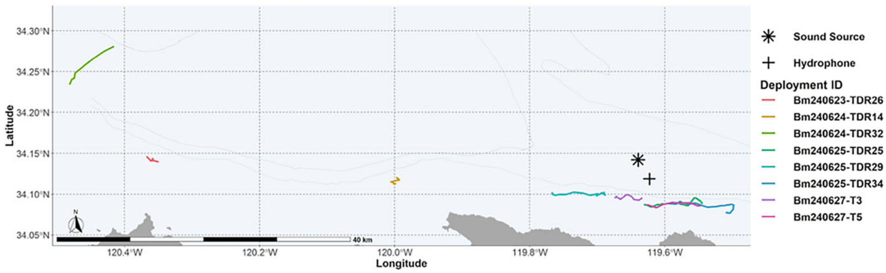

Fig. 2 Tracks from eight simultaneously tagged blue whales tracked during CEE #24_01 on 27 June 2024 shown relative to the MV source location (star symbol) and PAM hydrophone array (plus symbol). Focal whales were affixed with CATS tags (Bm240627-T3 and Bm240627-T4) and were at source-whale distances of 5–8 km at the start of the CEE. Non-focal whales were at greater, variable ranges

2019b, 2023a) were quantified. Examples of spatial maps and detailed behavioral parameters for the same focal individuals from CEE #24_01 shown in Fig. 2 are provided in Figs. 3 and 4.

Results suggested some but limited responses of VLF whales (almost exclusively blue whales) to MV exposures. Results from pilot CEEs using simulated MV playbacks suggested temporary avoidance responses by individual blue whales that were relatively close (~1 km) to MV sources and that were either traveling or feeding in areas of lower prey density. Field observations and initial analyses of the

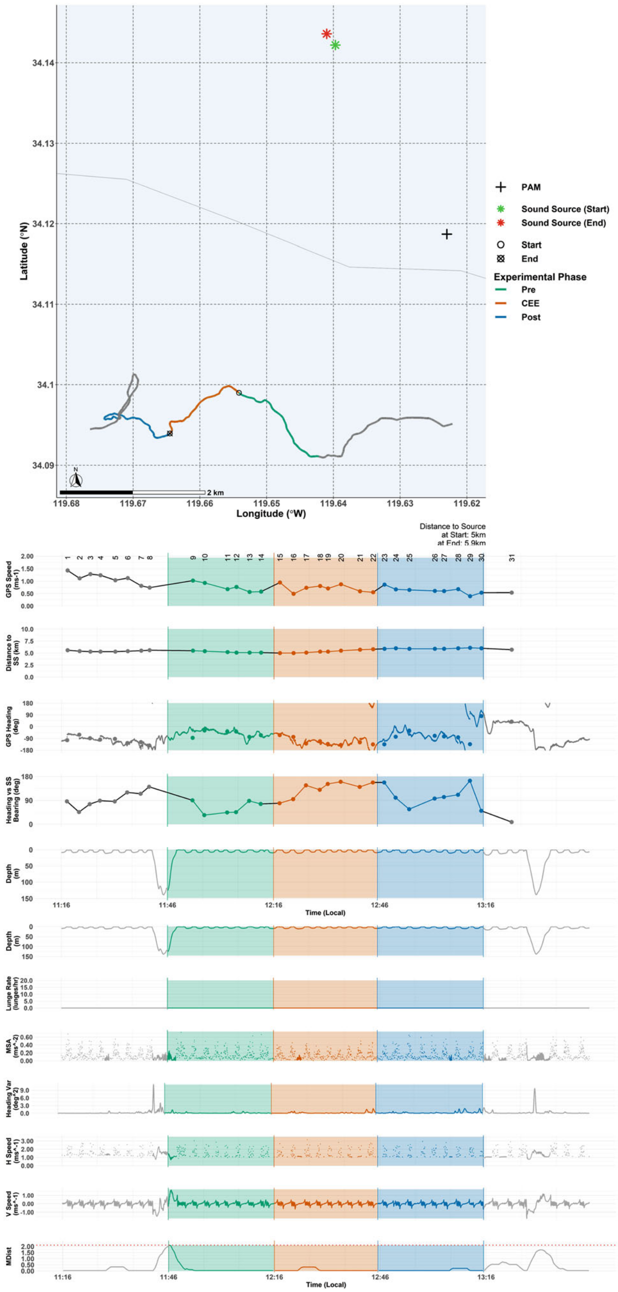

Fig. 3 Movement, diving, and derived behavioral data for focal CATS-tagged blue whale Bm240627-T3 in CEE #24_01. Map (top panel) shows whale-track spatial movement coded by pre-exposure (green), exposure (orange), and post-exposure phases. Data plots for the same phases provide movement and behavioral parameters. Horizontal speed between GPS locations, distance to

