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Impact of magnetic fields generated by AC/DC submarine power cables on the behavior of juvenile European lobster (*Homarus gammarus*)

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ABSTRACT

The number of submarine power cables using either direct or alternating current is expected to increase drastically in coming decades. Data concerning the impact of magnetic fields generated by these cables on marine invertebrates are scarce. In this context, the aim of this study was to explore the potential impact of anthropogenic static and time-varying magnetic fields on the behavior of recently settled juvenile European lobsters (*Homarus gammarus*) using two different behavioral assays. Day-light conditions were used to stimulate the sheltering behavior and facilitate the video tracking. We showed that juvenile lobsters did not exhibit any change of behavior when submitted to an artificial magnetic field gradient (maximum intensity of 200 μT) compared to non-exposed lobsters in the ambient magnetic field. Additionally, no influence was noted on either the lobsters' ability to find shelter or modified their exploratory behavior after one week of exposure to anthropogenic magnetic fields (225 ± 5 μT) which remained similar to those observed in control individuals. It appears that static and time-varying anthropogenic magnetic fields, at these intensities, do not significantly impact the behavior of juvenile European lobsters in daylight conditions. Nevertheless, to form a complete picture for this biological model, further studies are needed on the other life stages as they may respond differently.

1. Introduction

Submarine power cables are used worldwide for numerous applications: to connect autonomous grids, to supply power to islands, marine platforms or subsea observatories, and to carry power generated by marine renewable energy installations (offshore wind farms, tidal and wave turbines). In 2015, almost 8000 km of HVDC (High Voltage Direct-Current) cables were present on the seabed worldwide, 70 % of which were in European waters (Ardelean and Minnebo, 2015). The number of submarine power cables, using either direct (DC) or alternating current (AC), is expected to increase dramatically in the coming decades. This rise is in part due to an increase in grids connecting islands and archipelagos, and also to the development of marine renewable energy projects. Indeed, marine renewable energy development is a possible solution to the global increasing demand for renewable energy in order to combat climate change (Copping et al., 2014).

Submarine power cables, like any other man-made installation or human activity at sea may temporarily or permanently impact the marine life and habitats through habitat damage or loss, introduction of artificial substrates, noise, chemical pollution, heat emission, risk of entanglement and the creation of reserve effects (Taormina et al., 2018). Among all these potential environmental incidences, one of the main concerns is related to the emission of electromagnetic fields

Abbreviations: HVDC, high-voltage direct current; DC, direct current; AC, alternating current; EMF, electromagnetic fields; MF, magnetic fields; HMF1, high magnetic field 1; HMF2, high magnetic field 2; L MF3, low magnetic field 3; LMF4, low magnetic field 4; CL, carapace length

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(EMF), which are generated by the electric current flowing through power cables. EMF can be divided into electric fields (measured in volts per meter, V. m^{-1}) and magnetic fields (MF, measured in teslas, T). Electric fields are generally confined inside cables because of the armouring whereas MF are not, their strength increasing with electric current flow. MF characteristics vary greatly as a function of the cable type (distance between conductors, load balance between the three phases in the cable, *etc.*) just as much as the power and type of current, *i.e.* DC *vs*. AC (DC producing a static MF and AC a time-varying MF; Copping et al., 2016; Ohman et al., 2007). The MF produced at the surface of the cable by either DC or AC cables can be highly heterogeneous, with intensity ranging from 1 μT for smallest cables to 3200 μT for the most powerful HVDC cables (Bochert and Zettler, 2006; Normandeau Associates Inc. et al., 2011). However, the MF strength rapidly declines with distance from the cable, typically decreasing to 200 μT at 1 m from a 1000 A cable (Normandeau Associates Inc. et al., 2011).

Numerous marine species harness the Earth's geomagnetic field for orientation and migration, including elasmobranchs (rays and sharks), teleosts, mammals, turtles, mollusks and crustaceans (Cresci et al., 2017; Durif et al., 2013; Kirschvink, 1997; Lohmann et al., 2008; Lohmann and Ernst, 2014; Walker et al., 2002; Willows, 1999). Consequently, anthropogenic MF can potentially impact species capable of magnetoreception through effects on predator/prey interactions, avoidance/attraction behaviors, navigation/orientation capabilities or induce physiological and developmental effects (Copping et al., 2016). Data concerning anthropogenic MF impacts on invertebrates are scarce. Among the few studies, some have reported minor or non-significant impact of anthropogenic MF (Bochert and Zettler, 2004; Hutchison et al., 2018; Love et al., 2017, 2015, Woodruff et al., 2013, 2012), while other studies highlighted some stress responses (Malagoli et al., 2004; Stankevičiūtė et al., 2019).

The European lobster (*Homarus gammarus*) is widely distributed along the continental shelf in the North-East Atlantic from Morocco to near the Arctic Circle. This species is heavily exploited in some areas and represents great economic value. In 2016, the global catch was estimated at 4713 t (Source = FAO FishStat). European lobsters show a preference for rocky habitats which provide shelters (Childress and Jury, 2007). Consequently they are frequently observed within artificial reefs, including those related to marine renewable energy installations and their submarine power cables (Hooper and Austen, 2014; Krone et al., 2013). This behavioral trait can lead to extended MF exposures which may induce stress for the lobster. Although two experimental studies showed low impact of EMF exposure on the behavioral activity of a similar species, the American lobster (*Homarus americanus*; Hutchison et al., 2018; Woodruff et al., 2013), no study has focused on the European lobster so far. Furthermore, no attention has been paid to early developmental stages of either of these species, which can be assumed to be more vulnerable to disturbances than adult specimens.

