#### APRIL 02 2025

# Pile driving sound induces short-term behavioral changes in black sea bass (*Centropristis striata*): A field study<sup>a)</sup> **FREE**

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J. Acoust. Soc. Am. 157, 2350–2364 (2025) https://doi.org/10.1121/10.0036347



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# Pile driving sound induces short-term behavioral changes in black sea bass (Centropristis striata): A field study<sup>a)</sup>

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#### **ABSTRACT:**

Offshore wind represents a renewable energy alternative as countries seek to limit the climate-altering effects of fossil fuels. The global investment in wind energy has generated substantial concern, as turbine construction emits high-intensity sounds and the associated impacts on marine fauna remain largely unknown. This in situ experimental study quantified behavioral changes of commercially important black sea bass (Centropristis striata) to nearshore pile driving using video observation. Behavior of caged black sea bass was characterized at near and far sites before and during repeated bouts of two contrasting pile driving techniques: impact and vibratory hammering (VH), over two consecutive days. At impact hammer onset, animals at both sites reduced swimming in midwater, switching to bottom-associated freezing behaviors consistent with heightened alertness. Yet they returned to pre-exposure states during VH and later impact hammer sequences, even at close sites with the highest peak-to-peak sound pressure levels (203–213 dB re 1 $\mu$ Pa). Behavioral changes were more persistent at the near site, but neither distance elicited significant behavioral changes on the second day of exposure. The results indicate that black sea bass behavior may be initially altered by impact hammer sound, but these effects are short-lived and do not continue through multiple exposures or consecutive days. © 2025 Acoustical Society of America. https://doi.org/10.1121/10.0036347

(Received 5 November 2024; revised 5 March 2025; accepted 12 March 2025; published online 2 April 2025) [Editor: Lauren A. Freeman] Pages: 2350-2364

#### I. INTRODUCTION

In response to the growing clean energy demands around the world, offshore wind farms (OSWs) have advanced globally in recent years as a more sustainable alternative energy source (Musial et al., 2023). Despite accelerated investment in OSWs, the impacts on cooccurring fauna from construction, maintenance, operation, and decommission phases need to be addressed as stakeholders and resource managers seek to mitigate potential impacts (Mooney et al., 2020). The construction phase has received the most attention and concern, as multiple foundation types- monopiles, tripods, and jacket foundations, all require massive steel piles to be driven into the seabed through repeated hammering (Wu et al., 2019). Monopiles, by far the most common foundation, utilize piles averaging 5-6 m in diameter, although recent models can be as large as 10 m in diameter (Díaz and Guedes Soares, 2020; Lapastoure et al., 2023; Negro et al., 2017). Pile driving can be done through two contrasting techniques, often both are required: vibratory hammering (VH) and impact hammering

(IH). While VH produces lower amplitude continuous sounds, IH produces high-amplitude impulsive sounds that can propagate up to tens of kilometers through the water column and have the potential to affect diverse marine fauna (Amaral et al., 2020; Brandt et al., 2011).

Previous studies have connected pile driving sound to behavioral and physical detriment to fishes. In controlled laboratory studies, behavioral impacts resulting from impulsive anthropogenic sound included disruption to group cohesion (Herbert-Read et al., 2017), reflexive startling (Spiga et al., 2017), and reduced feeding (Stanley et al., 2023), although habituation was also noted in several species (Kastelein et al., 2017; Stanley et al., 2023). European seabass (Dicentrarchus labrax) are sensitive to both impulsive and continuous pile driving sounds, displaying heightened respiration rates and lowered anti-predator avoidance (Spiga et al., 2017). With high-intensity sound exposures, hearing systems and other anatomical structures can also be physically damaged, which can manifest as inner ear hair cell injury and barotrauma, particularly affecting fish with swim bladders (Casper et al., 2013; Halvorsen et al., 2012). In the field, physiological and behavioral detriment has also been observed with the onset of impact pile driving sound in several marine species. Heightened stress, indicated by oxygen

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<sup>&</sup>lt;sup>a)</sup>This paper is part of a special issue on Climate Change: How the Sound of the Planet Reflects the Health of the Planet.

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uptake, following pile driving sound commencement has been reported in European sea bass (Debusschere et al., 2016) and black seabream (Spondyliosoma cantharus) (Bruintjes et al., 2017). Similar field-based studies have also demonstrated behavioral changes, such as reduced swimming and conspecific interaction (Debusschere et al., 2017), changes in depth (Hawkins et al., 2014), and abrupt changes in swimming direction and speed with the onset of impact hammer stimulus (Mueller-Blenkle et al., 2010; Hawkins et al., 2014). Free-ranging animals have more ability to remove themselves from the stressor, although species with high site fidelity may not actually leave (Iafrate et al., 2016), and any displacement from their preferred habitat may have subsequent consequences. For those taxa, it is critical to understand the behavioral consequences of sound exposure from OSW development.

Along the northeast Atlantic seaboard of the United States, over a dozen active leases for OSWs are in various stages of planning, construction, or operation (Musial et al., 2023). This region is also home to a number of economically valuable species, including black sea bass (Centropristis striata). The northern stock of black sea bass can be found all along the Mid-Atlantic bight, overlapping with the majority of leased OSWs (Moser and Shepherd, 2009, see boem.gov). They seasonally migrate offshore during the winter and have a high degree of site fidelity when returning to coastal areas for summer (Moser and Shepherd, 2009; Miller et al., 2016). Given the expected increase in pile driving sound exposure in areas inhabited by black sea bass, it is vital to study potential impacts on this species now.

