

Static magnetic fields reduce swimming activity of Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) larvae

Alessandro Cresci ^{*}, Caroline M.F. Durif , Torkel Larsen, Reidun Bjelland, Anne Berit Skiftesvik
 Howard I. Browman 

Institute of Marine Research, Ecosystem Acoustics Group, Austevoll Research Station, Sauganeset 16, N-5392 Storebø, Norway

^{*}Corresponding author. Institute of Marine Research, Austevoll Research Station, Sauganeset 16, N-5392 Storebø, Norway. E-mail: alessandro.cresci@hi.no

Abstract

Static magnetic fields (B-fields) are introduced in marine ecosystems by anthropogenic sources such as subsea power cables. Larvae of the gadoids Atlantic haddock (*Melanogrammus aeglefinus*) and Atlantic cod (*Gadus morhua*) disperse over the continental shelf and may encounter B-fields, which could alter their behavior. We tested the behavior of 184 gadoid larvae while they were being exposed to a B-field (22–156 μT), which is in the intensity range of that produced by a high-voltage direct current cable, for a duration of 10 min in a raceway tank. We present a reanalysis of published data on 92 haddock larvae combined with newly collected data on 92 cod larvae tested under the same settings. Exposure did not affect the spatial distribution of the larvae. Both species displayed the same proportion of nonexploratory (78%) and exploratory (22%) individuals. Exposure significantly reduced the average swimming speed of the nonexploratory larvae by 32% and the average acceleration by 30%. Exploratory larvae were not affected. These results indicate that the swimming behavior of a high proportion of gadoid larvae would be reduced by weak static B-fields. Consequences of exposure on dispersal and survival at the population scale awaits further work using biophysical-coupled models.

Keywords: static magnetic fields; subsea cables; renewable energy; offshore wind; anthropogenic magnetic field; fish larvae; larval dispersal

Introduction

During the early egg and larval stages, many fish undertake a dispersal phase from the spawning areas to reach feeding and nursery areas. A failure to find prey during this key period of the life history results in high mortality, affecting the abundance of adults and the size of future year classes (Hjort 1914). The larvae of many fish disperse through a combination of passive transport by ocean currents and active swimming and orientation (Leis 2006, Leis et al. 2013, Chaput et al. 2022). If anthropogenic disturbances introduced in marine environments affects larval swimming behavior, it would have consequences for their dispersal (Fiksen et al. 2007, Cresci et al. 2021), with potential downstream effects on spatial distribution and recruitment (Houde 2016). One such disturbance is static magnetic fields introduced by anthropogenic sources (Gill and Desender 2020). These static magnetic fields, which are the vector field of magnetic flux density measured in tesla ($\text{kg s}^{-2} \text{A}^{-1}$), are henceforth, referred to as “B-fields.”

Sources of anthropogenic B-fields in the ocean can be ships (Gill et al. 2014), bridges (Klimley et al. 2017), and surveys for minerals and oil exploration (Nabighian et al. 2005). However, the largest and most rapidly growing sources of anthropogenic B-field in the ocean are networks of subsea power cables (Taormina et al. 2018). Subsea cables transport power between islands, to/from nearshore and offshore structures, such as oil platforms and marine renewable energy devices, and they connect islands to the coast (Sutton et al. 2017). The increase in the number and size of offshore wind facilities needed to meet the increasing demand for renewable energy

(Methratta et al. 2020, Soares-Ramos et al. 2020, Soukissian et al. 2023) will lead to an expansion of the network of subsea cables connecting the turbines (Hutchison et al. 2020b, Soukissian et al. 2023). In the North Sea, the future power grid will connect wind facilities over 1000s of square kilometers (<https://ceruleanwinds.com/>).

When electricity moves through a high-voltage direct current (HVDC) subsea cable, it generates a static B-field in the proximity of the cable (Gill and Desender 2020, Hutchison et al. 2021). The B-field can reach intensities ranging from 10 s of nT to a few mT (Taormina et al. 2018, Gill and Desender 2020), extends radially from the cable, is highest at the cable surface and decreases inversely with distance away from it (Yang et al. 2018, Hutchison et al. 2021). When B-fields are produced by alternating current cables, they follow the temporal variability of the energy transmission through the cable, while when produced by direct current cables, the B-fields are static (Taormina et al. 2018, Hutchison et al. 2020b). B-fields can extend a few meters from the source and vary with the power being transmitted through the cable and with the type of cable (Yang et al. 2018). The decrease in B-field intensity with distance from the cable is nonlinear; it drops off sharply (Yang et al. 2018, Hutchison et al. 2021).

There is concern over the effects that exposure to anthropogenic static B-fields could have on marine organisms (Gill and Desender 2020, Hutchison et al. 2020b). Marine animals respond to anthropogenic B-fields, which can affect behaviors that determine spatial distribution, such as swimming and orientation (Nygqvist et al. 2020). For marine fish, the risk of

exposure is particularly relevant during the early life stages, when fish have limited swimming capacity and they are still developing (Degraer et al. 2023, chapter 17). For fish larvae, the likelihood of exposure to anthropogenic B-fields depends on whether the source is located in areas where larvae disperse or the depth at which larvae disperse. If the B-field source is a subsea cable, the likelihood of exposure also depends on whether the cable is buried, rests on the sea floor, or runs through the water column to connect devices at or above the sea surface (e.g. floating wind turbines and oil rigs). Understanding the likelihood of fish larvae being exposed to B-fields is challenging and requires simulations of larval dispersal at large scales. For such simulations to be realistic, empirical observations of the responses of fish larvae to B-fields are needed.

Laboratory-based studies indicate that anthropogenic B-fields alter the swimming and spatial distribution of some marine species (Durif et al. 2023, Hutchison et al. 2020a, 2021, Wyman et al. 2018). The effect of B-fields is species-specific. For example, B-fields affected the swimming of larval Atlantic haddock (*Melanogrammus aeglefinus*) (Cresci et al. 2022a) but not lesser sandeel (*Ammodytes marinus*) (Cresci et al. 2022b). This highlights the need for more research to identify the species that are affected by the B-fields generated by subsea cables.