In this context, the aim of this study was to explore the potential impact of anthropogenic MF produced by either AC or DC submarine power cables on the behavior of recently settled European lobster juveniles. To address this question, we studied using two different behavioral assays (*i*) the avoidance/attraction effect of anthropogenic MF and (*ii*) the effect of an extended MF exposure on their exploratory behavior and ability to find a shelter.

2. Methods

2.1. Specimens' origin and maintenance

European lobster juveniles (N = 203) at development stages VI-VIII were used. The offspring came from six berried females purchased from a local lobster dealer, close to Bergen and transferred May 2018 to the Institute of Marine Research Austevoll station (N60°05′15.36″, E5°15′54″). Hatching followed the set-up described by Agnalt et al. (2017), although the filtrated seawater was from 160 m depth (showing a constant salinity of 34.7 ppt) and heated to a temperature of 14° C. Once reaching stage IV, the post-larvae were transferred and raised individually in single compartments. The compartments were maintained inside a tank (1.5 × 1.5 m with 1 m depth of water with a flow of 30 L min^{-1}) with seawater at 14 °C in continuous flow at a 16:8 h light:dark cycle. The lobsters were fed daily with dry feed OTOHIME C2 (PTC Japan) or frozen shrimp. The postlarva stage IV, which still had a swimming behavior, continued their growth to stage V (*i.e.* juvenile), and then became fully benthic. To induce normal claw development (Govind and Pearce, 1989), grained sand was added to each individual unit at stage IV and V. Only juveniles with two intact claws were used in these experiments. Exposure treatment and testing described below took place in a separate room than the one used to rear the lobster juveniles. This experiment was carried out following The Code of Ethics of the World Medical Association for animal experiments.

2.2. Helmholtz coils

To produce artificial magnetic fields, Helmholtz coils designed by MAPPEM Geophysics© (http://www.mappem-geophysics.com/) were used. Each coil is constituted of 600 m of wire (conductor material composed of copper with a 2.5 mm^2 section) rolled up around a 1.5 × 1.5 m wooden frame. The coils' system (1.5 × 1.5 × 1.0 m) was designed to produce time varying (*i.e.* AC) or static (*i.e.* DC) magnetic fields with intensities reaching 230 μT, which is comparable to those produced by high power submarine cables at their close proximity. Based on data calculated by the French transmission system operator RTE, 200 μT corresponds to the intensity found at 1 m of a 1000 A DC / single core AC power cables. For DC treatment, each of the two coils was alimented by a 15 V electrical current generated by a BK Precision DC power supply (model BK-1745A). For AC treatment, each of the two coils was alimented by a 15 V electrical current generated by single phase variable auto transformers (model RS CMV 15E-1). The coils created (*i*) an area of homogeneous magnetic fields in the center, and (*ii*) an area of decreasing magnetic field gradient in the periphery (SI 1). The natural geomagnetic field had an intensity of 51 μT.

2.3. Avoidance/attraction test

In order to study the avoidance/attraction potential of anthropogenic MF on juvenile lobsters, individuals were tested under three MF gradient configurations: (*i*) with a time varying MF gradient (hereafter called AC MF, N = 30), (*ii*) with a static MF gradient (hereafter called DC MF, N = 31) and (*iii*) with ambient MF (*i.e.* control treatment, N = 31).

Long rectangular raceways made with white opaque walls (125 × 14 × 7 cm) were placed across the MF intensity gradient area, either AC or DC (Fig. 1.A). For control treatment, the coil was turned off, resulting in the absence of any MF gradient inside the raceway. Within the raceway, four different zones were defined *a posteriori* (Fig. 1.A): High Magnetic Field 1 (HMF1), High Magnetic Field 2 (HMF2), Low Magnetic Field 3 (LMF3) and Low Magnetic Field 4 (LMF4). Each raceway was filled with 3 cm of seawater (at 12 ± 1 °C; the seawater was replaced between each trial). To observe shelter seeking behavior, two grey and opaque half-cylinder shelters (2.50 × 7.50 × 1.25 cm), open on both sides, were positioned at each end of the raceway (at 2.5 cm from the wall; Fig. 1.A). Thus, one shelter was positioned in the high MF end of the raceway, and the other one in the low MF end of the raceway. Although *H. gammarus* is a nocturnal animal, more active during the night, the test was performed with daylight conditions, in order to stimulate their sheltering behavior. The luminosity intensity was measured at 5 different points along the raceway (Fig. 2) using a spectrophotometer (Ocean Optics FLAME-S-UV-VIS).