tests with the operational MV source, however, did not indicate broadscale avoidances or strong changes in behavior of blue whales feeding intensely in locations of concentrated prey. Finer scale analyses of exposure conditions including received noise levels, and possible changes in diving, foraging, acoustic calling behavior, and swim speed are ongoing.

Fig. 3 (continued) sound source, absolute heading, heading relative to the sound source, and dive depth profiles are shown from top to bottom in middle panel. Dive depth profile, feeding lunge rates, overall body acceleration (minimum specific acceleration), heading variance, tag-based speed parameters, and Mahalanobis distance statistics are shown in the bottom panel

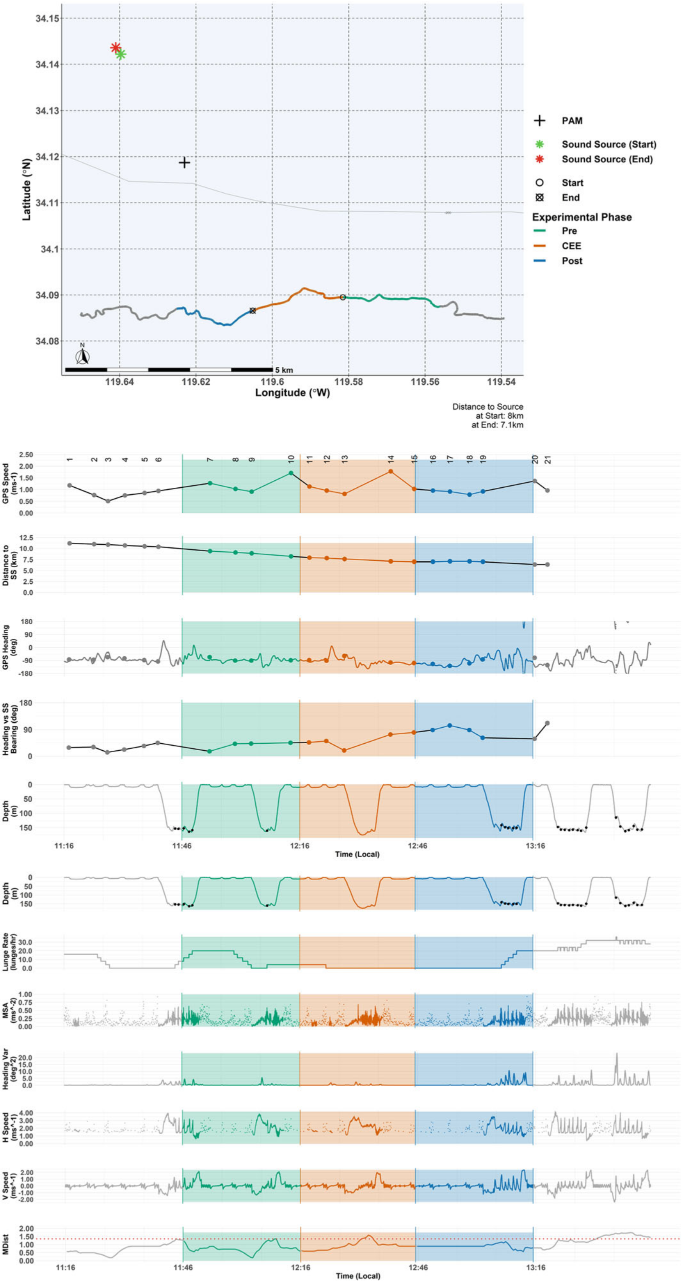

Fig. 4 Movement, diving, and derived behavioral data for focal CATS-tagged blue whale Bm240627-T5 in CEE #24_01. Map (top panel) shows whale-track spatial movement coded by pre-exposure (green), exposure (orange), and post-exposure phases. Data plots for the same phases provide movement and behavioral parameters. Data plots for detailed movement and behavioral parameters are as described in Fig. 3

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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