Black sea bass can perceive sounds below 2000 Hz, with the greatest sensitivity from 150 to 300 Hz (Stanley et al., 2020). This "low-frequency" hearing range and sensitivity overlaps with the predominant acoustic energy produced by pile driving: around 100 to 2000 Hz for IH (Bailey et al., 2010), and at the vibrational frequency and associated harmonics of the vibratory hammer (typically below 20-40 Hz; Koschinski and Lüdemann, 2020). As black sea bass have shown brief avoidance responses associated with other acoustic disturbances, such as sound from vessel traffic, particularly below 1 kHz (Secor et al., 2021), it stands to reason that they may also behaviorally respond to pile driving sound. Initial behavioral studies of black sea bass in large tanks have reported a decrease in active behaviors replaced by sinking, pivoting, and resting, when exposed to pile driving sound playback (Stanley et al., 2023). This change was particularly strong upon initial exposure, diminishing throughout a 15-min period. In a similar Serranid taxa, European sea bass (Dicentrarchus labrax), this movement toward the bottom and freezing is considered an antipredator response, associated with a threat (Malavasi et al., 2008). Indeed, immobility, coupled with heightened alertness, is an adaptive reaction to a perceived threat in many fish and is often associated with alterations in respiration and heart rate (Yoshida, 2021).

These controlled studies provide key insight into how black sea bass behaviors may be influenced by pile driving. Despite this preliminary work, field-based studies examining pile driving sound impacts on black sea bass, and many other taxa of interest, are lacking (Popper *et al.*, 2022). The sensory environment, behaviors, and acoustic field, including propagation and reflections, can be altered by the tank itself and the likely-distorted replayed sounds (Jones *et al.*, 2019; Jézéquel *et al.*, 2022a). Consequently, it can be challenging to accurately extrapolate aquaria-based data to *in situ* circumstances and needed management scenarios (Popper *et al.*, 2022). Thus, there is a clear need to address how black sea bass may respond to actual pile driving sound in a field-based setting.

This study sought to quantify potential behavioral changes of black sea bass during in situ pile driving in a nearshore marine environment. Responses were compared to pre-exposure baseline activity patterns. Animals were maintained in natural sea bass habitat via open sea cages at two different distances from the sound source to gauge received level-based impacts. Fish behavior and position in the cages were tracked through multiple IH (transient, impulsive, and high-intensity) and VH (continuous, loweramplitude) sequences in a day. Then, to evaluate multi-day consequences, the same fish were exposed to an identical treatment on a second, consecutive day. These experimental methods provide the first field-based investigation into black sea bass behavior to actual pile driving (1) upon initial onset, (2) through the course of multiple IH and VH sequences, over two consecutive days, and (3) at two biologically relevant received levels.

# **II. METHODS**

#### A. Fish acquisition and maintenance

A total of 46 adults black sea bass (Centropristis striata) were wild-caught via line fishing from Vineyard Sound (Massachusetts, USA) during August and September 2022 under a Massachusetts Division of Marine Fisheries Scientific Collecting Permit. Since black sea bass exhibit differences in hearing sensitivity with age and size (Stanley et al., 2020), we used medium-sized, sub-adult to adult individuals (range: 16-35 cm total length). This was a compromise between the greater hearing sensitivity of smaller fish and the commercial importance and visibility of larger fish in costal North Atlantic waters. Any fish that was deemed not healthy, owing to capture or otherwise, was returned to the local waters and not used in experiments. Prior to the experiment, fish were held in groups of 3-6 animals within a 1.2 or 2.0 m diameter fiberglass tanks for a minimum of 24 h before being used in the study. Tanks were constantly supplied with unfiltered ambient seawater pumped directly from Vineyard Sound (temperature range 21.0 °C–22.5 °C). All holding tanks were exposed to natural light cycles and fish were fed every other day with pieces of locally caught squid. All animals were fed at consistent times before fish were moved into experimental cages (24h before pile

https://doi.org/10.1121/10.0036347



driving and the start of the experiment), and then no feeding occurred for the two experimental days. This study was carried out in accordance with the principles of the Basel Declaration and recommendations and approval of the Wods Hole Oceanographic Institution (WHOI) Institutional Animal Care and Use Committee Scientific Protocol No. 27148.01 (Silverman *et al.*, 2014).

# B. Location and pile driving characteristics

Pile driving was conducted for 11 days between September 20th and October 12th, 2022, off a pier at WHOI (Woods Hole, MA). Pile driving operational methods were identical to previous experiments (see Cones *et al.*, 2022, and Jézéquel *et al.*, 2022b, for additional details), and will only be briefly described here. A combination of two techniques was used to repeatedly drive a cylindrical steel pile (length, 10 m; diameter, 0.3 m; wall thickness, 0.02 m) into the ground. First, a steel impact hammer (weight, 1500 kg) was dropped onto the pile from a height of 1.2 m at a rate of approximately 10 strikes/min, producing high intensity, impulsive sounds [Fig. 1(A)]. The IH sequences lasted 15 min, resulting in the steel pile penetrating at least 3 m into the seabed. Next, a vibratory hammer (weight, 212 kg; H&M model 135; vibrational frequency, 19.2 Hz, or 1150 blows per minute) was used to pull the pile out of the substrate and reposition it in an adjacent location for another round of the IH pile driving. The duration of VH sequences varied but typically lasted about 10 min. There was a 3–5-min period of no sound before and after VH while the two hammer types were swapped. This sequence was repeated five times per experiment day, with pile driving activity commencing at 13:00 and lasting for  $\sim$ 3 h. Hence, in total, each black sea bass individual was exposed to five IH and up to five VH sequences per day, always starting with the IH exposure.

#### C. Acoustic measurements and analysis

Sound pressure arising from pile driving was recorded using two different types of calibrated recorders located at various distances extending from the pile. Similar to the cages, the precise distance of each recorder varied during





FIG. 1. Diagram of *in situ* pile driving set-up. (A) Side view of the pile driving apparatus, with the crane and impact hammer hovering over the pile (red star). Blue arrows denote the underwater locations of the two close cages of black sea bass. (B) Top view of the entire set up, with two close cages (blue squares) located within 4-13 m of the pile (red star), and two far cages located around 60 m from the pile. (C) Design of the cages with two black sea bass inside each (eight fish total per experimental day). The approximate locations of sound recorders in relation to cages and pile are shown with gray rectangles. Note that each treatment (near and far) consisted of two identical cages, while only one is shown for each. Each cage was outfitted with two GoPro's, one on the top and one on the side net. Additionally, a square crate was secured inside each cage for habitat.

