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1 **Title**

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

4 **Authors**

5 Bastien Taormina^{ab}, Carole Di Poi^c, Ann-Lisbeth Agnalt^d, Antoine Carlier^b, Nicolas Desroy^e, Rosa
6 Helena Escobar-Lux^f, Jean-François D'eu^g, Florian Freytet^f, Caroline M.F. Durif^f

7 **Affiliations**

8 **a** France Energies Marines ; 525 avenue Alexis de Rochon 29280 Plouzané, France

9 **b** Ifremer, Centre de Bretagne, DYNECO - Laboratoire d'écologie benthique côtière; ZI de la Pointe
10 du Diable - CS 10070, 29280 Plouzané, France

11 **c** Ifremer, Laboratoire des Sciences de l'Environnement Marin (LEMAR) UMR 6539
12 UBO/CNRS/IRD/Ifremer ; CS 10070, 29280 Plouzané, France

13 **d** Institute of Marine Research ; P.O. Box 1870, Nordnes, 5817 Bergen, Norway

14 **e** Ifremer, Laboratoire Environnement Ressources Bretagne Nord ; 38 rue du Port Blanc, 35801
15 Dinard, France

16 **f** Institute of Marine Research ; Austevoll Research Station, Sauganeset 16, N-5392 Storebø, Norway

17 **g** Mappem Geophysics ; Batiment Tech-Iroise, 1 rue des Ateliers, Zone de Mespaol 29290, Saint-
18 Renan, France

19 **Corresponding author**

20 Bastien Taormina, bastien.taormina@france-energies-marines.org , Ifremer, Centre de Bretagne,
21 DYNECO - Laboratoire d'écologie benthique côtière, ZI de la Pointe du Diable - CS 10070, 29280
22 Plouzané, France

23 **Abstract**

24 The number of submarine power cables using either direct or alternating current is expected to
25 increase drastically in coming decades. Data concerning the impact of magnetic fields generated by
26 these cables on marine invertebrates are scarce. In this context, the aim of this study was to explore the
27 potential impact of anthropogenic static and time-varying magnetic fields on the behavior of recently

1 settled juvenile European lobsters (*Homarus gammarus*) using two different behavioral assays. Day-
2 light conditions were used to stimulate the sheltering behavior and facilitate the video tracking. We
3 showed that juvenile lobsters did not exhibit any change of behavior when submitted to an artificial
4 magnetic field gradient (maximum intensity of 200 μ T) compared to non-exposed lobsters in the
5 ambient magnetic field. Additionally, no influence was noted on either the lobsters' ability to find shelter
6 or modified their exploratory behavior after one week of exposure to anthropogenic magnetic fields (225
7 \pm 5 μ T) which remained similar to those observed in control individuals. It appears that static and time-
8 varying anthropogenic magnetic fields, at these intensities, do not significantly impact the behavior of
9 juvenile European lobsters in daylight conditions. Nevertheless, to form a complete picture for this
10 biological model, further studies are needed on the other life stages as they may respond differently.

11 **Keywords**

12 Anthropogenic impact – Behavior - *Homarus gammarus* - Magnetic field - Submarine power cable

13 **Abbreviations**

14 HVDC, High-Voltage Direct Current; DC, Direct Current; AC, Alternating Current; EMF,
15 ElectroMagnetic Fields; MF, Magnetic Fields; HMF1, High Magnetic Field 1; HMF2, High Magnetic
16 Field 2; LMF3, Low Magnetic Field 3; LMF4, Low Magnetic Field 4; CL, Carapace Length.

1 **1. Introduction**

2 Submarine power cables are used worldwide for numerous applications: to connect autonomous
3 grids, to supply power to islands, marine platforms or subsea observatories, and to carry power generated
4 by marine renewable energy installations (offshore wind farms, tidal and wave turbines). In 2015, almost
5 8,000 km of HVDC (High Voltage Direct-Current) cables were present on the seabed worldwide, 70%
6 of which were in European waters (Ardelean and Minnebo, 2015). The number of submarine power
7 cables, using either direct (DC) or alternating current (AC), is expected to increase dramatically in the
8 coming decades. This rise is in part due to an increase in grids connecting islands and archipelagos, and
9 also to the development of marine renewable energy projects. Indeed, marine renewable energy
10 development is a possible solution to the global increasing demand for renewable energy in order to
11 combat climate change (Copping et al., 2014).

