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Magnetic fields generated by the DC cables of offshore wind farms have no effect on spatial distribution or swimming behavior of lesser sandeel larvae (*Ammodytes marinus*)

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ABSTRACT

In the North Sea, the number and size of offshore wind (OW) turbines, together with the associated network of High Voltage Direct Current (HVDC) subsea cables, will increase rapidly over the coming years. HVDC cables produce magnetic fields (MFs) that might have an impact on marine animals that encounter them. One of the fish species that is at risk of exposure to MF associated with OW is the lesser sandeel (*Ammodytes marinus*), a keystone species of the North Sea basin. Lesser sandeel could be exposed to MF as larvae, when they drift in proximity of OW turbines. Whether MFs impact the behavior of lesser sandeel larvae, with possible downstream effects on their dispersal and survival, is unknown. We tested the behavior of 56 lesser sandeel larvae, using a setup designed to simulate the scenario of larvae drifting past a DC cable. We exposed the larvae to a MF intensity gradient (150-50 μT) that is within the range of MFs produced by HVDC subsea cables. Exposure to the MF gradient did not affect the spatial distribution of lesser sandeel larvae in a raceway tank 50 cm long, 7 cm wide and 3.5 cm deep. Nor did the MF alter their swimming speed, acceleration or distance moved. These results show that static MF from DC cables would not impact behavior of lesser sandeel larvae during the larval period of their life although it does not exclude the possibility that later life stages could be affected.

1. Introduction

Northern European seas currently host more than 2400 wind turbines producing approximately 22 GW of energy (https://equinoreu.ft.com/). The number and size of offshore wind facilities (OWF) is expanding exponentially to meet global energy needs from a renewable source (deCastro et al., 2019; Soares-Ramos et al., 2020). With the introduction of new technology for distribution and storage of electricity, floating OWFs can be installed much further offshore than bottom-moored OWFs. The Hywind OWF in Scotland is located 25 km offshore in the North Sea (https://windeurope.org/about-wind/history/), but the Dogger Bank and Tampen Hywind OWFs will be placed 130 and 140 km off the coasts of England and Norway, respectively (https://www.rechargenews.com/wind/uks-first-hvdc-system-eyed-for-worlds-biggest-offshore-wind-farm/2-1-697330; https://www.equinor.com/en/what-we-do/hywind-tampen.html).

Placing OWFs so far offshore is possible thanks to high voltage DC (HVDC) cables (Hutchison et al., 2020b; Taormina et al., 2018), which are efficient and cost effective in transporting power over long distances. However, when electricity passes through a HVDC cable, a static magnetic field (MF) is generated in the proximity of the cable (Gill and Desender, 2020; Hutchison et al., 2021). The induced MF has intensities that exceed the intensity of the earth's geomagnetic field by a 10s–100s of microtesla (μT) (Gill and Desender, 2020; Taormina et al., 2018). Although the MF intensity decreases with distance from the cable (about 10 μT/m with a cable that is buried 1.5 m in the sea bottom; Hutchison et al., 2021), there is concern over potential effects of anthropogenic MF on marine organisms, from invertebrates to fish and mammals (Gill and Desender, 2020; Hutchison et al., 2020b), and particular concern over benthic species, which are at the highest risk of exposure to anthropogenic MFs (Hutchison et al., 2020b).

Many marine animals use magnetic and electromagnetic fields for orientation during migration, and also for predator/prey detection (Nyqvist et al., 2020; Taormina et al., 2018). Magnetic field-based