JASA https://doi.org/10.1121/10.0036347

and among days as the pile shifted but was re-measured before each IH sequence.

Two Snap recorders (Loggerhead Instruments, Sarasota, FL) were located approximately 5 and 9 m from pile hammering [sensitivity, -209.7 and -210.0 dB re  $1\mu$ Pa/V, respectively, Fig. 1(C)]. The farthest site was measured with a SoundTrap 600 STD (Ocean Instruments, Auckland, NZ), placed approximately 55 m from the sound source [sensitivity, -176.0 dB re  $1\mu$ Pa/V, Fig. 1(C)]. Finally, one full day of pile driving was analyzed from a third Snap recorder (sensitivity, -210.5 dB re  $1\mu$ Pa/V) located beside one of the black sea bass near-site cages, ranging 7–10 m (mean, 8.3 m) from the pile over the course of the day analyzed.

Sound files were first bandpass filtered around 50–4000 Hz to focus on more biologically relevant frequencies for the black sea bass's hearing range (Stanley *et al.*, 2020). For the IH sequences, intensity was assessed by computing 0-peak sound pressure levels (SPL<sub>0-pk</sub>; dB re 1  $\mu$ Pa) and peak-to-peak sound pressure levels (SPL<sub>pp</sub>; dB re 1  $\mu$ Pa) for each strike. Next, single strike sound exposure levels (SEL<sub>ss</sub>; dB re 1  $\mu$ Pa<sup>2</sup> × s) were calculated by integrating the time series over the pulse length containing 90% of the signal energy, and cumulative sound exposure levels (SEL<sub>cum</sub>; dB re 1  $\mu$ Pa<sup>2</sup> × s) for each IH sequence and the full day were calculated using the following equation:

$$SEL_{cum} = 10 \log_{10} \left[ \sum_{n=1}^{n} (SEL_{ss}) dt \right], \tag{1}$$

where *n* is the *n*th impulse (following BOEM, 2023).

The VH sound levels were also assessed at these same distances using root-mean-squared sound pressure levels (SPL<sub>rms</sub>), which were calculated over 1-s durations and reported as mean  $\pm$  standard deviation.

The acoustic content of IH and VH were further examined and compared using power spectral density (PSD) curves for three distances, without any filtering. Ambient sound at the experimental site was similarly plotted for comparison. This background sound consisted of ten 5-s clips absent from boat or pile driving sound recorded with the SoundTrap, which had the highest sensitivity.

# D. Experimental design

To ensure a sufficient supply of black sea bass were located at a particular location and acoustic received level, animals were contained in *in situ*,  $3.4 \text{ m}^3$  cubic cages  $(1.5 \times 1.5 \times 1.5 \text{ m})$ . These cages were constructed with a polyvinyl chloride (PVC) frame (3.8 cm diameter pipe) and enclosed with 1.5 cm eye-size knotless polyester mesh netting, resulting in an acoustically transparent enclosing structure. Black sea bass tend to naturally aggregate around structures, thus a rectangular plastic "milk" crate  $(0.33 \times 0.33 \times 0.28 \text{ m})$  was provided in each cage; attached to the cage to provide a general replica of benthic structures, but the open side faced down so that the fish could not hide

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inside. Small holes were cut on the top and side of the cage to allow two underwater cameras (GoPro Hero 8 Black, San Mateo, CA) to be attached on the outside for easy deployment but provide unobstructed views. GoPros were provided with external batteries for long-term continuous recording (up to 3.5 h).

To test for any potential dose-dependent responses, fish were observed at two general distances from the sound source: "near" and "far" from the pile driving. Because the pile had to be repositioned each time after being driven into the seabed, the precise distance of each cage and received levels at the cages varied slightly among days and IH sequences within a day. Exact measurements were taken for each cage after every repositioning of the pile. Two cages were placed in both the "near" group (within 4.2-13.0 m), and the "far" group [56.6–62.6 m from the pile [Fig. 1(B)]. The day before experiments, two black sea bass were transferred from holding tanks into each cage via a hinged door on top of each cage. Upon latching the cage with fish inside, the cage was lowered to the seabed (4-6 m depth) and the fish were allowed to acclimatize in the cages overnight. At least 30 minutes before pile driving began, freedivers attached the cameras to the outside of each cage using Velcro straps, one on the top center facing down and one on the side net, about 0.5 m above the bottom of the cage [Fig. 1(C)]. This process was quick ( $<5 \min \text{ per cage}$ ) and required no opening or lifting of the cages, thus it was believed to be minimally disturbing for the fish. Still, 10 min of recovery was permitted before recording and annotating any behavioral observations. The "pre" control period started 20 min before the pile driving sound exposure started. This period was considered "normal," unaltered behavior, where fish exhibited many of the natural daytime behaviors typical of black sea bass, such as swimming and alternating between the bottom and the water column (Cullen and Stevens, 2017; Secor et al., 2021). This period was used as a baseline to determine behavioral changes once pile driving started. To evaluate habituation on a multi-day level, each pair of black sea bass was exposed to two consecutive days of pile driving. Following the second exposure, experimental black sea bass were released back into the Vineyard Sound.

#### E. Video Processing

#### 1. Behavioral analysis

Videos were manually analyzed in the program BORIS (version 8.20.4) (see Friard and Gamba, 2016) for fish behavior and position in the water column. An initial range of behaviors was assessed following Stanley *et al.* (2023). However, after preliminary analyses and given the constraints of water turbidity, behaviors exhibited, and subsequent analyses available, behaviors were simplified into these categories: swimming, stationary on the bottom, or hovering; and midwater or at the bottom, for behavior and position respectively (see Table I for a list of behaviors and full descriptions), without any context-specific quantifiers.