Atlantic haddock (*M. aeglefinus*) and Atlantic cod (*Gadus morhua*) are closely related species in the family Gadidae that are ecologically and commercially important in the North Atlantic (Pope and Macer 1996). These species are demersal and their larvae and juveniles disperse in midwater over the continental shelf for periods of 2–3 months (Albert 1994, Munk et al. 1999, Munk 2014). Haddock larvae use the geomagnetic field of the earth as a cue for orientation behavior (Cresci et al. 2019b). Although not yet determined, given their close phylogeny, Atlantic cod larvae may also be magnetosensitive. For these reasons, the swimming behavior of haddock and cod larvae could be impacted by B-fields generated by anthropogenic sources in proximity of the sea bottom and in the water column.

We conducted an experiment on Atlantic cod larvae to assess the potential impact of anthropogenic static B-fields on their swimming behavior. These new data on Atlantic cod larvae were combined with previously published data on the behavior of Atlantic haddock larvae to provide an assessment of the effects of B-fields on the swimming behavior of the larvae of closely related *Gadoids*. We tested the null hypothesis that an artificially modified B-field has no effect on spatial distribution or swimming behavior of phylogenetically close larvae from the same Gadidae family.

Methods

Experimental animals

Broodstock of Atlantic cod was used to obtain the larvae used in a new experiment. Haddock broodstock was used to obtain the larvae that were utilized to collect data on larval behavior in the experiment from Cresci et al. (2022a).

Broodstock of both species were collected locally from the waters near Austevoll (60.085 N, 5.261 E), Norway, and the fertilized eggs were obtained using standard procedures tailored to the species. For both species, fertilized eggs were collected from broodstock holding tanks with several males and

females. Eggs were kept in separate 90 l incubators till hatching. Prior to start feeding, larvae were placed in separate 500 l tanks at a density of 100 larvae l^{-1} . Water exchange was 4 $l\ min^{-1}$. Thus, the photoperiod was set to 24 h under $2 \times 25\ W$, 12 V halogen lamps. The rearing tanks used for cod and haddock broodstock and larvae were made of nonmagnetic material: fiberglass for the broodstock and polyethylene for the larvae, with supporting frames made of aluminium. There were no B-field-generating devices near the tank. The inflow of water is supplied by header tanks that are filled with pumps that are located far from the rearing facility. The magnetic field in the rearing tanks was 46.1 μT and was stable. This intensity is close to the total magnetic field intensity found in the North Sea, where cod and haddock spawn; 50–51 μT (World Magnetic Model, NOAA.gov). The larvae of both species were reared in green water (*Nannochloropsis*, Reed Mariculture) at a temperature of 11°C–12°C and a salinity of ca. 35 PSU. Oxygen saturation and pH did not change through time in the rearing tanks as there was continuous inflow of new seawater. Larvae were fed first on a diet of rotifers (*Brachionus* sp.) and natural plankton (mainly *Acartia* sp. nauplii), and then (25 days posthatch) on *Artemia* and natural plankton (mainly *Acartia* sp. copepod). Haddock eggs hatched on 19 March 2021 and larvae started feeding on 22 March. Cod eggs hatched on 18 March 2021 and larvae started feeding on 22 March 2021.

A total of 92 haddock larvae and 92 cod larvae were used in the experiments on larval behavior. At the time of the experiment (22 April 2021–24 April 2021), haddock larvae were 34–36 days posthatch and were 8.1 (1.6) mm standard length [median (interquartile range (IQR))]. Cod larvae were 38–40 days posthatch when they were tested (25 April 2021–27 April 2021) and were 9.7 (1.5) mm standard length.

Developmentally, larvae were at the beginning of the flexion stage, which in haddock and cod starts occurring at ~ 10 mm standard length (Auditore et al. 1994).

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 behavioral observations of a noninvasive potential stimulus.

Experimental setup and exposure to B-field

The experimental setup used in this study was similar to that described in Cresci et al. (2022b), Taormina et al. (2020), Cresci et al. (2022a), and Durif et al. (2023). It was designed to expose larvae to a B-field in the intensity range similar to that produced by an HVDC subsea cable, including a sharp decrease in intensity with distance (Fig. 1). In proximity of B-field sources such as a real HVDC subsea cable, the intensity would drop at a rate of $1/r$ or $1/r^2$, depending on the characteristics of the cable. The intensity of the B-field used in this study dropped sharply along a raceway tank, although not in exactly the same manner as would be the case for a real subsea cable. To accomplish this, we used two square Helmholtz coils (65 \times 65 cm; 30 wraps of copper wire for each coil) connected to a BK Precision 1745A DC power supply (0–10 A) that generated a B-field intensity (22–156 μT) in a tank with two separate raceways (Fig. 1). The raceway tank—50 cm long, 7 cm wide, and 3.5 cm deep—was produced using a 3D printer (Ultimaker Cura S5—material white tough PLA) and was placed