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orientation has also been reported in fish larvae (Bottesch et al., 2016; Cresci et al., 2019b; O'Connor and Muheim, 2017). Anthropogenic MF can impact and alter these ecologically important behaviors (orientation, predator/pray interactions) (Nyqvist et al., 2020). Specifically, when fish larvae drift in pelagic or continental shelf water, active swimming influences their horizontal trajectory (Cresci et al., 2021; Fiksen et al., 2007), as well as their ability to catch prey (Darowski et al., 1988). Thus, an impact on swimming behavior would alter their dispersal (Cresci et al., 2021; Fiksen et al., 2007), with possible downstream effects on survival and recruitment (Cresci et al., 2021; Houde, 2016). As the swimming capabilities of early-life stages of fish are more limited compared to the adults, impacts of MF could have more severe consequences as larvae cannot avoid subsea cables effectively. The expansion of OWFs further offshore, with a concomitant increase in the number of subsea cables, increases the risk of exposure to anthropogenic MF for dispersing fish larvae, both in mid-shallow and close-to-bottom waters. There is currently very little information on the effects of anthropogenic MF from the HVDC cables that connect wind turbines, or transport the energy to the coast, on the behavior of marine fish larvae that reside in, or disperse through, areas where OWF operate. However, previous studies demonstrated that anthropogenic MFs and EMFs can alter the swimming and spatial distribution of marine species (Hutchison et al., 2020a; Westerberg and Lagenfelt, 2008; Wyman et al., 2018).

Lesser sandeel (*Ammodytes marinus*) is a keystone fish species in the North Sea ecosystem (Furness, 2002), which is also a region in which large OWFs will be placed. This species is an important link in the food web between zooplankton and predators, including fish, mammals and sea birds (Wanless et al., 2018). As juveniles and adults, lesser sandeel live in association with specific areas of the sea bottom, where they remain buried most of the time (Wright et al., 2000). Although they spend much of their time burrowed in the sediment, they form schools that rise up into the water column to feed (Johnsen et al., 2017) or spawn (Bergstad et al., 2001; Gauld and Hutcheon, 1990). When lesser sandeel spawn, their adhesive eggs attach to the sandy bottom. After hatching, larvae drift with the current in deep layers (up to 100 m deep) for a period of 1–3 months and up to a body length of 20–30 mm, after which they start to congregate and settle (Jensen, 2001).

Lesser sandeel distribution overlaps with planned OWFs in the North Sea (Johnsen et al., 2021; https://www.equinor.com/no/what-we-do/floating-wind.html). Thus, lesser sandeel larvae drifting in deep layers could be exposed to MFs generated by the expansive network of benthic subsea cables that interconnect OWF turbines and OWFs to substations and to shore. If exposure to MFs affect the swimming or orientation of lesser sandeel larvae, it could have consequences on the dispersal, distribution and survival of this species in the North Sea.

Whether MFs generated by OW subsea cables affect the swimming behavior of lesser sandeel larvae is unknown. We conducted a behavioral experiment on lesser sandeel larvae to assess the possible impact of static magnetic fields from the DC cables that connect OWFs. We used an electric coil system to modify the MF in a manner that simulated the scenario of fish larvae swimming or drifting near a DC subsea cable. We tested the null hypothesis that a gradient of MF intensity would have no effect on the spatial distribution and swimming of sandeel larvae.

2. Methods

2.1. Experimental animals

Adult lesser sandeel (*Ammodytes marinus*) were collected in the area offshore of Karmøy, Norway (approximately 59.245 N, 5.117 E), using a bottom dredge (with a 65 × 15 cm opening). Bottom trawls were conducted from a local fisherman's vessel (Åkrabuen) on December 10th, 2020. Fish (45 individuals) were transported to the Austevoll Research Station (60.085 N, 5.261 E) and kept in a 500 L indoor tank with a sandy bottom. Lesser sandeel do not feed during the spawning season, so they were not fed. Adult sandeel were stripped on January 13, 2021 and January 18, 2021. Eggs were fertilized over a period of 40–50 min, and eggs were deposited in cylinders ending with plankton mesh. After hatching, larvae were intensively cultured in 50 L tanks at a temperature of 8 °C, constant seawater salinity (34.8 ppt), and fed with a mix of *Balanus crenatus* nauplii (Planktonic AS, Trondheim, Norway), *Acartia* sp. (CfeedAS, Trondheim, Norway) and live algae *Rhodomonas* sp. until 30 days post-hatching (dph).

Fifty-six larvae were used in the experiments on larval behavior. The larvae were 17–24 dph and were 11.7 ± 1.3 mm standard length (mean ± SD). Developmentally, larvae were at the flexion stage.