Ethogram glossary <sup>a</sup>									
Behavior	Definition	Position	Definition						
Stationary	Maintains position on the cage floor	At bottom	Fish is on or within 15-20 cm of bottom						
Swimming	Using fins to move through the water	Midwater	Fish is in the water column, not associated with bottom						
Hovering	Maintains position while suspended in the water column								
	Not visible		Fish is out of view of both camera angles, all other behaviors and positions are canceled out						

TABLE I. Description for each behavior and position used in video analysis.

<sup>a</sup>Fish were annotated with both a behavior and a position when they were visible if both could clearly be determined. If the fish went offscreen, they were labeled as "not visible," canceling out all other behaviors or positions.

For example, fast swimming, often a startle response, was not differentiated from casual exploratory swimming. Similarly, sheltering or freezing, a known reaction of many fish to threatening stimuli (Malavasi *et al.*, 2008; Yoshida, 2021), could not be visually distinguished in this set-up from resting, a natural behavior for black sea bass (Cullen and Stevens, 2017), although both behaviors likely occurred throughout the experiment. Hovering can also be indicative of freezing but was relatively rare, so analysis was not conducted on that behavior specifically, although it was worth noting that it is an absence of swimming or stationary on the bottom.

After comparing several methods with continuously analyzed videos, a subsampling schedule of 5-min on, 5-min off was determined to sufficiently capture both short-term reactions and long-duration behavioral trends. Intervals were framed around the onset of IH pile driving, beginning 20 min before the start of pile driving. For the pre-period, and every IH and VH sequence thereafter, two 5-min sequences were annotated, thus capturing the first 5 min and last 5 min of each IH sequence [Fig. 2(A)]. Due to occasional camera failure or poor water clarity, a subset of videos was analyzed, and within these videos, the duration able to be annotated varied. Shifts to the subsampling schedule occurred if IH paused for any reason. Despite these adjustments, analysis intervals were always exactly 5 min long, with two observation intervals completed for each treatment. After these adjustments, a resulting 16.5 h of video was manually annotated.

As to not disturb behaviors (e.g., through tagging) fish were not marked in any way and occasionally went offscreen. Thus, it was not possible to assess behavioral responses by specific individuals throughout the experiment and no attempt was made to differentiate fish within a cage. If at any point the fish went off screen or were obstructed, their behavior and position were labeled "not visible."

# 2. Statistical analyses

Black sea bass behavior was analyzed with two different metrics: duration of time spent in each behavioral state to compare between treatments (close vs far cages, day 1 vs



FIG. 2. Video observation of black sea bass. (A) Observation schedule for video analysis, demonstrating the order of 5-min intervals annotated during pre ("Pre 1" and "Pre 2"), and first two IH and VH sequences. For days with longer video durations, the pattern continued. Each labeled box corresponded with a 5-min annotated interval, unlabeled boxes were also approximately 5-min, although it varied based on visibility and external factors, duration of VH, or any pauses in IH. (B) Top view example, one black sea bass can be seen swimming in the midwater. (C) Side view example, two fish can be seen at the bottom.

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day 2), and point sampling of the percentage of fish in each behavioral state before and after the first IH onset. All statistical analysis and figure production was done in MATLAB R2023A (Mathworks, Natick, MA).

Duration metrics were employed to assess behavioral changes between "Near" and "Far" cages throughout multiple IH sequences over a day, as well as gauge reactions to the IH onset between the first exposure and second day exposure. For each individual fish, duration was calculated for each behavioral state based on the percent of time visible, after subtracting the duration of "not visible" time from total seconds (300 s per observation interval). Then, since fish were not uniquely identifiable, the two fish in each cage were averaged together forming one sample point. Averaging between two fish per sample not only increased the visibility of the targets but also minimized the impacts of individual variation in behavioral responses, allowing us to examine broader trends. If one fish was not observed the entire period, it was treated as null for that period and not included in any averaging. Cages were grouped by treatment—near vs far, day 1 vs day 2 (sample size for each treatment are summarized in Table II). A paired t-test was then used to statistically compare each observation interval to their corresponding pre-control period (average of pre1 and pre2). Observation intervals with a sample size of less than three were not statistically evaluated or plotted.

To evaluate day 1 vs day 2 treatments at the initial onset of IH, a magnitude of change was calculated between preand the first 5-min IH interval. Percent of visible time spent in each behavior and position was calculated as an average for pre1 and pre2 and subtracted from IH1. Thus, behaviors that increased under IH conditions were positive, and behaviors that decreased were negative.

Durations of "not visible" times were averaged for each observation period by treatment. To test whether significant shifts in visibility throughout the day occurred and could influence results, a Kruskal-Wallis test (KW) was administered on the slightly non-normal data.

With the inconsistent visibility of fish inherent in the experimental design, a second analysis method was implemented to evaluate behavioral trends irrespective of duration and ensure patterns were not driven by a few visible fish. In addition to the duration of behaviors, point sampling at a higher resolution (every 3 s) assessed the proportion of fish in each behavioral state before and during the onset of the first exposure. Only near cages on the first day of exposure were included in this, to examine fine scale behavioral trends in individual fish with the most impacted treatment.

TABLE II. Number of cages for each treatment, representing sample size at the start of the experiment; each cage contained two fish. A total of 36 individuals were analyzed.

	Near	Far
Day 1	6	4
Day 2	4	4

Each visible black sea bass was treated as an independent sample for this analysis. A moving average line, taken every four samples (12 s), with standard deviation shading was overlayed. The proportion of fish exhibiting a given behavioral state before and after IH onset was statistically assessed with two-sample t-tests. To gauge the precise timing of greatest impact, we compared the pre-period (5-min) to the first minute, second minute, and third through fifth minutes of IH exposure.