The behavioral tests were carried out by carefully placing each

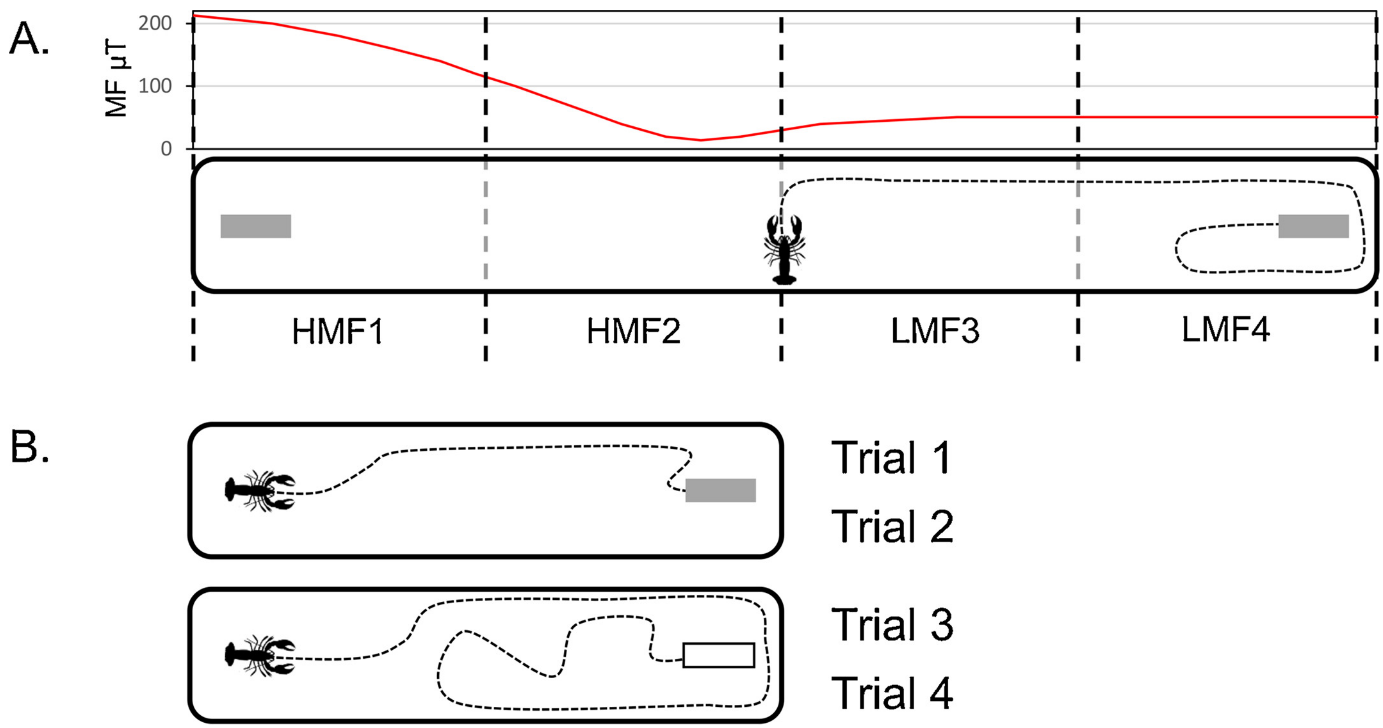

Fig. 1. Experimental setup **A**. Avoidance/attraction test: raceway of 125 × 14 × 7 cm with two half-cylinder shelters were used at each side. Zones were labelled into 4 different zones depending on the intensity of the magnetic field: HMF1: High Magnetic Field 1, HMF2: High Magnetic Field 2, LMF3: Low Magnetic Field 3, LMF4: Low Magnetic Field 4 ; the magnetic field gradient generated for the AC and DC treatments is shown at the top. **B**. Post-exposure test: raceway of 66 × 14 × 7 cm was used, one shelter was positioned at one end, four consecutive trials were performed, trials 1 and 2 with grey opaque shelter, trials 3 and 4 with white opaque shelter. The Dotted line represent possible paths of movement of lobsters. All figures to scale except lobster representation.

lobster inside a circular ring (5 × 5 cm) at the center of the raceway (mid distance between the two shelters). After 10 min of acclimation, the lobster was released by removing the ring, and the animal's behavior was then recorded over a 45-minute period with a GoPro hero 5 Black (1080 p, 25 fps) placed above the raceway. No one was present in the experimental room during video-tracking of lobster behavior. The lobsters used in the experiments had never been used in prior experimentation. Each individual (N = 92) was tested once and treatments were randomized. Between 16 and 32 different individuals were tested per day. All experiments were undertaken between 11 a.m. and 4 p.m. The carapace length of each lobster was measured after the test.

Each video was analyzed with the video tracking software Ethovision XT (Noldus ©). From each footage, we extracted *i*) the time the lobster took to find the shelter (in minutes; when the lobster did not enter any shelter, a maximum time was assigned *i.e.* 45 min.), *ii*) the time spent inside the two different shelters and the four raceway zones when outside shelters (as a percentage), *iii*) the total distance travelled overall and per zone (distances are expressed in Carapace Length CL, in order to avoid any bias of the specimens' size on the distance travelled), *iv*) the mean velocity in overall and per zone (in CL s^{-1}) and *v*) the movement/immobility ratio (*i.e.*, when outside a shelter, the ratio between the time when the lobster moved and the total time) overall and per each zone.

2.4. Exposure treatment

To study juvenile lobster exploratory and shelter seeking behavior after MF exposure, 111 individuals were exposed to the following treatments for one week prior to the test: (*i*) time varying MF (hereafter called AC MF, N = 38, MF = 225 ± 5 µT), (*ii*) static MF (hereafter called DC MF, N = 35, MF = 225 ± 5 µT) or (*iii*) ambient MF (*i.e.* control treatment, N = 38). During the exposure, lobsters were maintained in separate units (7.0 × 3.5 × 7.0 cm) within a tank (40 × 30 × 10 cm) which was placed in a homogeneous MF area. The tank was filled with 8 cm of seawater at 12 ± 1 °C in current flow (0.85 L min^{-1}). The room was submitted to a 9:15 h light:dark cycle, and the lobsters were fed daily with dried food or frozen shrimp alternately.

After one week of exposure, the ability to find a shelter of each lobster was assessed following the method described by Cresci et al. (2018). To do so, rectangular raceways with white opaque walls (66 × 14 × 7 cm) were used (Fig. 1.B). Raceways were placed in the MF homogeneous area used to exposure, and filled with 3 cm of seawater (at 12 ± 1 °C; the water was entirely replaced between each trial). A half-cylinder shelter (2.50 × 7.50 × 1.25 cm) was positioned at one end of the raceway. As for the attraction/avoidance test, the test was performed with day-light conditions, in order to stimulate their sheltering behavior.