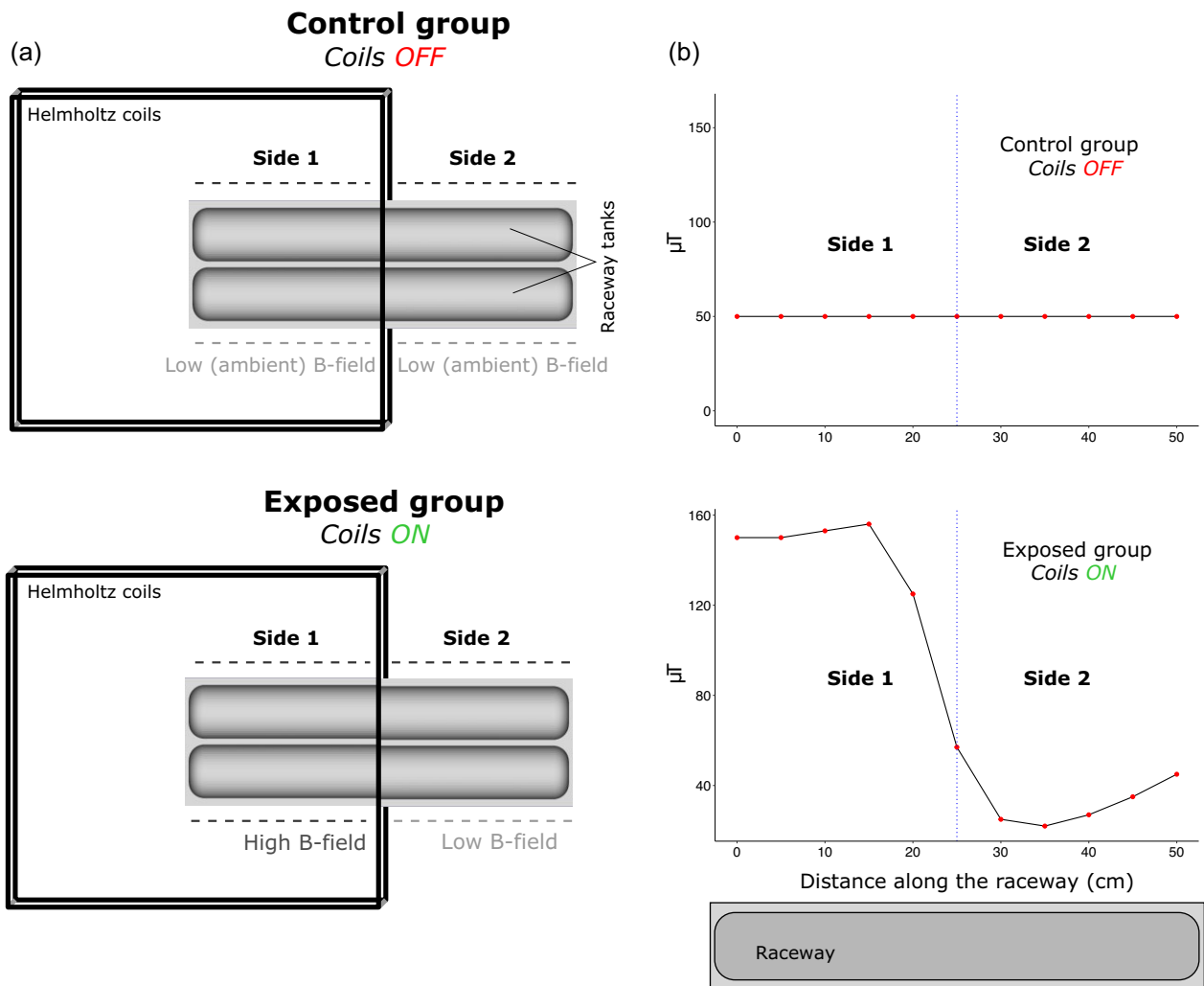


Figure 1. Experimental setup used to test the behavior of Atlantic cod (*G. morhua*) and Atlantic haddock (*M. aeglefinus*) in response to simulated anthropogenic B-fields. (a) Experimental setup (top view) used to expose the larvae to a static magnetic field (B-field) sharp gradient. The black squares are a pair of parallel Helmholtz coils (65 × 65 cm; 30 wraps of copper wire for each coil). The two gray rectangles with smoothed corners are two raceways in which larvae were swimming. The raceway tank was 50 cm long, 7 cm wide, and 3.5 cm deep. Black-dashed lines show the two sides of the raceway (side 1 inside the coils and side 2 outside the coils). Light and dark gray-dashed lines show the intensity of the B-field on each side of the raceway. In the Control group (coils OFF), there was an ambient geomagnetic field in both sides of the raceway. In the Exposed group (coils ON), there was higher B-field intensity on side 1, and lower intensity on side 2. (b) B-field 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 B-field intensity had a gradient going from 156 μT on Side 1, decreasing toward the end of side 2, to settle at ~22–50 μT at the right end of half 2. Haddock and cod larvae were free to swim along the whole raceway during the experiment. Figure modified from Cresci et al. (2022a).

halfway inside the coils and filled with filtered seawater (Fig. 1a). With the raceway positioned in this way, running a current through the coils generated a high B-field intensity (relative to the local geomagnetic field) on side 1 of the raceways, and a low B-field intensity on side 2 (see Fig. 1b). The B-field was highest (~150 μT) on one side of the raceway, sharply dropped in intensity, and was lowest at the other end of the raceway (22–50 μT). A similar pattern in B-field intensity is found in proximity of HVDC subsea cables (Dhanak et al. 2016, Hutchison et al. 2021). These B-field intensities are in the range of those produced by HVDC subsea cables associated with facilities such as offshore wind farms (Taormina et al. 2018, Gill and Desender 2020). The experimental 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°). The intensity of the B-field was recorded using an AKM AK09918C tri-axial magnetometer (range $\pm 4912 \mu\text{T}$, sensitivity: 0.15 $\mu\text{T LSB}^{-1}$).

Larvae could swim freely from the high to the low B-field intensity area in the raceway and vice versa. To minimize possible attraction-aggregation areas, the raceway was designed so that there were no sharp edges, and the corners were rounded (Fig. 1a). All of the experiments were conducted in the dark to eliminate any possible visual cues. 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 12 V 96 LED infrared illuminators were placed beside the camera. The room temperature was 11°C, which was the same temperature as the water in the rearing tanks of the larvae.

Behavioral observations and data analysis

The experiment on cod larvae was conducted using the same experimental protocol used to test the behavior of haddock larvae, as reported in Cresci et al. 2022a. The experiment and all handling of animals at the start/end of every test, was conducted in the dark. This was to minimize exposure to any other external cue other than the B-field. The day of the experiment, larvae were transferred to 6.3 l tanks containing filtered seawater at a density of 3 larvae l^{-1} . The tanks were in the dark. Larvae were transferred to the dark tanks 1 h before the experiments.

A single larva was placed in the middle of the raceway using a small cup and was allowed 5 min to acclimate to the raceway, after which its behavior was recorded for 10 min. To eliminate possible disturbance to the larva in the raceway tank, the observer started and stopped the video recording from outside the room using a remote control. This protocol was replicated for one larva at a time in each of the two raceways, replacing the larvae with new individuals at the end of each 15 min test (Fig. 1a). A total of 92 cod and 92 haddock larvae were tested. For each species, half of these (Controls: $N = 46$ replicates for cod larvae, $N = 46$ haddock larvae) were observed in the raceway with the electric coils switched OFF (Fig. 1). The other half of the larvae (Exposed: $N = 46$ replicates for cod larvae, $N = 46$ haddock larvae) were observed with the coils switched ON and were, therefore, exposed to a B-field intensity ranging from 22 to 156 μT with a sharp drop in intensity in the middle of the raceway (Fig. 1b).