#### **III. RESULTS**

#### A. Sound characterization

For simplicity, an example day of underwater sound pressure recordings, co-located with a near-site black sea bass cage, was analyzed from an entire pile driving experiment (including five IH and four VH sequences) (see Table III and Fig. 3). Given the *in situ* and realistic nature of this actual pile driving, strike amplitudes varied as the pile changed locations between IH sequences [Fig. 3(A)]. Even within an IH sequence, pulse amplitudes varied slightly as the pile was driven into the sediment [Fig. 3(B)]. The variability in these metrics across impulses reflects that which a wild black sea bass may experience near an offshore pile driving site.

To address representative received levels at precise distances relevant to the black sea bass cages, analyses from two individual IH sequences, as well as a representative VH sequence, were quantified (Table III). The near site was always characterized by higher SPL compared to the far site (>30 dB difference). For example, peak-to-peak SPLs were 212.6  $\pm$  1.3 dB re 1 µPa (mean  $\pm$  SD) at the near site, and 178.3  $\pm$  2.7 at the far site. Similarly, SEL<sub>cum</sub> for a single sequence of pile driving strikes was 186.2  $\pm$  0.4 dB re 1 µPa<sup>2</sup> × s but dropped by approximately 33 dB to 153.7  $\pm$  1.0 re 1 µPa<sup>2</sup> × s at the far site.

The acoustic power generated by both IH and VH were particularly elevated in the low frequencies below 1000 Hz, even at the far site cages (Fig. 4). In contrast to IH, VH reported lower overall acoustic power in the same frequency band [Fig. 4(B)], although it was still more than 10 dB above ambient sound levels at 55 m (Table III).

#### **B.** Behavioral responses

Overall, IH pile driving elicited increased stationary behaviors and association with the bottom, and concomitant declines in time swimming and use of the water column. Animals returned to behavior conditions that were not significantly different from "pre" during each intermittent VH sequence in every treatment (Figs. 5 and 6), including immediately after the first IH sequence. The strength of this response to IH varied based on the distance to the pile and the novelty of exposure.

For Day 1 exposures, time spent swimming significantly declined in both the near and far cages during the first 5 min of the first IH sequence [paired t-test, near: t(5) = 2.81, p = 0.0375, far: t(3) = 5.80, p = 0.0102, see



	Distance from sound source (m)	Impact Hammer					Vibratory Hammer
		SPL <sub>0-pk</sub> (dB re 1 µPa)	SPL <sub>pp</sub> (dB re 1 µPa)	$\frac{\text{SEL}_{\text{ss}}}{(\text{dB re 1 } \mu\text{Pa}^2 \times \text{s})}$	$\begin{array}{c} \text{SEL}_{\text{cum}} \\ (\text{dB re 1 } \mu\text{Pa}^2 \times \text{s}) \\ \text{Single sequence} \end{array}$	$\begin{array}{c} \text{SEL}_{\text{cum}} \\ (\text{dB re 1 } \mu \text{Pa}^2 \times \text{s}) \\ \text{Full day} \end{array}$	SPL <sub>rms</sub> (dB re 1 µPa)
Individual sequence <sup>a</sup>	4.9 m	$206.8 \pm 1.6$	$212.6\pm1.3$	$165.6\pm0.8$	$186.2 \pm 0.4$	_	$138.5\pm5.9$
	8.7 m	$196.9\pm1.9$	$203.2\pm1.7$	$156.2 \pm 1.4$	$176.8\pm1.3$	_	$132.0\pm3.8$
	55.4 m	$172.3\pm2.8$	$178.3\pm2.7$	$132.7\pm2.2$	$153.7\pm1.0$	_	$115.6\pm3.7$
Full day of PD <sup>b</sup>	7 - 10  m (mean = 8.3  m)	$203.8\pm2.4$	$209.8\pm2.5$	$162.4\pm1.9$	$183.2\pm1.8$	190.4	$134.5\pm8.0$

TABLE III. Acoustic levels of IH and VH measured at three different distances from the pile (top), as well as a full day of pile driving (5 IH and 4 VH sequences) recorded at one of the near cages (bottom). All values are reported as mean  $\pm$  standard deviation.

<sup>a</sup>SPLs and SELs were calculated over two different IH sequences at the exact distances of 4.9, 8.7, and 55.4 m on the 26th and 27th of September 2022, while the SPLrms was calculated for one VH sequence at the same distances on the 27th of September. SELcum were calculated for 113 strikes at each distance.

<sup>b</sup>Analysis from an entire day of pile driving on the 26th of September 2022, averaged over 5 IH and 4 VH sequences. The SELcum for a single IH sequence was calculated over an average of 115 strikes, while the SELcum over a full day of pile driving was calculated over 577 strikes.

Fig. 5]. Stationary on the bottom correspondingly increased [paired t-test, near: t(5) = -3.08, p = 0.0276; far: t(3) = -4.77, p = 0.0175, see Fig. 5]. Additionally, at the near cages, the altered behavioral state persisted through the entire first IH, as the average of the first and last 5 min of IH

significantly differed from pre levels in swimming [paired ttest, t(5) = 2.99, p = 0.0306) and stationary duration (t(5) = -3.45, p = 0.0183, see Fig. 5]. For the far cages, fish activity patterns returned to no difference from the pre by the end (last 5 min) of the first IH sequence.



FIG. 3. (A) One full day of pile driving, showing sound pressure ( $\mu$ Pa) of five bouts of high intensity IH separated by four lower amplitude continuous VH sequences, recorded 7–10 m from the pile driving. (B) Zoomed in view of the first IH sequence (left box in red) represented in sound pressure ( $\mu$ Pa). Each strike is clearly visible as a short duration, high intensity impulse. (C) A section of VH (right box in purple) characterized by continuous, lower intensity sound. Note that the ranges of values reported on the y axes differ between (B) and (C).



FIG. 4. The PSDs of IH (A) and VH (B) at three distances from the sound source, compared to ambient sound (black line), recorded with the SoundTrap. (A) Impact hammer: Averaged PSD of each strike from two IH sequences. Grey shading represents the standard deviation. (B) Vibratory hammer: PSD of a single VH sequence from 4.9, 8.7, and 55.4 m. Despite lower acoustic power than IH, VH is still elevated above ambient sound, even at 55 m.