For each trial, one lobster was released at the end of the raceway (opposite the shelter) and the behavior of the animal was recorded for 30 min with a GoPro hero 5 Black (1080 p, 25 fps) placed above. The lobsters used in the experiments had never been tested before. To study their learning abilities, each lobster performed 4 consecutive trials of 30 min using two different colored opaque shelters open on both sides: grey shelters for the first two trials and white shelters for the last two trials (Fig. 1.B). Different colors were used to simulate different difficulties. The lobsters used in this experiment were different from those used in the "attraction/avoidance test". Treatments were randomized for each individual. Between 6 and 8 different individuals per day were tested and all experiments were achieved between 11 a.m. and 4 pm. The carapace length of each lobster (N = 111) was measured after the trials.

Each video was analyzed *posteriori* with the video tracking software Ethovision (Noldus ©). We extracted *i*) the time the lobster used to find the shelter (in min; when the lobster did not enter the shelter, the maximum time was assigned *i.e.* 30 min), *ii*) the total distance travelled

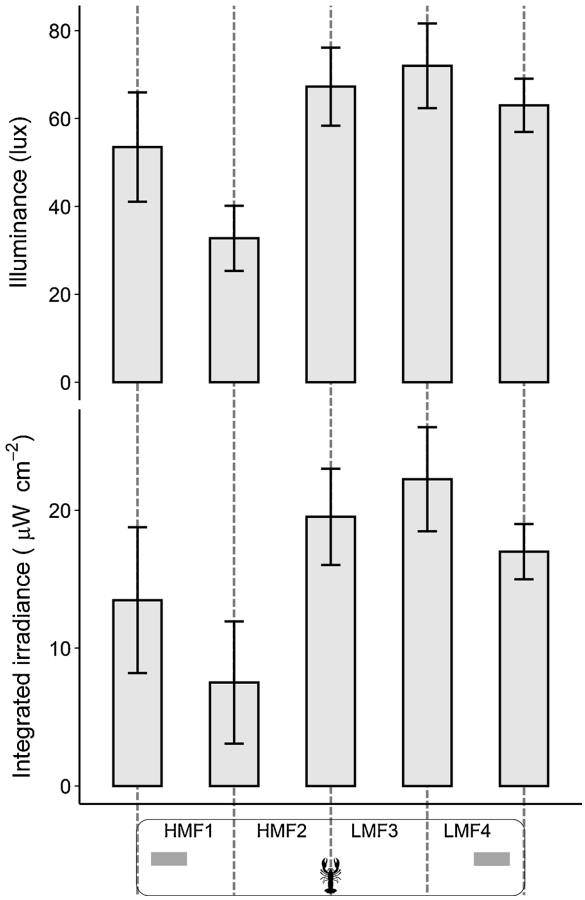

Fig. 2. Light measurement along the raceways used for avoidance/attraction experiment. The luminosity intensity was measured at 5 different points along the raceway using a spectrophotometer (Ocean Optics FLAME-S-UV-VIS). Error bar represents the standard deviation. Up: illuminance, bottom : integrated irradiance.

(for the same reasons than for the avoidance/attraction test, the distances are expressed in Carapace Length CL), *iii*) the mean velocity (in CL s^{-1}) and *iv*) the activity ratio (*i.e.*, when outside the shelter, the ratio between the time where the lobster moves and the total time).

2.5. Statistical analysis

Results are given as mean ± standard error. We tested the data for normality assumption using the Shapiro-Wilk test as well as variance homoscedasticity by examining graphed residuals. When possible, two-way repeated-measures ANOVA (RM-ANOVA) with the intra-subject factor "zone" (for avoidance/attraction test) or "trial" (for exposure experiment) and the inter-subject factor "treatment", were used to study the different behavior (*i.e.* the time to find a shelter, the total distance travelled, the mean velocity and the activity ratio) of the lobsters. For each RM-ANOVA, variance-covariance matrix sphericity was verified using Mauchly test. When significant, p-values were recalculated using the Greenhouse-Geisser correction. Non-parametric rank test of Kruskal-Wallis was used when the use of RM-ANOVA was not possible. Finally, to compare the proportions of time spent in the different shelters or in the different zones of the raceway, permutational analysis of variance (PERMANOVA) with euclidian distance was applied. The statistical analyses were performed using RStudio (V 3.4.3; RStudio Team, 2015) with the packages *vegan* (Oksanen et al., 2018), *lme4* (Bates et al., 2015), *Rmisc* (Hope, 2013) and *ggplot2* (Wickham, 2016).

3. Results

3.1. Avoidance/attraction test

Once released, lobsters typically headed in one direction until they made contact with the side of the raceway, then, progressed exploring the area in either direction by feeling the raceway wall using their antennae. Once lobsters perceived or made physical contact with one of the shelters, 68.5 % of them entered it and remained there until the end of the test. Lobsters which never entered a shelter during the test, usually spent part of their time exploring the raceway, before staying immobile in a corner of the raceway until the end of the test.

All treatments taken together, 87 % of the lobsters entered at least one of the shelters, the first entrance occurred on average 13.8 min after the beginning of the test. This time did not differ significantly between treatments (14.4 ± 2.7 min for Control; 14.4 ± 2.6 min for AC and 12.6 ± 2.7 min for DC; Kruskal-Wallis test P = 0.96).