Cod and haddock larvae in the videos were tracked manually using Tracker 5.1.5. (Copyright© 2020 Douglas Brown, <https://physlets.org/tracker>). We tracked the position of each larva, every second, for the 10-min observation period (600 data points per larva). The tracks were used to calculate the position of larvae along the raceway, and to measure their swimming kinematics (median and maximum speed, and acceleration).

The tracks from the videos were also used to assess whether fish larvae had the tendency to explore the raceway tank. The long and narrow shape of the raceway, together with its limited size relative to the size of the fish larvae, allowed easy identification of the individuals with exploratory or nonexploratory tendencies. Larvae that were categorized as “exploratory” crossed the middle of the raceway at least once during the 10 min-long test, and swam along the raceway exploring the entire space available to them. The rest of the larvae settled on one of the two sides of the raceway and never crossed the middle of it during the test. These larvae were categorized as “nonexploratory.”

The cod and haddock larvae were tested under the exact same experimental conditions and using the same protocol (from Cresci et al. 2022a). To correct for possible effects of differences in body size within and between the species, the data on swimming behavior of both cod and haddock were normalized according to the body length of the larvae. Body length was measured from the videos. Swimming speed is reported as body lengths per second ($BL s^{-1}$) and acceleration as $BL s^{-2}$.

We tested the effect of B-fields on swimming speed and acceleration according to whether the larvae were exploratory or nonexploratory. B-field effects were investigated on the complete dataset, merging cod and haddock larvae (using a two-way analysis of variance; ANOVA), and separately

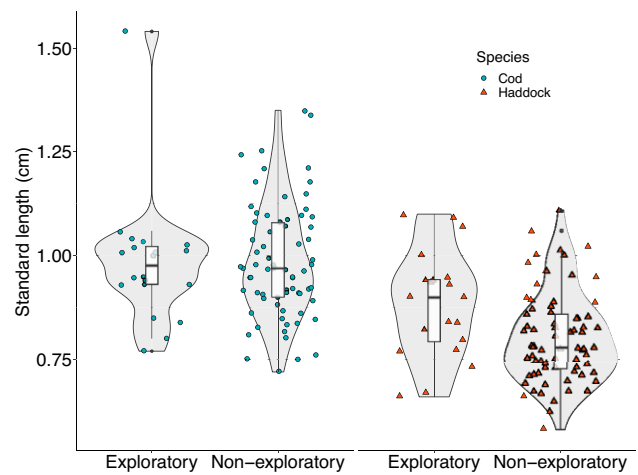


Figure 2. Standard length of the Atlantic cod (*G. morhua*) and Atlantic haddock (*M. aeglefinus*) larvae used in the study. The standard length is displayed according to the exploratory tendency of the larvae in the experimental setup. Data are displayed in box plots reporting minimum, 25th percentile, median, 75th percentile, and maximum values. The horizontal spread of the data is for visualization purposes.

on each species (using a Wilcoxon test). Using the two-way ANOVA on the complete dataset, we tested for the relative effect and possible interaction between the factors fish “species” and “B-field exposure” in the variance of the swimming speed and acceleration data. The two-way ANOVA was performed on rank transformed data, as these did not meet the requirements for normality (tested using Shapiro–Wilk test) and homogeneity of variance (tested using the Levene test). This rank-based procedure is recommended for many distributions that do not meet the normality and homogeneity requirements (Conover and Iman 1981).

Effects of B-fields on position along the raceway were tested with the nonparametric Wilcoxon test both on the whole dataset and for exploratory and nonexploratory larvae assessed as categories. The possible relationship between the body length and exploratory behavior was tested using the Wilcoxon test. Values for each group are reported as median and IQR.

Results

Behavior of gadoid larvae in the raceway

Gadoid larvae displayed distinct interindividual differences in exploratory and swimming behavior that were consistent across the two species. Following the 5-min habituation period, 22% of the gadoid larvae (20 out of 92 cod; 20 out of 92 haddock) were categorized as “exploratory.” The remaining 78% of the larvae (72 out of 92 cod; 72 out of 92 haddock) settled on one of the two sides of the raceway and were categorized as “nonexploratory.”

Exploratory gadoid larvae had a median speed of 0.34 (0.86) $BL s^{-1}$ [median (IQR)], which was significantly higher ($W = 3973$, $P < .01$) than the median speed of 0.17 (IQR = 0.29) $BL s^{-1}$ displayed by nonexploratory larvae. Exploratory haddock larvae had a median standard length of 9.0 (1.5) mm, which was significantly greater ($W = 983$, $P = .01$) than the median length of 7.8 (1.3) mm of nonexploratory larvae (Fig. 2). There was no difference in the body length

of exploratory and nonexploratory cod larvae [median = 9.7 (IQR = 0.09) mm; $W = 701.5$, $P = .86$] (Fig. 2).

Effect of B-field

Exposure to a B-field did not affect the distribution (position along the raceway) of gadoid larvae ($W = 4600$, $P = .31$). The B-field did not affect the spatial distribution when exploratory larvae ($W = 159$, $P = .33$) or nonexploratory larvae ($W = 2836$, $P = .32$) were assessed as categories.

There was a significant reduction (-32%) in the average swimming speeds of nonexploratory gadoid larvae ($N = 184$, $DF = 1$, $F = 13.3$, $P = .0004$) and of their acceleration (-30% ; $N = 184$, $DF = 1$, $F = 11.7$, $P = .0008$) when exposed to the B-field (Fig. 3a–b). The factor “species” affected both the average speed ($N = 184$, $DF = 1$, $F = 123.0$, $P < .001$) and acceleration ($N = 184$, $DF = 1$, $F = 116.4$, $P < .001$). However, species was unrelated to the observed effect of B-field exposure, as there was no statistically significant interaction between B-field exposure and species for either average speed ($DF = 1$, $F = 0.49$, $P = .48$) or acceleration ($DF = 1$, $F = 0.19$, $P = .66$).