2.2. Experimental setup and exposure to MF

The experimental setup used in this study was designed to simulate the scenario of a lesser sandeel larva swimming or drifting by a DC subsea cable (Fig. 1), and followed the general outline of the setup described in Taormina et al. (2020). To accomplish this, we used two square-shaped Helmholtz coils (65 × 65 cm; 30 wraps of copper wire for each coil) connected to a BK Precision 1745A DC power supply (0–10 A), and generated a gradient of MF intensity (150-50 μT) in a raceway (Fig. 1). The MF intensities produced are in the range of those produced by HVDC subsea cables associated with OWFs (Gill and Desender, 2020; Taormina et al., 2018). The coils were parallel to the ground and modified the vertical component of the geomagnetic field, which had a total intensity (F) of 50 μT (73° Inclination and deviation of <1°). MF intensity was measured using a MLX90393 Triaxis® Magnetic Node magnetometer from Melexis Inspired Engineering (Belgium).

A raceway filled with seawater was positioned halfway inside the coils (Fig. 1A). With the raceway positioned in this way, running a current through the coils generated a high MF intensity in side 1 of the raceways, and a low MF intensity in side 2 (see Fig. 1B). Larvae could swim freely from the high to the low MF intensity area and vice versa. The raceway - 50 cm long, 7 cm wide and 3.5 cm deep - was produced using a 3D printer (Ultimaker Cura 006-afc). To minimize possible attraction-aggregation areas the raceway was designed so that there were no sharp edges, and the corners were rounded (Fig. 1A). A GOPRO HERO 7, modified for night vision and positioned above the raceway looking down onto it, was used to video record fish larvae during the experiments. Two DC 12V 96 LED infrared illuminators placed beside the camera allowed us to record larval swimming behavior in the dark. The raceway setup was located in a temperature-controlled laboratory at 8 °C, the same temperature as the water in the tanks in which larvae were cultured.

2.3. Behavioral observations and data analysis

Before the experiments started, larvae were acclimated to darkness for at least 1 h. Thereafter, one larva at a time was placed in the raceway using a small cup. Larvae were allowed 10 min to acclimate to the raceway after which their behavior was recorded for 15 min. The GOPRO recording was started and stopped from outside the room using a remote control.

Larvae were tested individually: one larva at a time in each one of the two raceways (Fig. 1A). A total of 56 lesser sandeel larvae were tested. Half of these (Controls, N = 28) were video recorded in the raceway with the electric coils turned OFF. (Fig. 1). The other half of the larvae (Exposed, N = 28) were recorded with the coils turned ON and were, therefore, exposed to a gradient of MF intensity in the raceway, from high (150 μT) to low (50 μT) (Fig. 1B).

Lesser sandeel larvae in the videos were tracked manually using Tracker 5.1.5. (Copyright © 2020 Douglas Brown, https://physlets.org/tracker). The tracks were used to calculate the position of larvae along the raceway, the time spent on each side of the raceway (high MF in side 1; low MF in side 2; Fig. 1), and their swimming kinematics (average and maximum speed, and acceleration). We tracked the position of each fish larva, every second, for the 15-min observation period