In all three treatments, lobsters spent more time inside the shelters (68 ± 3.5 % of the time) than outside. Across all treatments, lobsters spent more time in the high MF-shelter end (38.9 ± 4.5 % of its time, Fig. 3) than in the low MF-shelter (29 ± 4.2 % of its time, Fig. 3). When outside shelter, in all treatments, lobsters spent twice as long in the high MF end of the raceway (*i.e* zones HMF1 and HMF2, 21.9 ± 2.9 % of time outside shelters) than in the low MF end of the raceway (*i.e.* zone LMF3 and LMF4, 9.7 ± 1.4 % of time outside shelters; Fig. 3). The proportion of time spent in the low MF side shelters, high MF side shelter and in the different area did not change

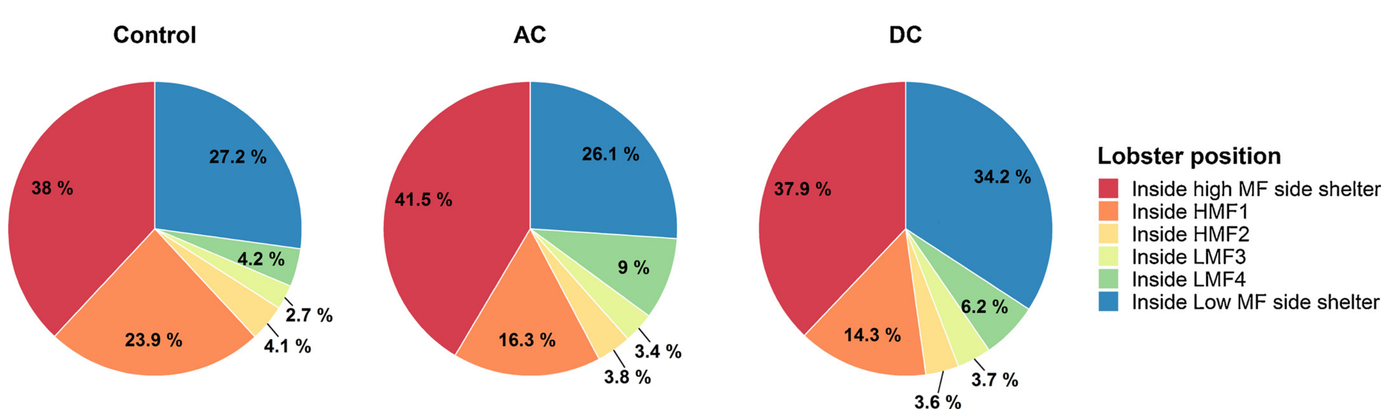

Fig. 3. Effect of the magnetic field gradient on attraction/avoidance behavior of the European lobster (Homarus gammarus). Percentage of time spent in the two different shelters and in the different zones of the raceway. HMF1: High Magnetic Field 1, HMF2: High Magnetic Field 2, LMF3: Low Magnetic Field 3, LMF4: Low Magnetic Field 4. The three treatments were Control: coil off (n = 31); AC: coil on in alternative current mode (n = 30); DC: coil on in continuous current mode (n = 31).

Table 1
Summary of the different two-way ANOVAs for repeated measures on the effects of the treatment and the interaction of treatment and zone on the different behavior of the European lobster (Homarus gammarus) for the attraction/avoidance test.

Effect	df	F	p.value
Mean velocity			
Treatment	89	0.15	0.86
Treatment:Zone	267	0.99	0.43
Distance travelled			
Treatment	89	1.17	0.31
Treatment:Zone	267	1.59	0.15
Activity ratio			
Treatment	89	0.75	0.48
Treatment:Zone	267	1.01	0.42

across treatments (PERMANOVA, df = 2, pseudo-F = 0.39, P = 0.82, Fig. 3).

Within the entire raceway and within each zone of the raceway, the total distance travelled, the mean velocity and the activity ratio of the lobsters did not differ significantly between the three treatments (RM-ANOVA P > 0.05 in all cases; Table 1; Fig. 4).

3.2. Exposure test

During the week of exposure, no mortality occurred.

Typical behavior of lobsters during this test was similar to that observed during the avoidance/attraction test. When released, lobsters chose a direction until they made contact with the wall of the raceway, then, explored the raceway using their antennae. Once they found the shelter, they usually entered and remained there for the rest of the test. When considering all trials and all treatments together, 71.5 % of the lobsters entered the shelter at least once, and among them, 77.2 % did not get out for the rest of the trial after the first entrance. When a lobster did not enter a shelter, it usually spent part of its time exploring the aquarium, and eventually, remained motionless until the end of the test.

Across all treatments, a larger number of lobsters entered the grey shelter (*i.e.* trials 1 and 2, respectively 93.6 % and 95.7 % of the lobsters had entered the shelter) than the white shelter (*i.e.* trials 3 and 4, respectively 46.8 % and 53.2 % of the lobsters had entered the shelter). They also took less time to enter the grey shelter (5.6 ± 0.8 min and 4.5 ± 0.7 min for trial 1 and 2) than the white shelter (21.5 ± 1.1 min and 19.9 ± 1.2 min for trial 3 and 4; Fig. 5).

All trials taken together and within each trial, the time to enter the shelter did not significantly change between treatments (RM-ANOVA P > 0.05; Table 2; Fig. 5). In the same way, the total distance travelled, the mean velocity and the movement/immobility ratio of the lobsters did not differ significantly between the three treatments (RM-ANOVA P > 0.05 in all cases; Table 2; Fig. 5).

Lobsters did not show any signs of learning in any of the treatments; *i.e.* lobsters did not take significantly less time to find the shelter in trial 2 compared to trial 1, and in trial 4 compared to trial 3 (Fig. 5).