The effect of B-field exposure on swimming activity was visible in each of the two species even when analyzed separately. The speed of exposed nonexploratory cod larvae [$N = 35$, median = 0.08 (IQR = 0.07) BL s^{-1}] was 39% lower than the speed of control nonexploratory cod larvae [$N = 37$, median = 0.14 (IQR = 0.12) BL s^{-1}] ($W = 838$, $P = .03$). The speed of exposed nonexploratory haddock larvae [$N = 34$, median = 0.30 (IQR = 0.41) BL s^{-1}] was also significantly reduced by 38% ($W = 859$, $P = .01$) compared to the speed of control nonexploratory haddock larvae [$N = 38$, median = 0.48 (IQR = 0.31) BL s^{-1}]. B-field exposure also reduced the acceleration of nonexploratory cod larvae (-37% ; $W = 827$, $P = .04$) and haddock larvae (-30% ; $W = 833$, $P = .03$).

There was no effect of exposure to B-fields on average speed ($W = 164$, $P = .40$) or average acceleration ($W = 152$, $P = .24$) of exploratory gadoid larvae (Fig. 3a–b).

Maximum speed or acceleration was not affected by B-field in neither exploratory nor nonexploratory larvae (Wicox. $P > .05$) (Fig. 3c–d).

Discussion

Exposure to a static B-field of intensities ranging between 22 and 156 μT did not affect the spatial distribution of either Atlantic haddock or cod larvae in a raceway tank, but it reduced their swimming activity. This effect was consistent in both Atlantic haddock and in Atlantic cod larvae, suggesting that these Gadoid species are sensitive to static anthropogenic B-fields of weak intensity. It is important to note that B-fields from anthropogenic sources have x , y , and z components, but the experimental setup used in this study only allowed for the study of B-field effects in 2D. Further studies are needed to explore the effects of the horizontal and vertical components of B-fields on larval behavior.

At high latitudes, fish larvae disperse over long distances by using a combination of passive transport (from ocean currents) and active swimming behavior (Leis 2006, Leis et al. 2013). A reduction in swimming activity could alter the dispersal trajectories of these gadoid larvae, as swimming behavior and orientation play an important role in the dispersal of

fish larvae (Chaput et al. 2022). Altered dispersal trajectories could cause gadoid larvae to disperse to areas with less food and more predation compared to their usual dispersal routes and nursery areas (Houde 2016). Atlantic haddock are magnetoreceptive, and use a magnetic compass as an orientation mechanism during dispersal (Cresci et al. 2019b). This orientation mechanism has not yet been reported in Atlantic cod larvae. However, considering the close phylogeny of cod to haddock, and the behavioral response of cod larvae to B-fields reported in this study, it is possible that cod larvae also employ geomagnetic field-based orientation mechanisms during dispersal. Exposure to B-fields could alter the orientation direction of haddock larvae (and perhaps of cod larvae) in addition to their swimming; that hypothesis will be tested in future work. Considering the spatial scale of the near-future development of anthropogenic sources of B-fields (such as networks of subsea cables) in areas like the North Sea, where haddock and cod larvae disperse toward feeding and nursery areas, exposure to anthropogenic B-fields could have consequences for their dispersal ecology.

The effects of anthropogenic B-fields on haddock and cod reported in this study are consistent with reports of the effect of B-fields on other marine species (Nygqvist et al. 2020). Juvenile lumpfish (*Cyclopterus lumpus*) exhibited a similar reduction in swimming activity following exposure to a B-field of up to 230 μT (Durif et al. 2023). Small variations (1–3 μT compared to the background field) of B-field intensity altered the spatial preference of the electrosensitive little skate (*Leucoraja erinacea*) (Hutchison et al. 2020a). Strong B-fields (2.8 mT) affected the spatial distribution of the crab *Cancer pagurus* (Scott et al. 2018). Exposure to the same strong B-fields (2.8 mT) during the embryonic development of European lobster (*Homarus Gammarus*) and edible crab (*C. pagurus*) affected the morphological development of their larvae (Harsanyi et al. 2022).

Some marine species are not affected by static B-fields at the low intensities used in this study. Neither the spatial distribution nor the swimming activity of larvae of lesser sandeel (*Ammodytes marinus*) were influenced by 22–156 μT B-fields (Cresci et al. 2022b). The spatial preference and the shelter-seeking behavior of juvenile European lobster was not affected by B-fields of up to 200 μT (Taormina et al. 2020). Rainbow trout (*Oncorhynchus mykiss*) juveniles did not avoid either static or time-varying strong B-field of 10 mT (Jakubowska et al. 2021). It is clear from all of these studies that the effects of B-fields on marine animals is species-specific. More work should be conducted to identify the species at risk of being impacted by the rapidly increasing introduction of B-fields, such as the networks of subsea cables connecting offshore wind facilities.

Offshore wind farms will be developed in the North Sea and this will introduce power grids of $> 1000 \text{ km}^2$ (<https://ceruleanwinds.com/>). These power grids will produce anthropogenic B-fields along the cables of the grid. It is likely that haddock and cod larvae will drift by or through these areas. Cod larvae respond to, and are attracted by, continuous low-frequency noise of intensity comparable to that of the operational noise of wind facilities (Cresci et al. 2023). Larvae drifting by subsea cables within, or in proximity of, wind facilities will be exposed to anthropogenic B-field and an altered soundscape. Future work should investigate the potential combined effect of B-field and continuous noise on larvae and other life stages of haddock, cod, and other species.