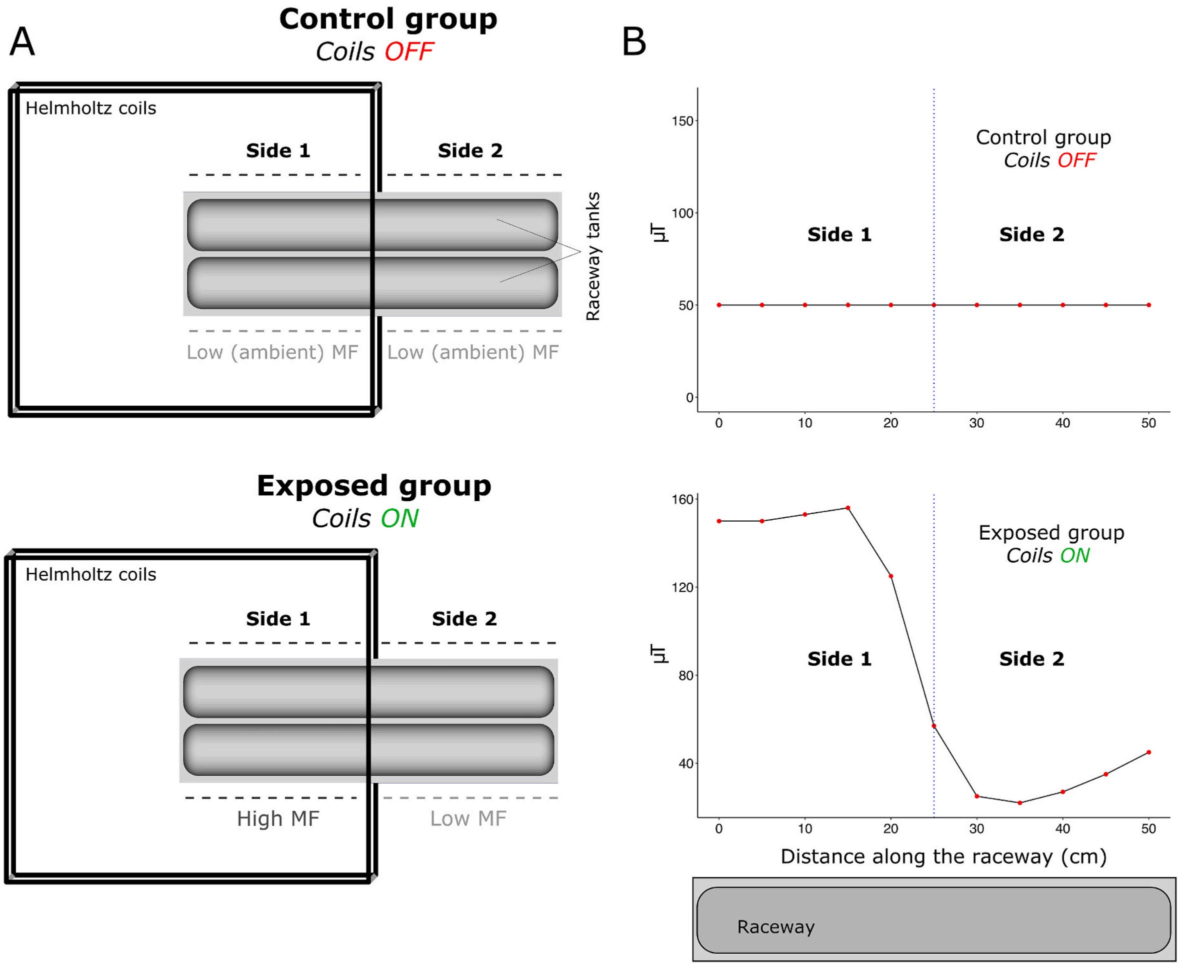

Fig. 1. **A –** Experimental setup (top view) used in this study for exposure of lesser sandeel (*Ammodytes marinus*) larvae to a static magnetic field (MF) gradient. The black squares are a pair of parallel Helmholtz coils. The two grey rectangles with smoothed corners are two raceways where larvae were swimming. Black dashed lines show the two sides of the raceway (Side 1 inside the coils; Side 2 outside the coils). Light and dark grey dashed lines show the intensity of the MF in each side of the raceway. In the Control group (coils OFF), there was ambient geomagnetic field in both side of the raceway. In the Exposed group (coils ON), there was higher intensity MF in Side 1, and lower intensity (close to the geomagnetic field intensity) in Side 2. **B –** MF intensity along the raceway (x axis) with coils ON and coils OFF. In the Control group, the geomagnetic field had the same value along the whole raceway (50 μT). In the Exposed group, the MF intensity had a gradient going from 150 μT in Side 1, decreasing towards the end of Side 2, to settle at approximately 50 μT at the right end of Half 2. Fish larvae were free to swim along the whole raceway during the experiment.

(900 data points per lesser sandeel larva).

The variance of the data of time spent in a specific side of the raceway was compared between the Controls and Exposed groups using the F test, and differences in means tested with a two-sample *t*-test. Data on fish position, average and maximum swimming speed and acceleration were tested for normality using the Shapiro-Wilk test. As data were not normally distributed, comparisons between the Controls and Exposed groups were conducted using the non-parametric Wilcoxon test.

3. Results

The median position of the larvae was close to the center of the raceway in both groups and was not impacted by exposure to MF ($W = 380$, $p = 0.86$; Fig. 2).