12 Submarine power cables, like any other man-made installation or human activity at sea may
13 temporarily or permanently impact the marine life and habitats through habitat damage or loss,
14 introduction of artificial substrates, noise, chemical pollution, heat emission, risk of entanglement and
15 the creation of reserve effects (Taormina et al., 2018). Among all these potential environmental
16 incidences, one of the main concerns is related to the emission of electromagnetic fields (EMF), which
17 are generated by the electric current flowing through power cables. EMF can be divided into electric
18 fields (measured in volts per meter, $V.m^{-1}$) and magnetic fields (MF, measured in teslas, T). Electric
19 fields are generally confined inside cables because of the armouring whereas MF are not, their strength
20 increasing with electric current flow. MF characteristics vary greatly as a function of the cable type
21 (distance between conductors, load balance between the three phases in the cable, *etc.*) just as much as
22 the power and type of current, *i.e.* DC *vs.* AC (DC producing a static MF and AC a time-varying MF;
23 Copping et al., 2016; Ohman et al., 2007). The MF produced at the surface of the cable by either DC or
24 AC cables can be highly heterogeneous, with intensity ranging from 1 μ T for smallest cables to 3,200
25 μ T for the most powerful HVDC cables (Bochert and Zettler, 2006; Normandeau Associates Inc. et al.,
26 2011). However, the MF strength rapidly declines with distance from the cable, typically decreasing to
27 200 μ T at 1 meter from a 1000 A cable (Normandeau Associates Inc. et al., 2011).

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

11 The European lobster (*Homarus gammarus*) is widely distributed along the continental shelf in
12 the North-East Atlantic from Morocco to near the Arctic Circle. This species is heavily exploited in
13 some areas and represents great economic value. In 2016, the global catch was estimated at 4,713 t
14 (Source = FAO FishStat). European lobsters show a preference for rocky habitats which provide shelters
15 (Childress and Jury, 2007). Consequently they are frequently observed within artificial reefs, including
16 those related to marine renewable energy installations and their submarine power cables (Hooper and
17 Austen, 2014; Krone et al., 2013). This behavioral trait can lead to extended MF exposures which may
18 induce stress for the lobster. Although two experimental studies showed low impact of EMF exposure
19 on the behavioral activity of a similar species, the American lobster (*Homarus americanus*; Hutchison
20 et al., 2018; Woodruff et al., 2013), no study has focused on the European lobster so far. Furthermore,
21 no attention has been paid to early developmental stages of either of these species, which can be assumed
22 to be more vulnerable to disturbances than adult specimens.

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

1

2 **2. Methods**

3 **2.1. Specimens' origin and maintenance**

4 European lobster juveniles (N=203) at development stages VI-VIII were used. The offspring
5 came from six berried females purchased from a local lobster dealer, close to Bergen and transferred
6 May 2018 to the Institute of Marine Research Austevoll station (N60°05'15.36", E5°15'54"). Hatching
7 followed the set-up described by Agnalt et al. (2017), although the filtrated seawater was from 160 m
8 depth (showing a constant salinity of 34.7 ppt) and heated to a temperature of 14°C. Once reaching stage
9 IV, the post-larvae were transferred and raised individually in single compartments. The compartments
10 were maintained inside a tank (1.5x1.5 m with 1 m depth of water with a flow of 30 L min⁻¹) with
11 seawater at 14 °C in continuous flow at a 16:8 h light:dark cycle. The lobsters were fed daily with dry
12 feed OTOHIME C2 (PTC Japan) or frozen shrimp. The postlarva stage IV, which still had a swimming
13 behavior, continued their growth to stage V (*i.e.* juvenile), and then became fully benthic. To induce
14 normal claw development (Govind and Pearce, 1989), grained sand was added to each individual unit
15 at stage IV and V. Only juveniles with two intact claws were used in these experiments. Exposure
16 treatment and testing described below took place in a separate room than the one used to rear the lobster
17 juveniles. This experiment was carried out following The Code of Ethics of the World Medical
18 Association for animal experiments.

19 **2.2. Helmholtz coils**

20 To produce artificial magnetic fields, Helmholtz coils designed by MAPPEM Geophysics©
21 (<http://www.mappem-geophysics.com/>) were used. Each coil is constituted of 600 m of wire (conductor
22 material composed of copper with a 2.5 mm² section) rolled up around a 1.5 x 1.5 m wooden frame. The
23 coils' system (1.5 x 1.5 x 1.0 m) was designed to produce time varying (*i.e.* AC) or static (*i.e.* DC)
24 magnetic fields with intensities reaching 230 µT, which is comparable to those produced by high power
25 submarine cables at their close proximity. Based on data calculated by the French transmission system
26 operator RTE, 200 µT corresponds to the intensity found at 1 m of a 1000 A DC / single core AC power

1 cables. For DC treatment, each of the two coils was alimeted by a 15 V electrical current generated by
2 a BK Precision DC power supply (model BK-1745A). For AC treatment, each of the two coils was
3 alimeted by a 15 V electrical current generated by single phase variable auto transformers (model RS
4 CMV 15E-1). The coils created (i) an area of homogeneous magnetic fields in the center, and (ii) an
5 area of decreasing magnetic field gradient in the periphery (SI 1). The natural geomagnetic field had an
6 intensity of 51 μ T.