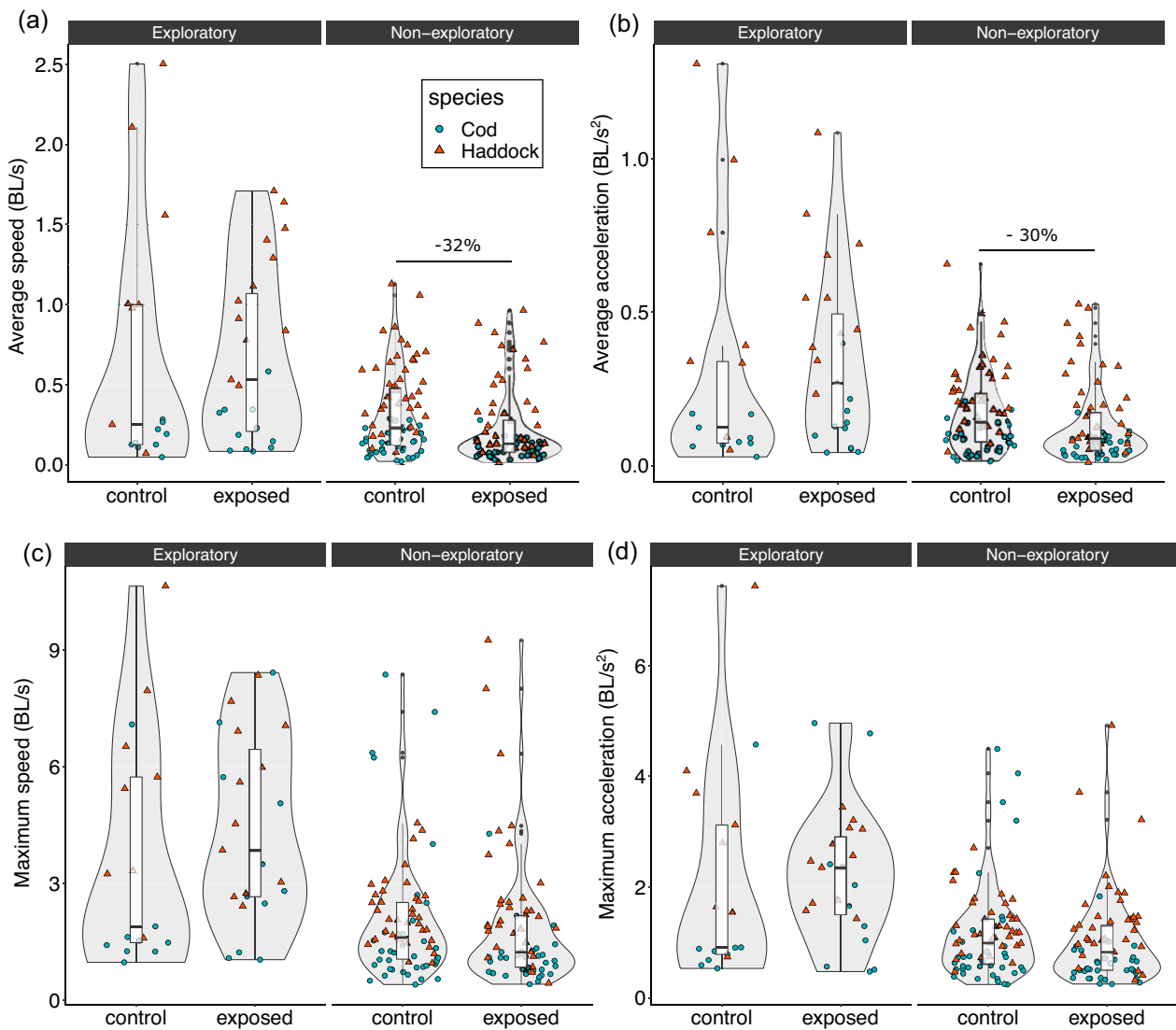


Figure 3. Speed and acceleration of the Atlantic cod (*G. morhua*) and Atlantic haddock (*M. aeglefinus*) larvae used in the study. The data are displayed according to the experimental group (Control and Exposed to B-fields) and to the exploratory behavior of the larvae in the experimental setup. The box plots report minimum, 25th percentile, median, 75th percentile, and maximum values. The horizontal spread of the data is for visualization purposes. The horizontal black line marks the percentage of reduction caused by exposure to B-fields. (a) Average speed. (b) Average acceleration. (c) Maximum speed. (d) Maximum acceleration.

Exposure to B-fields did not impact all of the haddock and cod larvae; the effect was dependent on interindividual differences in exploratory behavior. The majority of the larvae (78%) did not explore the entirety of the space available to them, while the remaining 22% actively swam and explored the raceway tank. This proportion of exploratory/nonexploratory individuals was the same in both cod and haddock larvae. This proportion is consistent with that reported in the literature about proactive/reactive phenotypes (Baker et al. 2018, Villegas-Ríos et al. 2018). Reactive individuals (nonexploratory) typically constitute the larger proportion (>70%) (Cresci et al. 2018, Rey et al. 2013, Villegas-Ríos et al. 2018) and respond to subtle environmental cues, such as B-fields, while proactive individuals do not (Cresci et al. 2018, 2019a). This behavior-dependent effect of B-fields could have implications for cohorts of larvae interacting with B-field sources because reactive individuals (nonexploratory)

tend to be risk averse (Ibarra-Zatarain et al. 2019) and are more adaptable to changes in the environment (Carbonara et al. 2019).

In future work, the results of this study should be integrated into biophysical models to estimate the possible impacts of exposure to B-fields on dispersal at the population scale. How long the effects of short exposure to B-fields lasts in gadoid larvae should also be investigated. The thresholds of B-field intensity that alter the behavior of gadoid larvae should be identified to support the estimation of areas around B-field sources where there is a higher probability of eliciting measurable effects. In addition, follow up experiments should focus on making realistic estimates of the duration of exposure of fish larvae to B-fields from anthropogenic sources *in situ*. The effect of B-fields on juvenile cod and haddock, which live in close association to the sea bottom after settlement, should also be studied.

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Conflict of interest: The authors declare no conflict of interest.

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Data availability

Data are available from the corresponding author upon reasonable request.

Author contributions

A.C. designed the study, collected, analyzed, and interpreted the data, and wrote the paper; C.M.F.D. designed the study, interpreted the data, and wrote the paper. T.L. analyzed and interpreted the data; R.B. interpreted the data and wrote the paper; A.B.S. designed the study, interpreted the data, wrote the paper. H.I.B. designed the study, interpreted the data, wrote the paper, and is the leader of the project that funded the research.