The vertical shift out of the water column to the bottom was strongly influenced by proximity to the pile driving. During the first IH exposure, fish in the near cage spent significantly more time on the bottom in the first 5-min interval [paired t-test, t(5) = -6.98, p < 0.0001] and the entire first IH sequence [t(5) = -5.78, p = 0.0022, Fig. 6]. Fish in the near cages also responded to the second IH sequence, spending significantly more time at the bottom vs mid water during the first 5 min [paired t-test, t(5) = -4.08, p = 0.0095], and persisting for the whole sequence [t(5) = -2.92, p = 0.0332]. While the far cages observed similar trends in position, the changes were not significantly different, likely due to elevated levels in the pre-period.

For Day 2 exposures, both vertical position and behavior showed no significant changes (p > 0.05) between pre and IH states at either distance, although the same general trends in behavior were still observed. The discrepancy between the strength of reaction to the initial exposure over consecutive days was particularly remarkable at the near cages (Fig. 7).

While there was some unavoidable fluctuation in visibility throughout the experiments, a KW test revealed that no observation periods were significantly outstanding in average "not visible" time, indicating that visibility did not largely factor into behavior results.

Further, an in-depth examination (3-s interval) of the proportion of fish exhibiting each behavior before and during the first IH suggests that these patterns were not driven by just a few visible fish (Fig. 8). For Day 1 near exposures, the proportion of fish, out of 12 total, that shifted to stationary and to the cage bottom significantly increased in the first 5 min of IH1 compared to the second pre-period [two sample t-test, stationary: t(219) = -18.6, p < 0.0001, at bottom: t(219) = -16.7, p < 0.0001]. This corresponded with declines in the number of fish swimming and the midwater upon commencement of IH [two sample t-test, swimming, t(219) = 5.43, p < 0.0001;midwater, t(219) = 13.12, p < 0.0001]. Further, each of the aforementioned behavioral and positional shifts was significant (p < 0.01) across the first minute, second minute, and third through fifth minute of IH, suggesting immediate onset of behavioral disruption (Fig. 8).

#### **IV. DISCUSSION**

This is the first field-based study examining fine-scale behavioral responses of black sea bass to actual pile driving sound. The *in situ* set-up achieved single strike SEL of up to 166 dB re 1  $\mu$ Pa<sup>2</sup> × s at the closest cages, matching





FIG. 5. Duration of fish stationary and swimming throughout multiple IH and VH sequences for Day 1 pile driving. Grey mean line calculated for each 5min observation interval overlays colored boxes showing 1st and 3rd quartiles with the median line in black. Only periods of statistical relevance  $(n \ge 3)$  are shown. Stars represent a significant change in behavior between the two pre intervals averaged together and the IH observation interval, or intervals, of interest (paired t-test,  $\star p < 0.05$ ,  $\star \star p < 0.01$ ,  $\star \star \star p < 0.001$ ). (A) Time spent swimming significantly decreased in near cages (left) during the first 5-min of IH as well as the entire first IH. A decline in swimming during the last 5-min of IH 3 also reported significance. The far cages (right) also saw a decrease in swimming that was significant during the first 5-min interval of IH 1. Similar trends were observed during IH 2, although not significant. (B) Stationary duration similarly increased during the first IH for both close and far cages. For both cages, activity levels returned to "pre" during VH.

empirically recorded values approximately 3 km away from offshore windfarm construction (Brandt *et al.*, 2018). Black sea bass significantly altered their behavior in response to pile driving sound exposure, moving from typical mid-water column swimming to staying motionless on the bottom. This increased crypsis and apparent vigilance was a clear divergence from the "normal" daytime behaviors of this taxa, and may come at a cost, particularly to other daytime behaviors like foraging and social behaviors.

The strong shift from swimming to stationary in response to the acoustic stimuli [see Figs. 5 and 8(B)] was likely a "crypsis" like behavior, where there is defensive arousal, freezing, and increased vigilance, all defense responses to a potential threat (Kennedy, 2022; Yoshida, 2021). This supports previous aquaria-based studies which similarly noted a reduction in active behaviors upon the introduction of a stimulus (Stanley *et al.*, 2023). Although resting on the bottom is a natural behavior for black sea bass

(Cullen and Stevens, 2017) that could not be visually distinguished from defensive immobility behaviors in *in situ* conditions, the context of the pile driving sound onset provides insight. The discrepancy between pre- and post-exposure levels of stationary behavior suggests that impact hammer pile driving induced heightened levels of sheltering that are unnatural for these fish during the day.

The extent of pile driving sound impact was greater than initially predicted, as even fish in the far cages (SEL<sub>ss</sub> < 133 dB re 1  $\mu$ Pa<sup>2</sup> × s, SPL<sub>0-pk</sub> < 172 dB re 1  $\mu$ Pa) observed a significant transition from swimming to a vigilance state upon the onset of IH pile driving sound. For empirical comparison, these sound levels correspond to received levels detected nearly 7.5 km away from Block Island Wind Farm construction (Amaral *et al.*, 2020). Proximity to the sound source did, however, prolong the response and strongly impacted the vertical position of fish in the cage. Far cages reported no significant effect of IH on





FIG. 6. Duration of fish at the bottom and in midwater throughout multiple IH and VH sequences for Day 1 pile driving exposures. Grey mean line calculated for each 5-min observation interval overlays colored boxes showing 1st and 3rd quartiles with the median line in black. Only periods of statistical relevance ( $n \ge 3$ ) are shown. Stars represent significant change in position between the two pre intervals averaged together and the IH observation interval, or intervals, of interest (paired t-test,  $\star p < 0.05$ ,  $\star \star p < 0.001$ ). (A) In near cages (left), fish spent significantly more time in the midwater during the first 5-min of IH 1 and 2, as well as the entire first and second IH (both 5-min intervals averaged together). Far cages (right) observed declines in time in the midwater upon IH onset, but no significance was found. (B) Similar to in the midwater, fish located in the near cages spent significantly more time at the bottom during the first and second IH sequences, although far cages saw no significant change. Time spent in each position returns to "pre" (i.e., before IH 1) levels during each VH sequence. Variability in fish behaviors, as seen by the spread of the boxes, increased during VH and later IH sequences for both behaviors and distances.