The average time that larvae spent on side 1 did not differ between groups ($t = -17$, $p = 0.87$; Table 1), and neither did the average time spent on side 2 ($t = -0.23$, $p = 0.78$; Table 1).

The larvae from the Control group swam a median distance of 68.8 (98.6) cm (median (IQR)), which was not significantly different ($W = 420$, $p = 0.65$; Table 2) from the median distance of 50.6 (66.3) cm covered by the larvae of the Exposed group. No difference between groups was observed in the medians of average swimming speeds ($W = 433$, $p = 0.50$), maximum speeds ($W = 319.5$, $p = 0.23$), mean accelerations ($W = 423$, $p = 0.61$) and maximum accelerations ($W = 336.5$, $p = 0.36$) (Fig. 3; Table 2).

4. Discussion

Exposure to a static magnetic field gradient of 50–150 μT did not affect the spatial preference of lesser sandeel larvae (*Ammodytes marinus*). The larvae from the Exposed group were neither attracted to nor repelled from the side of the raceway with higher MF intensity. These results suggest that lesser sandeel larvae would not be attracted to or repelled from HVDC subsea cables associated with OWFs. When lesser sandeel larvae are around 1 cm in total length (the size observed in this study), they drift in mid-deep waters during a dispersal period (Jensen, 2001). During this period, larvae could drift in proximity of subsea cables close to the sea bottom, especially in relatively shallow areas such as the North Sea. This study indicates that the MF produced by HVDC cables will not have strong effects on the swimming or spatial preference of lesser sandeel larvae.

Research on impacts of MF and EMF on marine species has been conducted using a wide range of intensities, from a few 100s of microtesla (simulating the scenario of an animal passing within a few cm-m of

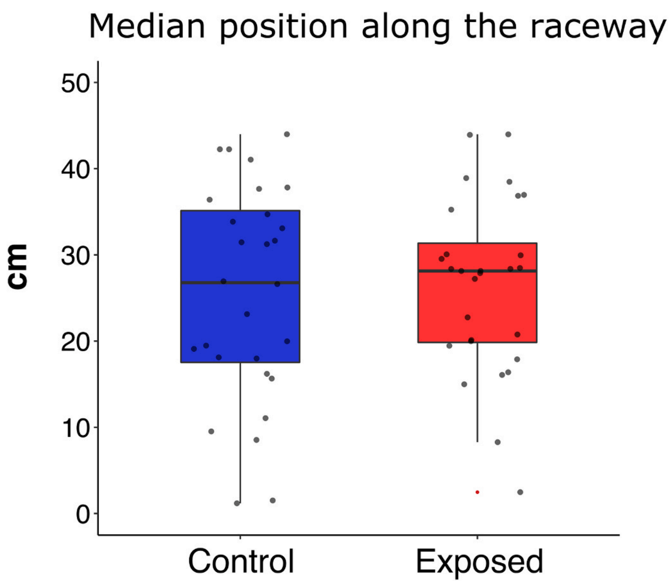

Fig. 2. A – Median position of lesser sandeel (*Ammodytes marinus*) larvae in the raceway. Boxplots show minimum, 25th percentile, median, 75th percentile and maximum values. Data points show the value of median position along the raceway for each individual. Data are spread along the x axis to avoid overlap for visual purpose.

Table 1
Time spent in each side of the raceway (Fig. 1) by lesser sandeel (*Ammodytes marinus*) larvae from the Control (coils off) and Exposed (coils on) group. Values are reported as mean ± SD.

	Time in Side 1 (s)	Time in Side 2 (s)
Controls	356.6 ± 426.7	444.4 ± 443.2
Exposed	375.8 ± 434.2	476.5 ± 423.3

Table 2
Swimming kinematics of the individual lesser sandeel (*Ammodytes marinus*) larvae from the Control (coils off) and Exposed (coils on) group. Values are reported as median (IQR) for each experimental group.