4. Discussion

Homarus gammarus is perceived as a species potentially exposed to the emission of man induced MF, since it colonizes artificial reefs created by submarine power cables. Moreover, its relatively sedentary way of life may expose them durably (Normandeau Associates Inc. et al., 2011). Potential risks of artificial MF on juvenile lobsters are alteration of sheltering capability and exploratory behavior.

4.1. Impact of magnetic fields on behavior

We demonstrated that juvenile European lobsters do not exhibit any

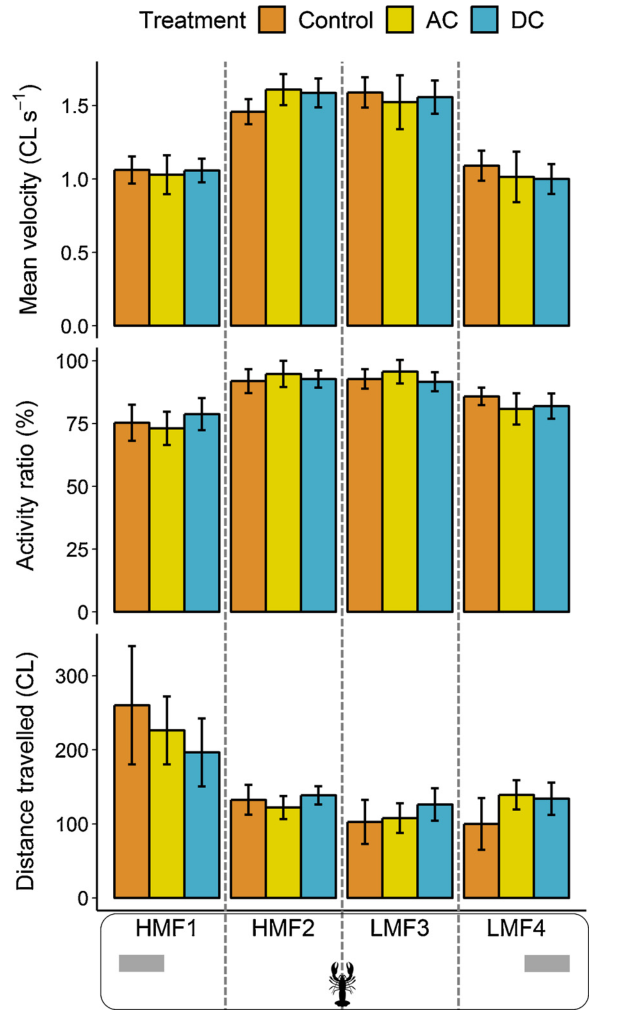

Fig. 4. Effect of the magnetic field gradient on the behavior of the European lobster (Homarus gammarus). CL: Carapace length of lobster, HMF1: High Magnetic Field 1, HMF2: High Magnetic Field 2, LMF3: Low Magnetic Field 3, LMF4: Low Magnetic Field 4. Error bars represent the 95 % confidence-interval corrected for interindividual variability (Loftus and Masson, 1994). The three treatments were Control: coil off (n = 31); AC: coil on in alternative current mode (n = 30); DC: coil on in continuous current mode (n = 31).

change of behavior when submitted to an artificial static or time-varying magnetic field gradient (with maximum intensity of 200 μT) compared to non-exposed lobsters in the ambient magnetic field. Indeed, their exploratory behavior (described by mean velocity, total distance travelled and activity ratio), the choice of shelter as well as the proportion of time spent in the different areas of the MF gradient were not significantly different from the ones exhibited by control lobsters.

Our results showed that lobsters were preferentially attracted to one side of the raceway, whatever the treatment (*i.e.* Control, AC MF gradient or DC MF gradient). This attraction was likely due to a light gradient within the raceway created by the shadow of the upper Helmholtz coil. Indeed, the side that lobsters preferred was darker (illuminance: 43.1 ± 5.1 lx, Fig. 2) than the other side of the raceway (67.5 ± 3.1 lx, Fig. 2). Considering that lobsters show a strong light avoidance (Botero and Atema, 1982; Johns and Mann, 1987), this light gradient can explain this attraction. Nevertheless, we can however conclude that static and time-varying MF do not constitute a primary factor determining European lobster's exploratory and sheltering behavior *via* any attraction or repulsion and is at least overridden by subtle light heterogeneity. However, it cannot be excluded that without this subtle light gradient, the behavioral answer of the juvenile lobsters