the use of the water column, although similar patterns of relocation to the bottom, as well as similar levels of these states to near cages during IH, were observed (Fig. 6). Perhaps a larger sample size or investigation into the elevated pre- levels at the far distance could elucidate these trends. Meanwhile, at the near cages, significant relocations to the bottom persisted over multiple IH sequences. However, even at the near site (SEL<sub>ss</sub> ~ 156–166 dB re 1  $\mu$ Pa<sup>2</sup> × s, SPL<sub>0-pk</sub> ~ 197–207 dB re 1  $\mu$ Pa), fish returned to states similar to pre-levels by the third IH sequence. As this nearshore setup only allowed for 15-min of continuous IH pile driving, it is not clear how fish would behave if IH pile driving operated continuously for several hours, as is typical in OSW constructions (Sigray *et al.*, 2022).

The intermittent VH sequences, although still 12–35 dB higher than background sound (Table III), appeared to allow the fish to return to "pre" levels. Whether this periodic

reprieve delayed habituation or accelerated it is unclear, and would need to be tested with longer IH sequences than this nearshore setup could provide.

Decreased responses to sound exposure, whether through habituation or other mechanisms, carried into Day 2 of pile driving, as none of the reactions at close or far cages reported significant alterations from baseline. This is interesting, as nearly 20 h passed between exposures, suggesting that multi-day pile driving, at these sound levels at least, may have minimal impact on fish behavior. This suggests that animals exposed to similar sound levels in the wild across multiple days (i.e., perhaps located between pile installation locations) would see similarly diminished impacts as days progressed.

Given that these sound exposure levels are on par with National Marine Fisheries Service Endangered Species Act criteria for physical injury onset to fishes of this size

https://doi.org/10.1121/10.0036347





FIG. 7. Magnitude of change in time spent in position or behavioral state upon onset of the first IH between the first day of exposure (green) and the second consecutive day (yellow). Positive values show an increase in behavior from pre to IH and negative values indicate a decrease. Despite strong reactions in all behaviors and positions to the first exposure on Day 1 in the Near cages, on the second day, there were no significant reactions and distance seemed to have very little effect.

 $(SPL_{0-pk} = 206 \text{ dB re } 1 \ \mu Pa; FHWG, 2008)$  and temporary threshold shifts for fish with swim bladders (SEL<sub>cum</sub> > 186 dB re 1  $\mu$ Pa<sup>2</sup> × s; Popper *et al.*, 2014), one key factor that should be considered is potential sound-induced hearing loss. Sound-related auditory damage has been observed with impulsive sounds in other physoclistous swim bladder species, such as the hybrid striped bass (Morone chrysops/ saxatilis) and Mozambique tilapia (Oreochromis mossambicus), both showing barotrauma and damaged inner ear hair cells after exposure to 960 pile driving strikes [SEL<sub>cum</sub> = 216 dB re  $(1 \mu Pa)^2 \times$  sp; Casper *et al.*, 2013]. Indeed, fish with a connected physoclistous swim bladder, a characteristic of black sea bass, have shown more susceptibility to injury from impulsive sounds than physostomous species or fish lacking a swim bladder (Casper et al., 2013; Halvorsen et al., 2012). Hearing loss can also take days to recover in certain fishes (Smith et al., 2004), thus such persisting threshold shifts could have potentially occurred here. As further evidence, fish in the near cages, exposed to the highest sound levels, experienced a much stronger decline between Day 1 and Day 2 reactions to the onset of IH sound (Fig. 7). Overall, while no significant reactions were found on Day 2, we did observe similar general trends in behavior and position as the first day (particularly in the far cages), suggesting that responses were waning or sensory systems were impacted to a subset of animals.

Black sea bass are visual predators, active and up in the water column to hunt during the day (Secor *et al.*, 2021). Given these stationary responses, daytime pile driving sound exposure could potentially impact their fitness, as black sea bass may sacrifice foraging time to shelter or increase vigilance near the benthos. The responses here were ultimately

fleeting, with generally rapid recovery back to seemingly normal, pre-exposure behaviors in a matter of hours, a relatively small loss to foraging time. However, our intermittent exposure (15 min of IH at a time) contrasts with actual windfarm pile driving, which is highly variable and may occur for up to hours without stopping, making it difficult to predict the net impact of black sea bass behavior and fitness. The effects of nighttime pile driving sound exposure were also not evaluated in this study, but we predict there would be fewer changes in behavior and position, as black sea bass are known to shelter on the bottom at night (Secor *et al.*, 2021).

This study took place adjacent to an active waterway, resulting in occasional vessel traffic throughout the experimental days. Black sea bass are known to react to vessels (Secor et al., 2021). While most were small boats, several large passenger and car ferries (from 69 to 72 m long), operate nearby as well. Disturbance from the ferries was mitigated by removing any video sections that were audibly or visibly disrupted (immediate drop in visibility) from analysis, particularly at the far cages, which were closer to the ferry path. Further, fish used in this study were likely habituated to these sound conditions, having been locally caught, and were given ample time to adjust to ambient sound levels in the harbor (18 + hours). Finally, the presence of boats throughout the study meant that vessel traffic overlapped with most observation periods at some point, yet cyclical shifts in behavior and position corresponding with the onset of IH were clear and related to distance from the pile. The coexistence of vessel and pile driving sounds better reflected the soundscape a black sea bass would experience during offshore windfarm construction, as the process requires