	Mean Speed (cm/s)	Max Speed (cm/s)	Mean Acceleration (cm/s^2)	Max Acceleration (cm/s^2)	Total distance covered (cm)
Controls	0.067 (0.106)	1.490 (1.093)	0.046 (0.068)	0.833 (0.628)	68.8 (98.6)
Exposed	0.044 (0.088)	1.559 (0.907)	0.033 (0.060)	0.885 (0.386)	50.6 (66.3)

a cable), to millitesla (mT), which reproduces the scenario of being adjacent to a subsea cable. In this study, lesser sandeel larvae did not exhibit spatial preference associated with changes in MF intensity of 10s of microtesla. These results are consistent with previous studies on impacts of anthropogenic EMFs conducted on other marine species. Juvenile European lobsters (*Homarus gammarus*) exposed to magnetic field intensities of up to 200 μT (which is close to the intensity used in this study and within the range of MF produced by subsea DC cables) did not show any change in spatial preference, exploratory behavior and shelter seeking behavior (Taormina et al., 2020). Rainbow trout (*Oncorhynchus mykiss*) juveniles did not show direct avoidance for either static or time varying strong MF of 10 mT (Jakubowska et al., 2021). Conversely, effects of strong MF (2.8 mT) on spatial distribution have been reported in the crab *Cancer pagurus*, which was attracted to areas with strong MF intensity (Scott et al., 2018). Similarly, impacts on spatial distribution were observed after exposure to small increases in MF intensity (10 μT higher than the background geomagnetic field) in an electrosensitive fish, the little skate *Leucoraja erinacea*, which spent less time in the center of the experimental arena when exposed to altered MF (Hutchison et al., 2020a).

Very little research has been conducted on the effect of changes of 10s–100s of microtesla (μT) on the behavior of marine fish larvae during their pelagic dispersal phase. The sensitivity of marine fish larvae to magnetic fields varies with species. For example, larvae of Atlantic herring (*Clupea harengus*) do not show orientation response associated with changes in the magnetic field (Cresci et al., 2020). On the other hand, larvae of Atlantic haddock (*Melanogrammus aeglefinus*) and post-larval European eel (*Anguilla anguilla*) exhibit complex magnetic field-based orientation behavior (Cresci, 2020; Cresci et al., 2019a). It is possible that lesser sandeel larvae are among those species that do not respond to MF during the early larval period, but this does not exclude the possibility that larvae of other marine fish would detect, and be affected by, MF from subsea cables.

Although we found no impact of MF on swimming kinematics and spatial distribution of lesser sandeel larvae, their behavior changes with ontogeny. Starting from when they reach 2–3 cm total body length, lesser sandeel move closer to the surface layer to feed, have more active horizontal swimming and also congregate in areas close to post-settled conspecifics (Jensen, 2001). Thus, larger lesser sandeel might respond differently than larvae to changes in MF. Future work should investigate possible effects of MF and EMF on juvenile and adult lesser sandeel. Since behavioral responses to EMF are species specific, future research on the impacts of subsea cables associated with WOFs should include the larvae of other marine organisms.

Competing interests

The authors declare no competing interests.

Data availability

Data are available from the corresponding author upon reasonable request.

Ethical statement

The Austevoll Research Station has a permit to operate as a Research Animal facility for fish (all developmental stages), under code 93 from the national Institutional Animal Care and Use Committee (IACUC); NARA. We did not require specific approval for these experiments because they are non-intrusive behavioral observations.

CRediT authorship contribution statement

Alessandro Cresci: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, and, Writing – review & editing. **Prescilla Perrichon:** Conceptualization, Investigation, Writing – original draft. **Caroline M.F. Durif:** Conceptualization, Investigation, Formal analysis, Writing – original draft, and, Writing – review & editing. **Elin Sørhus:** Conceptualization, Investigation, Writing – original draft. **Espen Johnsen:** Conceptualization, Investigation, Writing – original draft, Funding acquisition. **Reidun Bjelland:** Conceptualization, Investigation, Writing – original draft. **Torkel Larsen:** Conceptualization, Methodology, Software. **Anne Berit Skiftesvik:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, and, Writing – review & editing. **Howard I. Browman:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, and, Writing – review & editing, Funding acquisition.