7 **2.3. Avoidance/attraction test**

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

12 Long rectangular raceways made with white opaque walls (125x14x7 cm) were placed across
13 the MF intensity gradient area, either AC or DC (Figure 1.A). For control treatment, the coil was turned
14 off, resulting in the absence of any MF gradient inside the raceway. Within the raceway, four different
15 zones were defined *a posteriori* (Figure 1.A): High Magnetic Field 1 (HMF1), High Magnetic Field 2
16 (HMF2), Low Magnetic Field 3 (LMF3) and Low Magnetic Field 4 (LMF4). Each raceway was filled
17 with 3 cm of seawater (at 12 ± 1 °C; the seawater was replaced between each trial). To observe shelter
18 seeking behavior, two grey and opaque half-cylinder shelters (2.50x7.50x1.25 cm), open on both sides,
19 were positioned at each end of the raceway (at 2.5 cm from the wall; Figure 1.A). Thus, one shelter was
20 positioned in the high MF end of the raceway, and the other one in the low MF end of the raceway.
21 Although *H. gammarus* is a nocturnal animal, more active during the night, the test was performed with
22 day-light conditions, in order to stimulate their sheltering behavior. The luminosity intensity was
23 measured at 5 different points along the raceway (Figure 2) using a spectrophotometer (Ocean Optics
24 FLAME-S-UV-VIS).

25 The behavioral tests were carried out by carefully placing each lobster inside a circular ring (5x5
26 cm) at the center of the raceway (mid distance between the two shelters). After 10 minutes of

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

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

16 **2.4. Exposure treatment**

17 To study juvenile lobster exploratory and shelter seeking behavior after MF exposure, 111
18 individuals were exposed to the following treatments for one week prior to the test: *(i)* time varying MF
19 (hereafter called AC MF, N=38, MF = $225 \pm 5 \mu\text{T}$), *(ii)* static MF (hereafter called DC MF, N=35, MF
20 = $225 \pm 5 \mu\text{T}$) or *(iii)* ambient MF (*i.e.* control treatment, N=38). During the exposure, lobsters were
21 maintained in separate units (7.0x3.5x7.0 cm) within a tank (40x30x10 cm) which was placed in a
22 homogeneous MF area. The tank was filled with 8 cm of seawater at $12 \pm 1^\circ\text{C}$ in current flow (0.85 L
23 min^{-1}). The room was submitted to a 9:15 h light:dark cycle, and the lobsters were fed daily with dried
24 food or frozen shrimp alternately.

25 After one week of exposure, the ability to find a shelter of each lobster was assessed following
26 the method described by Cresci et al. (2018). To do so, rectangular raceways with white opaque walls

1 (66x14x7 cm) were used (Figure 1.B). Raceways were placed in the MF homogeneous area used to
2 exposure, and filled with 3 cm of seawater (at 12 ± 1 °C; the water was entirely replaced between each
3 trial). A half-cylinder shelter (2.50x7.50x1.25 cm) was positioned at one end of the raceway. As for the
4 attraction/avoidance test, the test was performed with day-light conditions, in order to stimulate their
5 sheltering behavior.

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

16 Each video was analyzed *posteriori* with the video tracking software Ethovision (Noldus ©).
17 We extracted *i*) the time the lobster used to find the shelter (in min; when the lobster did not enter the
18 shelter, the maximum time was assigned *i.e.* 30 min), *ii*) the total distance travelled (for the same reasons
19 than for the avoidance/attraction test, the distances are expressed in Carapace Length CL), *iii*) the mean
20 velocity (in $CL\ s^{-1}$) and *iv*) the activity ratio (*i.e.*, when outside the shelter, the ratio between the time
21 where the lobster moves and the total time).

22 **2.5. Statistical analysis**

23 Results are given as mean \pm standard error. We tested the data for normality assumption using
24 the Shapiro-Wilk test as well as variance homoscedasticity by examining graphed residuals. When
25 possible, two-way repeated-measures ANOVA (RM-ANOVA) with the intra-subject factor “zone” (for
26 avoidance/attraction test) or “trial” (for exposure experiment) and the inter-subject factor “treatment”,

1 were used to study the different behavior (*i.e.* the time to find a shelter, the total distance travelled, the
2 mean velocity and the activity ratio) of the lobsters. For each RM-ANOVA, variance-covariance matrix
3 sphericity was verified using Mauchly test. When significant, p-values were re-calculated using the
4 Greenhouse-Geisser correction. Non-parametric rank test of Kruskal-Wallis was used when the use of
5 RM-ANOVA was not possible. Finally, to compare the proportions of time spent in the different shelters
6 or in the different zones of the raceway, permutational analysis of variance (PERMANOVA) with
7 euclidian distance was applied. The statistical analyses were performed using RStudio (V 3.4.3; RStudio
8 Team, 2015) with the packages *vegan* (Oksanen et al., 2018), *lme4* (Bates et al., 2015), *Rmisc* (Hope,
9 2013) and *ggplot2* (Wickham, 2016).