https://doi.org/10.1121/10.0036347



FIG. 8. High resolution analysis of the number of total fish in each position and behavioral state before and upon onset of the first IH sequence in the near cages on the first day of exposure only (n = 6 cages, i.e., 12 fish). Observations (points), made every 3 s, are overlayed with an interpolated moving average (mean sampled every 12 s) line and shaded moving standard deviation. The vertical bar at 300s represents the onset of the first IH with the left side being the second 5-min pre-period. Note that these two observation periods were not continuous in real time. Stars reflect significant differences between the number of fish in a behavioral state between the 5-min pre-interval and the first minute, second minute, and third through fifth minute of IH (two sample t-test,  $\star p < 0.01$ ,  $\star \star p < 0.01$ ). (A) Position: Number of fish at the bottom (red, left) and midwater (blue, right) were randomly distributed during the control but bifurcate upon onset of IH, reflecting significant changes in positions throughout the first 5 min of IH. (B) Behavior: During the control, a few animals were stationary (red, left); the default state was generally swimming (blue, right). However, increases in stationary behavior and decreases in swimming during the first IH resulted in a more even balance of the two behaviors. Fish that were not visible or in a behavioral state other than swimming or stationary on the bottom, such as hovering, at a given time were not included in the analysis.

numerous boats on site. Indeed, evaluating the net and separate impacts of both sound types in the context of OSW constructions using evolving methodologies for *in situ* sound impacts (e.g., Ferguson *et al.*, 2017) would be valuable for this species.

This study represents a vital step towards quantifying OSW construction impacts on black sea bass, but still pales in comparison to construction methods used offshore in terms of sound levels produced, rate of IH strikes, and duration of pile driving (Amaral *et al.*, 2020). While it appears that fish stopped significantly responding to the impact hammer sequences by the first day, the combination of higher intensity, more rapid hammering, and extension over longer periods without breaks, may cause long term detriment to their fitness not predicted by this study. Further, OSWs can span tens to hundreds of square kilometers with numerous wind turbines, potentially impacting wide swaths of black sea bass habitat. For example, the planned commercial-scale

Coastal Virginia Offshore Windfarm on the US Atlantic seaboard, will contain 176 wind turbines in a 453 square kilometer lease (Dominion Energy, 2024). With their high site fidelity (Secor *et al.*, 2021; Tharp *et al.*, 2024) and temperature-driven migrations (Wiernicki *et al.*, 2020), it is uncertain whether black sea bass will attempt to relocate away from wind turbine constructions and what implications this may have. Larger scale lateral movement away from the sound source was beyond the scope of this study, which would assume the animals could locate the direction of the sound source, something not well understood in fish nor previously addressed in black sea bass (Hawkins and Popper, 2018). This phenomenon requires more study on freeranging animals, as cage and tank experiments can inhibit natural instinct to move away from the sound source.

While this study only looked at the construction phase of OSWs, impacts during other phases over an OSW lifespan must also be evaluated moving forward. During the



operational phase, OSWs produce low-frequency continuous sound, with source levels approximately 10-20 dB lower than ship sound in the same frequency range (Tougaard et al., 2020), and are a new structure and potential habitat for the area. Given their association with reef habitat and proclivity for settling on artificial reefs (Low and Waltz, 1991), once constructed, OSWs may actually provide valuable habitat and shelter for benthic, reef-associated species like black sea bass. In other parts of the world, several established windfarms (>five years of operation) have shown higher abundance and diversity of fish associated with them than in surrounding areas or before construction (Stenberg et al., 2015; Van Hal et al., 2017). Indeed, a before-after controlimpact study around the first operating OSW in American waters, Block Island Wind Farm, revealed that black sea bass numbers had actually increased near the operating windfarm compared to previous levels and surrounding areas (Wilber et al., 2022). It is important to note that during the operational phase, there is still a sound-associated cost of continuous low-frequency sound (Pangerc et al., 2016), the effect of which on black sea bass has not yet been quantified.

In conclusion, this study found that impact hammer pile driving significantly altered the behavior of caged, in situ black sea bass, whereas the interspersed VH did not. Similar to previous studies, black sea bass exhibited fewer active behaviors, which are typical during the day for the visual predator, and instead adopted bottom-associated freezing or sheltering behavior upon onset of IH. However, a return to "pre" behavior was observed within the first day and continued through the second day of exposure, suggesting that either some level of multi-day habituation or persevering hearing loss occurred. Exploration into hearing threshold changes and physical injury at these sound levels, as well as reactions of free-ranging animals, would provide critical insight into the net impact pile driving may have on black sea bass. After addressing these knowledge gaps, future work should be expanded to compare in situ impacts of pile driving on fish with other ecological strategies and different swim bladder anatomy, including those without one.

# ACKNOWLEDGMENTS

There was a multitude of WHOI staff that supported this effort and made it possible. We thank Nadege Aoki for assistance in the field. We thank Edward O'Brien and Kimberly Malkowski for facilitating SCUBA operations, Rick Galat and Kerry Strom for coordinating dock space, as well as many other members of WHOI Facilities. We thank the W.S. Shultz, Co. for their pile driving support and flexibility. Finally, we appreciate the support and suggestions of Shane Guan, Brian Hooker and Jacob Levenson, of BOEM's Ecosystem Studies Division and its Center for Marine Acoustics. This work was funded by the Bureau of Ocean Energy Management Cooperative Agreement Nos. M20AC10009 and M24AC00004-00 as well as by the National Science Foundation Biological Oceanography Award No. 1536782.

# AUTHOR DECLARATIONS Conflict of Interest

The 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.

# **Ethics Approval**

This study was carried out in accordance with the principles of the Basel Declaration and recommendations and approval of the Woods Hole Oceanographic Institution's (WHOI's) Institutional Animal Care and Use Committee scientific protocol to TAM.

# DATA AVAILABILITY

The raw data supporting the conclusions of this study are available upon reasonable request to the corresponding author.

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