References

- Albert O. Ecology of haddock (*Melanogrammus aeglefinus* L.) in the Norwegian Deep. *ICES J Mar Sci* 1994;51:31–44. <https://doi.org/10.1006/jmsc.1994.1004>
- Auditore PJ, Lough RG, Broughton EA. A review of the comparative development of Atlantic cod (*Gadus morhua* L.) and haddock (*Melanogrammus aeglefinus* L.) based on an illustrated series of larvae and juveniles from Georges Bank. *NAFO Sci Coun Studies* 1994;20:7–18.
- Baker MR, Goodman AC, Santo JB *et al.* Repeatability and reliability of exploratory behavior in proactive and reactive zebrafish, *Danio rerio*. *Sci Rep* 2018;8:1–9. <https://doi.org/10.1038/s41598-018-30630-3>
- Carbonara P, Alfonso S, Zupa W *et al.* Behavioral and physiological responses to stocking density in sea bream (*Sparus aurata*): do coping styles matter? *Physiol Behav* 2019;212:112698. <https://doi.org/10.1016/j.physbeh.2019.112698>
- Chaput R, Sochala P, Miron P *et al.* Quantitative uncertainty estimation in biophysical models of fish larval connectivity in the Florida Keys. *ICES J Mar Sci* 2022;79:609–32. <https://doi.org/10.1093/ICESJMS/FSAC021>
- Conover WJ, Iman RL. Rank transformations as a bridge between parametric and nonparametric statistics. *Am Stat* 1981;35:124–8. <https://doi.org/10.1080/00031305.1981.10479327>
- Cresci A, De Rosa R, Agnisola C. Assessing the influence of personality on sensitivity to magnetic fields in zebrafish. *J Vis Exp* 2019a;e59229. <https://doi.org/10.3791/59229>
- Cresci A, De Rosa R, Fraissinet S *et al.* Zebrafish "personality" influences sensitivity to magnetic fields. *Acta Ethol* 2018;21:195–201. <https://doi.org/10.1007/s10211-018-0292-9>
- Cresci A, Durif CMF, Larsen T *et al.* Magnetic fields produced by subsea high-voltage direct current cables reduce swimming activity of haddock larvae (*Melanogrammus aeglefinus*). *PNAS Nexus* 2022a;1:1–7. <https://doi.org/10.1093/PNASNEXUS/PGAC175>
- Cresci A, Paris CB, Foretich MA *et al.* Atlantic haddock (*Melanogrammus aeglefinus*) larvae have a magnetic compass that guides their orientation. *iScience* 2019b;19:1173–8. <https://doi.org/10.1016/j.isci.2019.09.001>
- Cresci A, Perrichon P, Durif CMF *et al.* 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*). *Mar Environ Res* 2022b;176:105609. <https://doi.org/10.1016/J.MARENRES.2022.105609>
- Cresci A, Sandvik AD, Sævik PN *et al.* The lunar compass of European glass eels (*Anguilla anguilla*) increases the probability that they recruit to North Sea coasts. *Fish Oceanogr* 2021;30:315–30. <https://doi.org/10.1111/FOG.12521>
- Cresci A, Zhang G, Durif CMF *et al.* Atlantic cod (*Gadus morhua*) larvae are attracted by low-frequency noise simulating that of operating offshore wind farms. *Commun Biol* 2023 6:1–10. <https://doi.org/10.1038/s42003-023-04728-y>
- Degraer S, Brabant R, Vanaverbeke J. *EDEN 2000—Exploring options for a nature-proof Development of offshore wind farms inside a Natura 2000 area*. Brussels: Memoirson the Marine Environment, 2023.
- Dhanak M, Coulson R, Dibiasio C *et al.* Assessment of electromagnetic field emissions from subsea cables. In: *Paper Presented at the 4th Marine Energy Technology Symposium*. Washington, DC, 2016. <https://tethys.pnnl.gov/publications/assessment-electromagnetic-field-emissions-subsea-cables>
- Durif CMF, Nyqvist D, Taormina B *et al.* Magnetic fields generated by submarine power cables have a negligible effect on the swimming behavior of Atlantic lumpfish (*Cyclopterus lumpus*) juveniles. *PeerJ* 2023;11:e14745. <https://doi.org/10.7717/PEERJ.14745/SUPP-1>
- Fiksen Ø, Jørgensen C, Kristiansen T *et al.* Linking behavioural ecology and oceanography: larval behaviour determines growth, mortality and dispersal. *Mar Ecol Prog Ser* 2007;347:195–205. <https://doi.org/10.3354/meps06978>
- Gill AB, Desender M. 2020 State of the Science Report, chapter 5: risk to animals from electromagnetic fields emitted by electric cables and marine renewable energy devices. Richland, WA: Pacific Northwest National Laboratory (PNNL), 2020. <https://doi.org/10.2172/1633088>
- Gill AB, Gloyne-Philips I, Kimber J *et al.* Marine renewable energy, electromagnetic (EM) fields and EM-sensitive animals. In *Humanity and the Sea*, Springer S, ed. by M. A. Shields, A. I. L. Payne, Springer, Dordrecht, 2014;61–79. https://doi.org/10.1007/978-94-017-8002-5_6
- Harsanyi P, Scott K, Easton BAA *et al.* The effects of anthropogenic electromagnetic fields (EMF) on the early development of two commercially important crustaceans, European lobster, *Homarus gammarus* (L.) and edible crab, *Cancer pagurus* (L.). *J Mar Sci Eng* 2022;10:564. <https://doi.org/10.3390/JMSE10050564>
- Hjort J. 1914. Fluctuations in the great fisheries of northern Europe viewed in the light of biological research, *Fluctuations in the great fisheries of northern Europe viewed in the light of biological research* 20;1–228.
- Houde ED. Recruitment variability. In: *Fish Reproductive Biology: Implications for Assessment and Management*. John Wiley & Sons, Ltd., Hoboken, New Jersey, 2016, 98–187.
- Hutchison ZL, Gill AB, Sigra P *et al.* A modelling evaluation of electromagnetic fields emitted by buried subsea power cables and encountered by marine animals: considerations for marine renewable energy development. *Renew Energy* 2021;177:72–81, <https://doi.org/10.1016/j.renene.2021.05.041>
- Hutchison ZL, Gill AB, Sigra P *et al.* Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. *Sci Rep* 2020a;10:1–15. <https://doi.org/10.1038/s41598-020-60793-x>
- Hutchison ZL, Secor DH, Gill AB. The interaction between resource species and electromagnetic fields associated with electricity production by offshore wind farms. *Oceanography* 2020b;33:96–107. <https://doi.org/10.5670/OCEANO.2020.409>