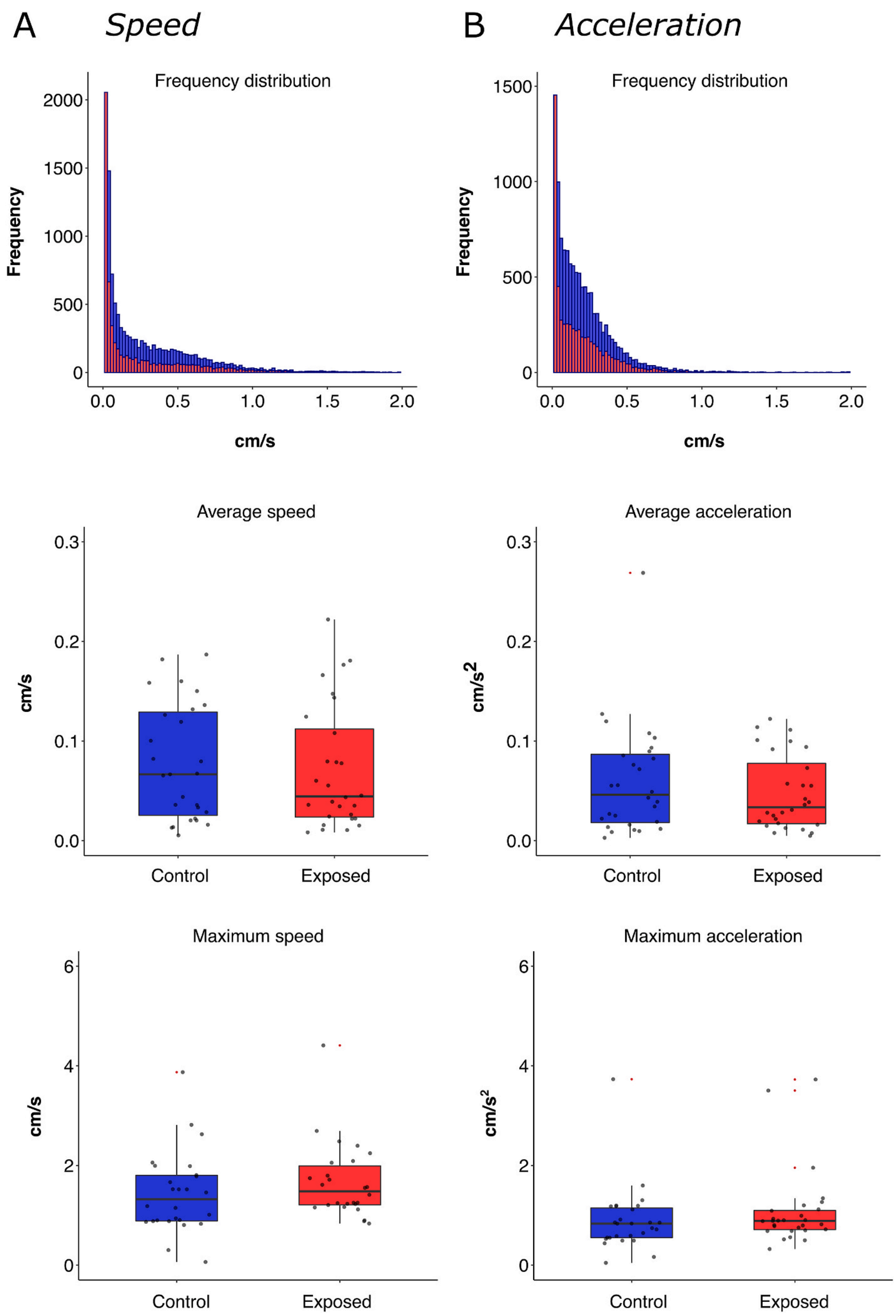

Fig. 3. Swimming speeds and accelerations of lesser sandeel (*Ammodytes marinus*) larvae in the raceway. Boxplots show minimum, 25th percentile, median, 75th percentile and maximum values. Data points in the boxplots are spread along the x axis to avoid overlap for visual purpose. **A –** Frequency distribution, mean and average maximum speeds of the sandeel larvae used in this experiment. Data points show the value of average speed and maximum speed for each individual. **B –** Frequency distribution, mean and average maximum acceleration of sandeel larvae. Data points show the value of average acceleration and maximum acceleration for each individual.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2022.105609.

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