1 **3. Results**

2 **3.1. Avoidance/attraction test**

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

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

13 In all three treatments, lobsters spent more time inside the shelters (68 ± 3.5 % of the time) than
14 outside. Across all treatments, lobsters spent more time in the high MF-shelter end (38.9 ± 4.5 % of its
15 time, Figure 3) than in the low MF-shelter (29 ± 4.2 % of its time, Figure 3). When outside shelter, in
16 all treatments, lobsters spent twice as long in the high MF end of the raceway (*i.e.* zones HMF1 and
17 HMF2, 21.9 ± 2.9 % of time outside shelters) than in the low MF end of the raceway (*i.e.* zone LMF3
18 and LMF4, 9.7 ± 1.4 % of time outside shelters; Figure 3). The proportion of time spent in the low MF
19 side shelters, high MF side shelter and in the different area did not change across treatments
20 (PERMANOVA, $df=2$, pseudo- $F=0.39$, $P=0.82$, Figure 3).

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

24

25 **3.2. Exposure test**

1 During the week of exposure, no mortality occurred.

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

9 Across all treatments, a larger number of lobsters entered the grey shelter (*i.e.* trials 1 and 2,
10 respectively 93.6% and 95.7% of the lobsters had entered the shelter) than the white shelter (*i.e.* trials 3
11 and 4, respectively 46.8% and 53.2% of the lobsters had entered the shelter). They also took less time
12 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 ($21.5 \pm$
13 1.1 min and 19.9 ± 1.2 min for trial 3 and 4; Figure 5).

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

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

21 **4. Discussion**

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

1 4.1. Impact of magnetic fields on behavior

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

8 Our results showed that lobsters were preferentially attracted to one side of the raceway, whatever
9 the treatment (*i.e.* Control, AC MF gradient or DC MF gradient). This attraction was likely due to a light
10 gradient within the raceway created by the shadow of the upper Helmholtz coil. Indeed, the side that
11 lobsters preferred was darker (illuminance: 43.1 ± 5.1 lux, Figure 2) than the other side of the raceway
12 (67.5 ± 3.1 lux, Figure 2). Considering that lobsters show a strong light avoidance (Botero and Atema,
13 1982; Johns and Mann, 1987), this light gradient can explain this attraction. Nevertheless, we can
14 however conclude that static and time-varying MF do not constitute a primary factor determining
15 European lobster's exploratory and sheltering behavior via any attraction or repulsion and is at least
16 overridden by subtle light heterogeneity. However, it cannot be excluded that without this subtle light
17 gradient, the behavioral answer of the juvenile lobsters to artificial magnetic fields could be different.

18 Previous studies on interaction between MF and other decapod species showed divergent
19 conclusions. Adult American lobsters (*Homarus americanus*) and Dungeness crab (*Metacarcinus*
20 *magister*) did not significantly change their behavior (*i.e.* activity and use of space) when submitted to
21 high MF intensities in laboratory (static MF from 500 to 1,100 μT ; Woodruff et al., 2013, 2012).
22 Nevertheless, the authors highlight that results of these two studies need to be treated carefully because
23 of a noteworthy large amount of variability between individuals, trials, and seasons. In a field study of
24 Love et al. (2017), the same species (Dungeness crab) and the rock crab (*Cancer productus*) had no
25 difficulty to cross 35 kV-AC power cables at intensities between 24.6 and 42.8 μT (for Dungeness crab)
26 and between 13.8 and 116.8 μT (for Rock crab).

1 On the other hand, in a field study, *H. americanus* responded to MF by a subtle but significant
2 change of its use of space during an exposure to a power cable (static MF of 65.3 μ T) but which did not
3 actually create any barrier to its displacement (Hutchison *et al.* 2018). In a recent laboratory experiment,
4 the edible crab *Cancer pagurus* showed an attraction to a high artificial MF (2,800 μ T) although the low
5 number of replicates (n=15) did not allow for robust conclusions (Scott *et al.* 2018). Similar results were
6 found in situ with the freshwater crayfish *Orconectes limosus*, which was more present inside shelters
7 submitted to a less intense artificial MF (800 μ T) than in non-exposed shelters (Tański *et al.* 2005).
8 Finally, the Caribbean spiny lobsters (*Palinurus argus*) showed contradictory results with a size-
9 dependent avoidance of artificial MF (300 μ T) *i.e.* only the biggest spiny lobsters avoided this artificial
10 MF (Ernst and Lohmann 2018).

11 *P. argus* can sense the Earth's MF, probably through magnetite-based magnetoreceptors organs
12 (Ernst and Lohmann, 2016), and use this information for navigation and homing (Boles and Lohmann,
13 2003; Lohmann *et al.*, 1995; Lohmann, 1985, 1984; Lohmann and Ernst, 2014). It is possible that some
14 *Homarus sp.* populations, which migrate seasonally on shore to reproduce (Pezzack and Duggan, 1986),
15 may possess similar sensory capacity, which could explain in part the results obtained by Hutchison *et*
16 *al.* (2018). However, to date, there is no evidence proving such ability to detect MF. Ernst and Lohmann
17 (2018) mentioned a possible ontogenic shift in the ability of the spiny lobster to respond to MF, this
18 species may acquire or improve their magnetosense as they grow. If this ontogenic shift exists also for
19 the European lobsters, the juveniles that did not show any significant response to artificial MF could be
20 too young to be impacted but may respond differently once older. This point highlights the need to fully
21 apprehend the impact of MF from power cables on *Homarus sp.* by considering its whole life cycle, and
22 that further knowledge on their physiological ability of magneto-reception is required.