- Ibarra-Zatarain Z, Parati K, Cenadelli S *et al.* Reproductive success of a marine teleost was correlated with proactive and reactive stress-coping styles. *J Fish Biol* 2019;94:402–13. <https://doi.org/10.1111/JFB.13907>
- Jakubowska M, Greszkiewicz M, Fey DP *et al.* Effects of magnetic fields related to submarine power cables on the behaviour of larval rainbow trout (*Oncorhynchus mykiss*). *Mar Freshw Res* 2021;72:1196–207. <https://doi.org/10.1071/MF20236>
- Klimley AP, Wyman MT, Kavet R. Chinook salmon and green sturgeon migrate through San Francisco Estuary despite large distortions in the local magnetic field produced by bridges. *PLoS One* 2017;12:e0169031. <https://doi.org/10.1371/JOURNAL.PONE.0169031>
- Leis JM, Caselle JE, Bradbury IR *et al.* Does fish larval dispersal differ between high and low latitudes? *Proc R Soc B Biol Sci* 2013;280:20130327. <https://doi.org/10.1098/RSPB.2013.0327>
- Leis JM. 2006. Are larvae of demersal fishes plankton or Nekton? In: *Advances in Marine Biology*. 51;57–141. [https://doi.org/10.1016/S0065-2881\(06\)51002-8](https://doi.org/10.1016/S0065-2881(06)51002-8)
- Methratta ET, Hawkins A, Hooker BR *et al.* Offshore wind development in the Northeast US Shelf Large Marine Ecosystem: ecological, human, and fishery management dimensions. *Oceanography* 2020;33:16–27. <https://doi.org/10.5670/OCEANO.2020.402>
- Munk P, Larsson P, Danielsen D *et al.* Variability in frontal zone formation and distribution of gadoid fish larvae at the shelf break in the northeastern North Sea. *Mar Ecol Prog Ser* 1999;177:221–33. <https://doi.org/10.3354/meps177221>
- Munk P. Fish larvae at fronts: horizontal and vertical distributions of gadoid fish larvae across a frontal zone at the Norwegian Trench. *Deep Sea Res Part II Top Stud Oceanogr* 2014;107:3–14. <https://doi.org/10.1016/J.DSR2.2014.01.016>
- Nabighian MN, Grauch VJS, Hansen RO *et al.* The historical development of the magnetic method in exploration. *Geophysics* 2005;70:33ND–61ND. <https://doi.org/10.1190/1.2133784>
- Nyqvist D, Durif C, Johnsen MG *et al.* Electric and magnetic senses in marine animals, and potential behavioral effects of electromagnetic surveys. *Mar Environ Res* 2020;155:104888. <https://doi.org/10.1016/j.marenvres.2020.104888>
- Pope J, Macer CT. An evaluation of the stock structure of North Sea cod, haddock, and whiting since 1920, together with a consideration of the impacts of fisheries and predation effects on their biomass and recruitment. *ICES J Mar Sci* 1996;53:1157–69. <https://doi.org/10.1006/jmsc.1996.0141>
- Rey S., Boltana S., Vargas R., Roher N., Mackenzie S. 2013. Combining animal personalities with transcriptomics resolves individual variation within a wild-type zebrafish population and identifies underpinning molecular differences in brain function. *Molecular Ecology*, 22: 6100–6115.
- Scott K, Harsanyi P, Lyndon AR. Understanding the effects of electromagnetic field emissions from Marine Renewable Energy Devices (MREDS) on the commercially important edible crab, *Cancer pagurus* (L.). *Mar Pollut Bull* 2018;131:580–8. <https://doi.org/10.1016/J.MARPOLBUL.2018.04.062>
- Soares-Ramos EPP, de Oliveira-Assis L, Sarrias-Mena R *et al.* Current status and future trends of offshore wind power in Europe. *Energy* 2020;202:117787. <https://doi.org/10.1016/J.ENERGY.2020.117787>
- Soukissian T, O'Hagan AM, Azzellino A *et al.* European offshore renewable energy: towards a sustainable future. In: JJ Heymans, P Kellett, B Alexander, Á Muñiz Piniella, A Rodriguez Perez, J Van Elslander (eds.), *Future Science Brief No. 9 of the European Marine Board*. Ostend, Belgium. European Marine Board 2023. <https://doi.org/10.5281/zenodo.7561906>
- Sutton SJ, Lewin PL, Swingler SG. Review of global HVDC subsea cable projects and the application of sea electrodes. *Int J Electr Power Energy Syst* 2017;87:121–35. <https://doi.org/10.1016/J.IJEPES.2016.11.009>
- Taormina B, Bald J, Want A *et al.* A review of potential impacts of submarine power cables on the marine environment: knowledge gaps, recommendations and future directions. *Renew Sustain Energy Rev* 2018;96:380–91. <https://doi.org/10.1016/j.rser.2018.07.026>
- Taormina B, Poi CD, Agnalt A-L *et al.* Impact of magnetic fields generated by AC/DC submarine power cables on the behavior of juvenile European lobster (*Homarus gammarus*). *Aquat Toxicol* 2020;220:105401. <https://doi.org/10.1016/j.aquatox.2019.105401>
- Villegas-Ríos D, Réale D, Freitas C *et al.* Personalities influence spatial responses to environmental fluctuations in wild fish. *J Anim Ecol* 2018;87:1309–19. <https://doi.org/10.1111/1365-2656.12872>
- Wyman M. T., Klimley A. P., Battleson R. D., Agosta V. T., Chapman E. D., Haverkamp P. J., Pagel M. D. *et al.*, . 2018. Behavioral responses by migrating juvenile salmonids to a subsea high-voltage DC power cable. *Marine Biology*, 165: 134. <https://doi.org/10.1007/s00227-018-3385-0> .
- Yang C, Xin Y, Li C *et al.* Simulation and analysis of magnetic field in HVDC transmission cable. *IOP Conf Ser Mater Sci Eng* 2018;382:032041. <https://doi.org/10.1088/1757-899X/382/3/032041>

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