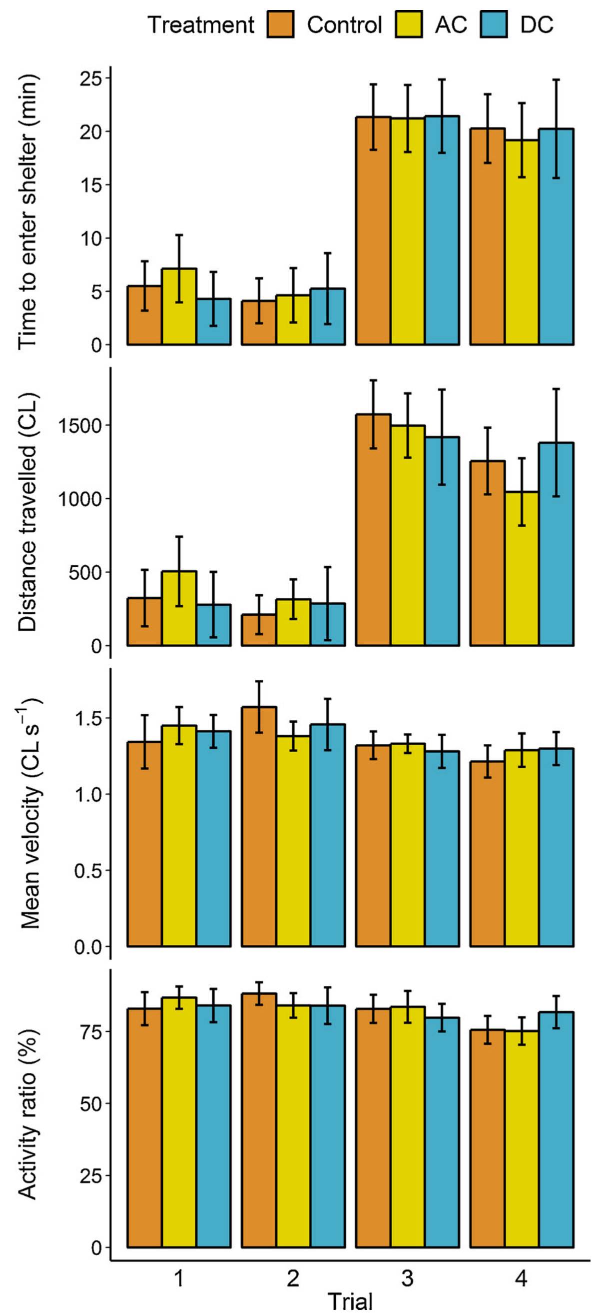

Fig. 5. Effect of 1-week exposure to different magnetic fields on the behavior of the European lobster (Homarus gammarus) during four consecutive trials. Trials 1 and 2 were with a grey opaque shelter, trials 3 and 4 with a white opaque shelter. CL: Carapace length of lobster, Error bars represent the 95 % confidence-interval corrected for interindividual variability (Loftus and Masson, 1994). The three treatments were Control: coil off (n = 38); AC: coil on in alternative current mode (n = 38); DC: coil on in continuous current mode (n = 35).

to artificial magnetic fields could be different.

Previous studies on interaction between MF and other decapod species showed divergent conclusions. Adult American lobsters (*Homarus americanus*) and Dungeness crab (*Metacarcinus magister)* did not significantly change their behavior (*i.e.* activity and use of space) when submitted to high MF intensities in laboratory (static MF from 500 to 1100 μT; Woodruff et al., 2013, 2012). Nevertheless, the authors highlight that results of these two studies need to be treated carefully because of a noteworthy large amount of variability between individuals, trials, and seasons. In a field study of Love et *al.* (2017), the same species (Dungeness crab) and the rock crab (*Cancer productus)* had no difficulty to cross 35 kV-AC power cables at intensities between 24.6 and 42.8 μT (for Dungeness crab) and between 13.8 and 116.8 μT (for Rock crab).

Table 2
Summary of the different two-way ANOVAs for repeated measures on the effects of the treatment and the interaction of treatment and trial on the different behavior of the European lobster (Homarus gammarus) after 1-week exposure.

Effect	df	F	p.value
Time to enter shelter			
Treatment	91	1.20	0.30
Treatment:Trial	273	0.39	0.84
Mean velocity			
Treatment	91	0.33	0.72
Treatment:Trial	273	1.42	0.22
Distance travelled			
Treatment	91	0.34	0.71
Treatment:Trial	273	1.32	0.26
Activity ratio			
Treatment	91	0.25	0.78
Treatment:Trial	273	1.43	0.20

On the other hand, in a field study, *H. americanus* responded to MF by a subtle but significant change of its use of space during an exposure to a power cable (static MF of 65.3 μT) but which did not actually create any barrier to its displacement (Hutchison et al., 2018). In a recent laboratory experiment, the edible crab *Cancer pagurus* showed an attraction to a high artificial MF (2800 μT) although the low number of replicates (n = 15) did not allow for robust conclusions (Scott et al., 2018). Similar results were found *in situ* with the freshwater crayfish *Orconectes limosus*, which was more present inside shelters submitted to a less intense artificial MF (800 μT) than in non-exposed shelters (Tański et al., 2005). Finally, the Caribbean spiny lobsters (*Palinurus argus*) showed contradictory results with a size-dependent avoidance of artificial MF (300 μT) *i.e.* only the biggest spiny lobsters avoided this artificial MF (Ernst and Lohmann, 2018).

P. argus can sense the Earth's MF, probably through magnetite-based magnetoreceptors organs (Ernst and Lohmann, 2016), and use this information for navigation and homing (Boles and Lohmann, 2003; Lohmann et al., 1995; Lohmann, 1985, 1984; Lohmann and Ernst, 2014). It is possible that some *Homarus sp*. populations, which migrate seasonally on shore to reproduce (Pezzack and Duggan, 1986), may possess similar sensory capacity, which could explain in part the results obtained by Hutchison et al. (2018). However, to date, there is no evidence proving such ability to detect MF. Ernst and Lohmann (2018) mentioned a possible ontogenic shift in the ability of the spiny lobster to respond to MF, this species may acquire or improve their magnetosense as they grow. If this ontogenic shift exists also for the European lobsters, the juveniles that did not show any significant response to artificial MF could be too young to be impacted but may respond differently once older. This point highlights the need to fully apprehend the impact of MF from power cables on *Homarus sp*. by considering its whole life cycle, and that further knowledge on their physiological ability of magneto-reception is required.

4.2. Magnetic fields exposure

In our experiments, all lobsters survived after one week of exposure to MF, whether from AC or DC (225 ± 5 μT). Also, after this exposure, the lobsters' ability to find a shelter and their exploratory behavior (mean velocity, total distance travelled and activity ratio) remained similar to those observed in the control individuals.