23 **4.2. Magnetic fields exposure**

24 In our experiments, all lobsters survived after one week of exposure to MF, whether from AC or
25 DC ($225 \pm 5 \mu$ T). Also, after this exposure, the lobsters' ability to find a shelter and their exploratory
26 behavior (mean velocity, total distance travelled and activity ratio) remained similar to those observed
27 in the control individuals.

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

16 During the behavioral tests, all the lobsters had more difficulties to find the white shelter compared
17 to the grey one whatever the treatment. Lobster vision, just as their sense of touch provided by their long
18 antennae, are both crucial for detecting and exploring potential shelters (Bayer et al., 2017; Cresci et al.,
19 2018). The high contrast of color between the grey shelter and white background of the raceway may
20 explain why lobsters were more able to visually locate the grey shelters. On the other hand, white shelters
21 on a white background became almost invisible to the lobsters, which had to physically touch the shelter
22 with their antennae to detect it, in a more random process. Considering that vision and touch senses of
23 juvenile lobsters as well as their sheltering behavior were not impacted by a 1-week exposure to static
24 or time-varying MF, their capacity to escape predation in the wild should remain unchanged in the
25 presence of artificial MF of similar intensities.

26 In the literature, lack of significant impact of MF on survival of marine organisms was also shown
27 by other laboratory studies using higher MF values. In a study of Bochert and Zettler (2004), the north

1 sea prawn (*Crangon crangon*), the round crab (*Rhithropanopeus harrisi*), the glacial relict isopod
2 (*Saduria entomon*), the blue mussel (*Mytilus edulis*) and young flounders (*Platichthys flesus*) showed no
3 difference of survival between control animals and animals exposed to a static MF of 3,700 μ T for
4 several weeks. In the same way, early life stages of the rainbow trout (*Oncorhynchus mykiss*, 36 days
5 with static MF of 10,000 μ T or time-varying MF of 1,000 μ T) and Northern pike (*Esox lucius*, around
6 20 days with static MF of 10,000 μ T), showed no significant impact on larval and embryonic mortality
7 despite an increase of the yolk-sac absorption rate for the exposed individuals (Fey et al. 2019a, 2019b).
8 Nevertheless, no information about post-exposure development of these larvae was given. Despite this
9 apparent absence of direct mortality caused by MF reported by the literature, Stankevičiūtė et al. (2019)
10 stressed for the first time a genotoxic and cytotoxic effect of exposure to 1,000 μ T AC MF on different
11 aquatic species: the rainbow trout (larval stage, 40 days exposure), the Baltic clam (*Limecola balthica*,
12 12 days exposure) and the common ragworm (*Hediste diversicolor*, 12 days exposure). The degrees of
13 genotoxicity and cytotoxicity of MF on aquatic organisms remain poorly known at present, but affected
14 integrity of genetic information may cause a variety of diseases and disorders, including tumors
15 (Stankevičiūtė et al., 2019). In conclusion, these genetic and physiological criteria should also be
16 considered in future studies.

17 **4.3. Influence of magnetic fields intensity**

18 The MF intensities used in experimental studies previously mentioned are in most cases higher or
19 equal to 1,000 μ T, which constitute very high values of MF that could be encountered at the surface of
20 high energy power cables. The low numbers of field studies which performed MF measures *in situ*,
21 highlighted significantly lower intensities (a maximum of 116.8 μ T in study of Love et al., 2017). Thus,
22 transposition of the results obtained experimentally to the field remains difficult. In a context where both
23 the number of connections and the individual power of submarine cables are quickly increasing, more
24 *in situ* measurements of the MF intensity produced, which remain extremely scarce, are needed to better
25 understand and evaluate the impact of this stressor on marine life.

26 Nevertheless, in the scope of providing accurate guidelines regarding technology used for energy
27 transmission, threshold values of sensitivity/tolerance must be evaluated for number of marine

1 organisms by using a wide range of MF intensities, even including high intensities probably unrealistic
2 for submarine power cables.

3 **5. Conclusion**

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

14

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22

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7

1 **Figure captions**

2 **Figure 1: Experimental setup A.** Avoidance/attraction test: raceway of 125x14x7 cm with two half-
3 cylinder shelters were used at each side. Zones were labelled into 4 different zones depending on the
4 intensity of the magnetic field: HMF1: High Magnetic Field 1, HMF2: High Magnetic Field 2, LMF3:
5 Low Magnetic Field 3, LMF4: Low Magnetic Field 4 ; the magnetic field gradient generated for the
6 AC and DC treatments is shown at the top. **B.** Post-exposure test: raceway of 66x14x7 cm was used,
7 one shelter was positioned at one end, four consecutive trials were performed, trials 1 and 2 with grey
8 opaque shelter, trials 3 and 4 with white opaque shelter. The Dotted line represent possible paths of
9 movement of lobsters. All figures to scale except lobster representation.

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

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

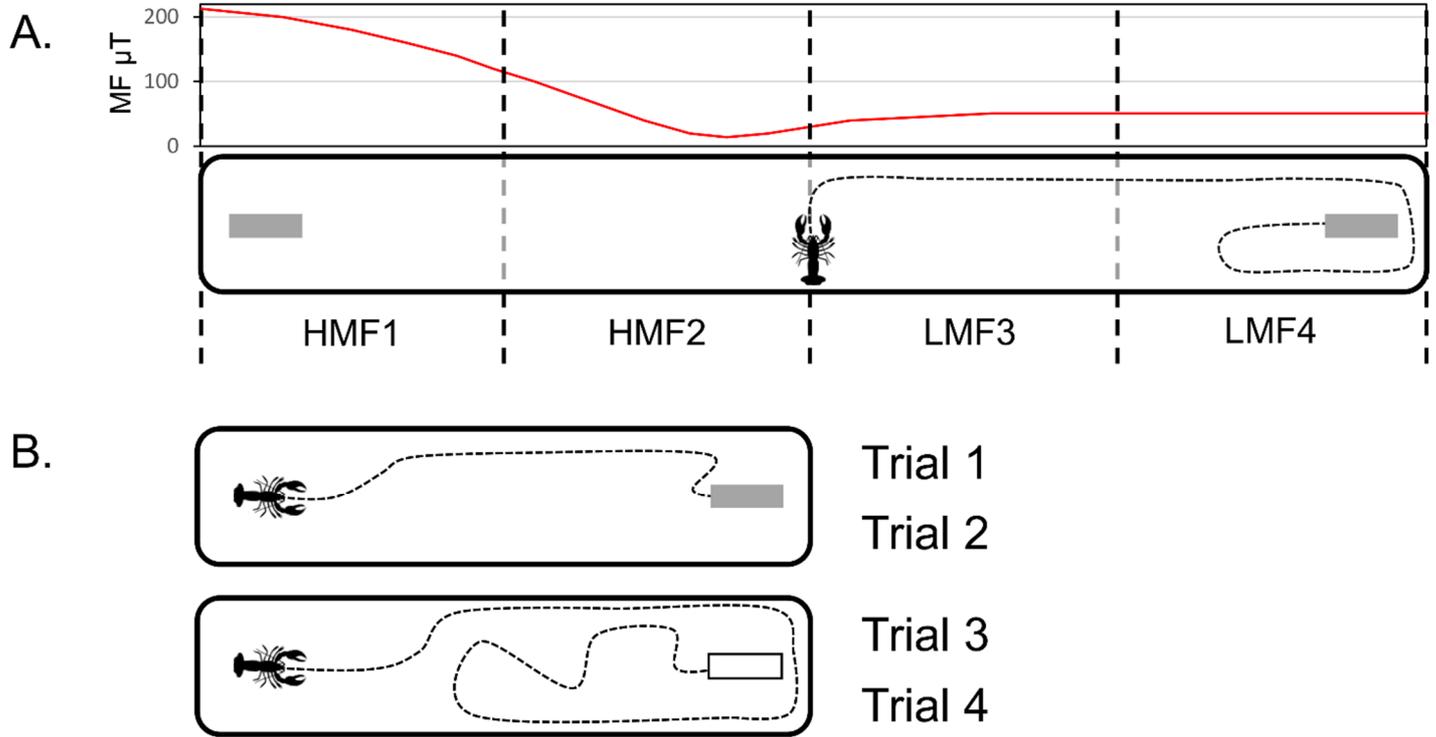
19 **Figure 4: Effect of the magnetic field gradient on the behavior of the European lobster (*Homarus***
20 ***gammarus*).** CL: Carapace length of lobster, HMF1: High Magnetic Field 1, HMF2: High Magnetic
21 Field 2, LMF3: Low Magnetic Field 3, LMF4: Low Magnetic Field 4. Error bars represent the 95%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

25 **Figure 5: Effect of 1-week exposure to different magnetic fields on the behavior of the European**
26 **lobster (*Homarus gammarus*) during four consecutive trials.** Trials 1 and 2 were with a grey

1 opaque shelter, trials 3 and 4 with a white opaque shelter. CL: Carapace length of lobster , Error bars
2 represent the 95% confidence-interval corrected for interindividual variability (Loftus and Masson,
3 1994). The three treatments were Control: coil off (n=38); AC: coil on in alternative current mode
4 (n=38); DC: coil on in continuous current mode (n=35).