Sheltering constitutes an important antipredator mechanism for juvenile lobsters in the wild. Consequently, if this behavior is modified by any disturbance, juvenile lobster mortality may be significantly impacted. For example, Cresci et al. (2018) showed that exposure to teflubenzuron, an in-feed pharmaceutical used in salmon aquaculture, significantly impacted the sheltering behavior of juvenile European lobsters, especially by reducing their learning abilities *i.e.* their capacity to learn the location of shelters and reach them more quickly. In the present study, lobsters did not show any signs of learning regardless of treatment. This lack of learning may be due to the young age of our lobsters (newly settled between stages VI and VIII, CL around 0.9 cm) compared to the later juveniles in the study by Cresci et al. (CL around 1.7 cm). Similarly, juvenile American lobsters at stage V did not show immediate learning when placed in similar conditions, *i.e.* an open area with a constant visual contact with the shelter (Bayer et al., 2017). An alternative explanation to the absence of learning in our study can be the absence of necessity to reach the shelter rapidly, *i.e.* no stress source or rewards existed in our experimental setup that could stimulate learning behavior. A number of studies show learning ability of several species of crustacean (mainly crayfish and crabs) increase to avoid stress (*e.g.* electrical shocks) or to obtain food reward (Tomsic and Romano, 2013).

During the behavioral tests, all the lobsters had more difficulties to find the white shelter compared to the grey one whatever the treatment. Lobster vision, just as their sense of touch provided by their long antennae, are both crucial for detecting and exploring potential shelters (Bayer et al., 2017; Cresci et al., 2018). The high contrast of color between the grey shelter and white background of the raceway may explain why lobsters were more able to visually locate the grey shelters. On the other hand, white shelters on a white background became almost invisible to the lobsters, which had to physically touch the shelter with their antennae to detect it, in a more random process. Considering that vision and touch senses of juvenile lobsters as well as their sheltering behavior were not impacted by a 1-week exposure to static or time-varying MF, their capacity to escape predation in the wild should remain unchanged in the presence of artificial MF of similar intensities.

In the literature, lack of significant impact of MF on survival of marine organisms was also shown by other laboratory studies using higher MF values. In a study of Bochert and Zettler (2004), the north sea prawn (*Crangon crangon*), the round crab (*Rhithropanopeus harrisii*), the glacial relict isopod (*Saduria entomon*), the blue mussel (*Mytilus edulis*) and young flounders (*Platichtys flesus*) showed no difference of survival between control animals and animals exposed to a static MF of 3700 μT for several weeks. In the same way, early life stages of the rainbow trout (*Oncorhynchus mykiss*, 36 days with static MF of 10,000 μT or time-varying MF of 1000 μT) and Northern pike (*Esox lucius*, around 20 days with static MF of 10,000 μT), showed no significant impact on larval and embryonic mortality despite an increase of the yolk-sac absorption rate for the exposed individuals (Fey et al., 2019a,b). Nevertheless, no information about post-exposure development of these larvae was given. Despite this apparent absence of direct mortality caused by MF reported by the literature, Stankevičiūtė et al. (2019) stressed for the first time a genotoxic and cytotoxic effect of exposure to 1000 μT AC MF on different aquatic species: the rainbow trout (larval stage, 40 days exposure), the Baltic clam (*Limecola balthica*, 12 days exposure) and the common ragworm (*Hediste diversicolor*, 12 days exposure). The degrees of genotoxicity and cytotoxicity of MF on aquatic organisms remain poorly known at present, but affected integrity of genetic information may cause a variety of diseases and disorders, including tumors (Stankevičiūtė et al., 2019). In conclusion, these genetic and physiological criteria should also be considered in future studies.

4.3. Influence of magnetic fields intensity

The MF intensities used in experimental studies previously mentioned are in most cases higher or equal to 1000 μT, which constitute very high values of MF that could be encountered at the surface of high energy power cables. The low numbers of field studies which performed MF measures *in situ*, highlighted significantly lower intensities (a maximum of 116.8 μT in study of Love et al., 2017). Thus, transposition of the results obtained experimentally to the field remains difficult. In a context where both the number of connections and the individual power of submarine cables are quickly increasing, more *in situ* measurements of the MF intensity produced, which remain extremely scarce, are needed to better understand and evaluate the impact of this stressor on marine life.

Nevertheless, in the scope of providing accurate guidelines regarding technology used for energy transmission, threshold values of sensitivity/tolerance must be evaluated for number of marine organisms by using a wide range of MF intensities, even including high intensities probably unrealistic for submarine power cables.

5. Conclusion

In our study, we showed that anthropogenic MF with realistic intensity values (around 200 μT), whether coming from DC or AC, did not impact juvenile European lobsters. The ability to find a shelter after a 1-week exposure remained unchanged and no avoidance or attraction to this anthropogenic MF can be demonstrated. However, we showed that a light intensity gradient affected their shelter seeking behavior. It cannot be excluded that higher values (which potentially might be encountered by juvenile lobsters while seeking shelter very close to the cable) might have an impact on the behavior of this species. To fully understand the impact of anthropogenic MF on this biological model, further studies, also including experiments on the effect of MF without the presence of any other cues (*e.g.* light) are necessary. Furthermore, further knowledge on *Homarus* sp. physiological ability of magneto-reception and how this potential magneto-sense can evolve during its life is required.

Author contributions

BT, CD, AC and ND are at the origin of the project. BT, CD, AC, ND, ALA, FF, JFD and REL conceived the experimental design. BT, CD and FF conducted the experiments. BT and CDP analyzed the video-data. BT analyzed the data. All authors contributed to writing the manuscript.

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 material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.aquatox.2019.105401.

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