5

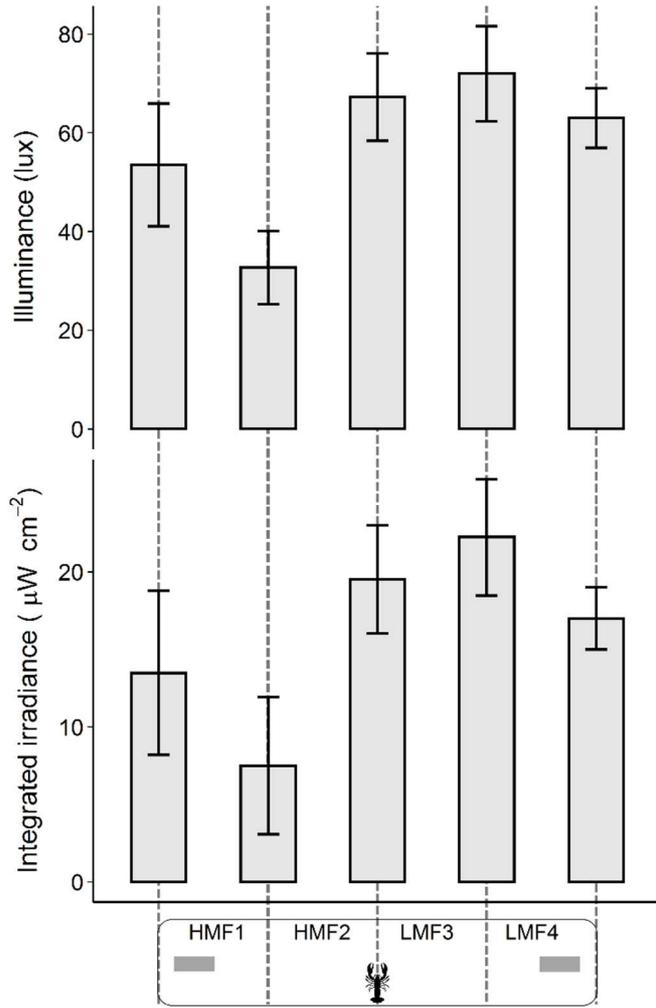
1 **Figure 1,2, 3, 4 and 5 :**



2

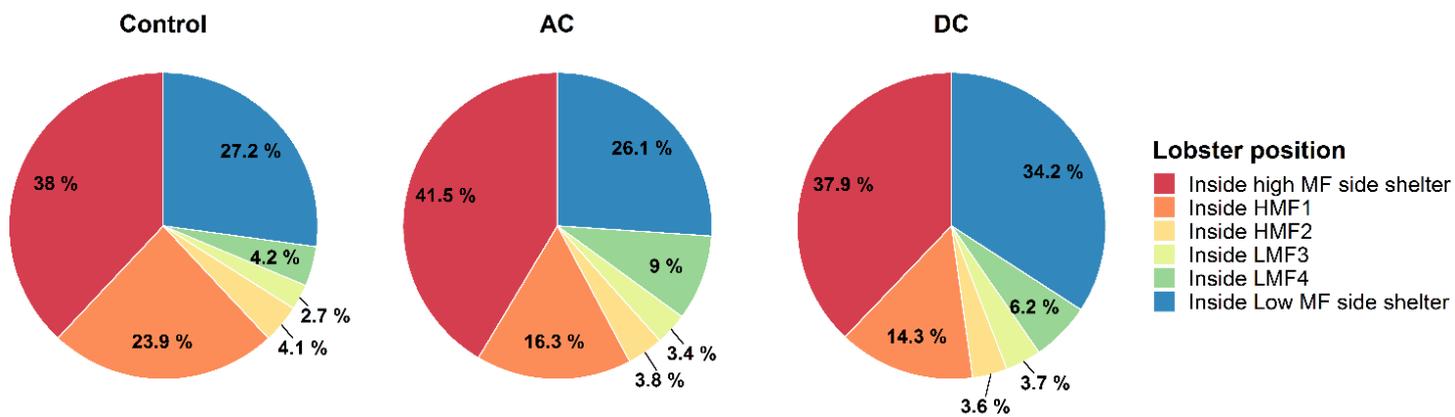
3 **Figure 1 (2 column)**

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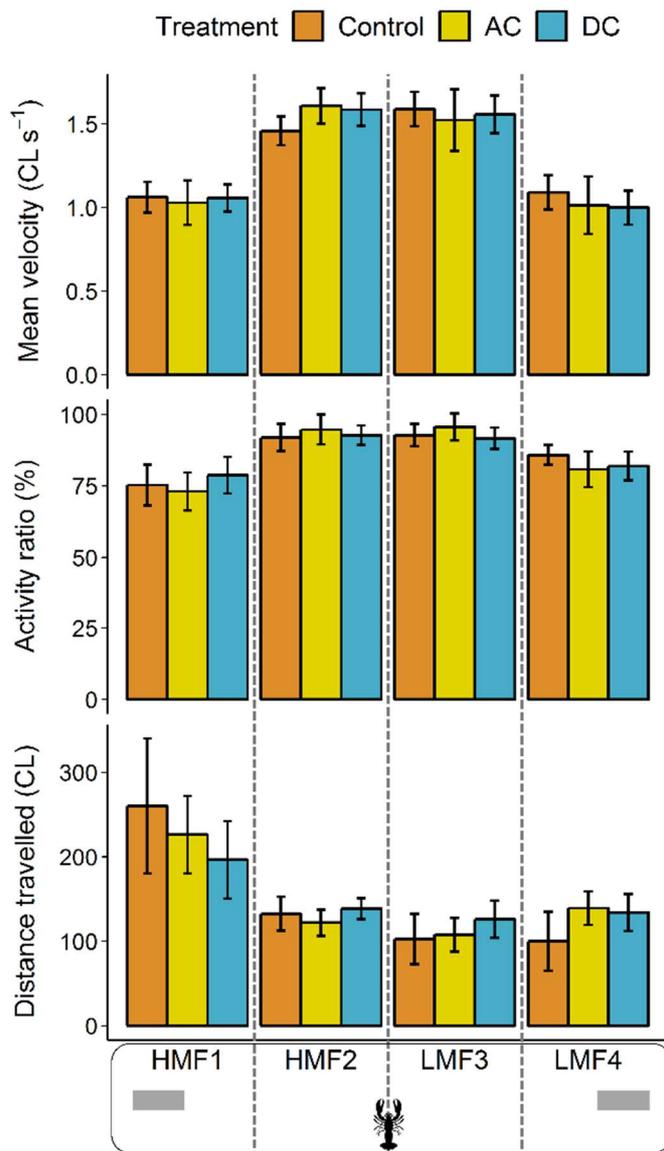


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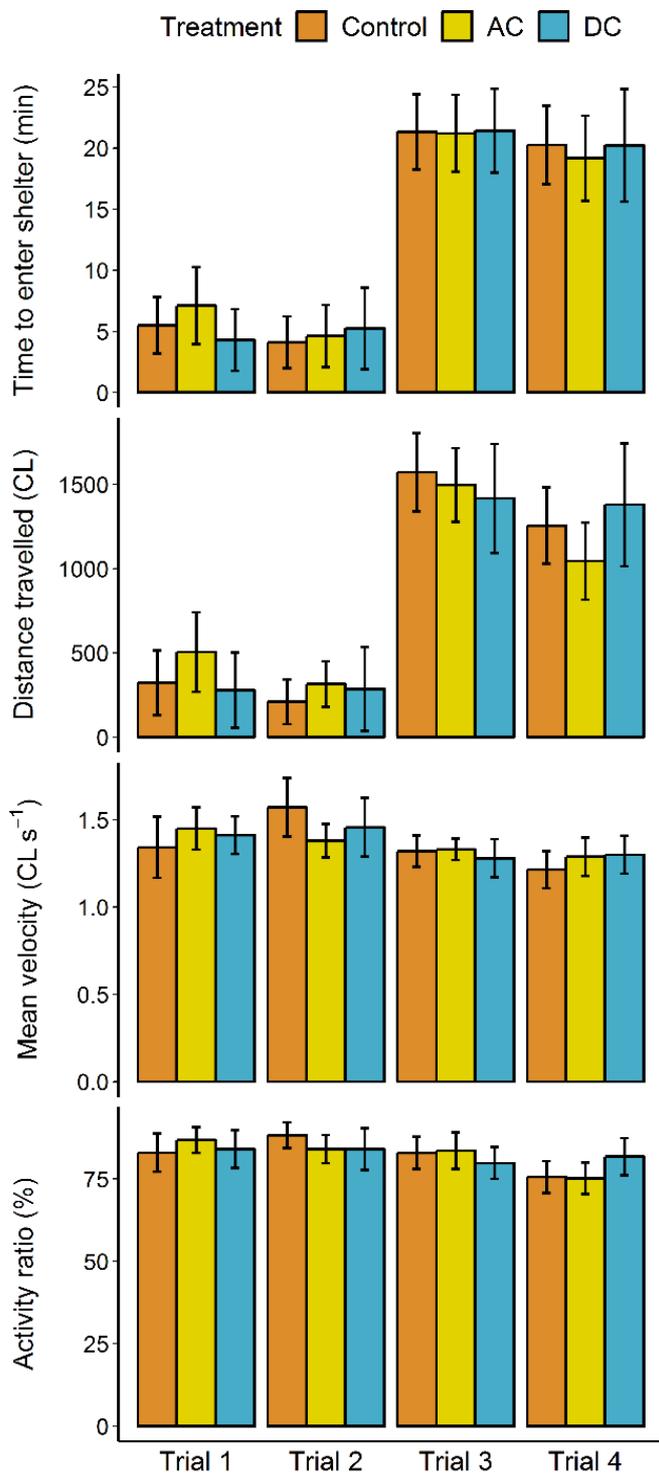
2 **Figure 2 (1 column)**

6 **Figure 3 (2column)**

1

2 **Figure 4 (1 column)**

1

2 **Figure 5 (1 column)**

1 **Tables 1 and 2**

	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
2	Treatment:Zone	267	1.01	0.42

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

	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
1	Treatment: Trial	273	1.43	0.20

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