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Effects of anthropogenic magnetic fields on the behavior of a major predator of the intertidal and subtidal zones, the velvet crab *Necora puber*

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Abstract :

With the progress of the offshore renewable energy sector and electrical interconnection projects, a substantial rise in the number of submarine power cables is expected soon. Such cables emit either alternating or direct current magnetic fields whose impact on marine invertebrates is currently unknown and hardly studied. In this context, this study aimed to assess potential short-term exposure (30 min) effects of both alternating and direct magnetic fields of increasing intensity (72–304 μ T) on the behavior of the high-ecological value velvet crab (*Necora puber*). Three experiments were designed to evaluate whether the strongest magnetic field intensities induce crabs' attraction or repulsion responses, and whether foraging and sheltering behaviors may be modified. We extracted from video analyses several variables as the time budgets crabs spent immobile, moving, feeding, or sheltering as well as total and maximal distance reached in the magnetic field (MF) gradient. The crabs exposed to artificial MF did not exhibit significant behavioral changes compared with those exposed to the "natural" MF. Overall, our results suggest that, at such intensities, artificial magnetic fields do not significantly alter behaviors of *N. puber*. Nevertheless, future studies should be conducted to examine the effects of longer exposure periods and to detect potential habituation or resilience processes.

Highlights

► Submarine power cables emit high-strength magnetic fields in their vicinity. ► Their protective rock cover can cause a reef effect and attract crustacean species. ► *Necora puber* crabs were exposed to AC and DC magnetic field gradients (max. 304 μ T). ► Exploratory, feeding and sheltering behaviors were studied across three scenarios. ► *Necora puber* behavior was not altered by short-term magnetic field exposures.

Keywords : magnetic fields, magneto-sensitivity, crustaceans, submarine power cables, marine renewable energy devices, behavior

39 1. INTRODUCTION

40 One of the most urgent challenges of the 21st century is to provide energy security for countries
41 facing climate change combined with demographic and industrial growth (Amorim et al., 2018). The
42 development of the offshore renewable energy sector (e.g., wind, wave, and tidal energy) is one of
43 the suggested ways to achieve carbon neutrality and sustainable energy systems. Wind farms, which
44 are the most advanced offshore technology, are thus expanding over coastal areas (Ellaban et al.,
45 2014; IRENA, 2019; Rinaldi, 2020; Soares-Ramos et al., 2020). As a result, numerous submarine
46 power cables (SPCs) have been installed to transfer electrical power to the shore and to establish
47 electrical connections between countries. When operational, SPCs generate magnetic fields (MFs,
48 expressed in teslas, T), whose values vary linearly with current intensity, and decrease with distance
49 from the cable (Meißner et al., 2006; Worzyk, 2009; Normandeau Associates Inc. et al., 2011).

50 The potential effects of cable emissions on marine ecosystems are of major societal concern
51 (Taormina et al., 2018). Many marine species from diverse taxonomic groups (e.g., teleost fish,
52 mammals, crustaceans, mollusks, and elasmobranchs; reviewed in Fischer and Slater, 2010), orient
53 their migratory movements using the latitudinal variations of the geomagnetic field, from 20 μT at
54 the equator to 70 μT at the poles (e.g., Wiltschko, 1995; Lohmann and Ernst, 2014; Klimley et al.,
55 2016). These natural cues are exclusively direct current (DC) fields, whereas SPC fields are either
56 direct current (DC) or alternating current (AC) and depend on the number, twisting and distance
57 between the electric wires embedded in the main cable. Dedicated to long-distance power transfers
58 (>50 km), DC cables produce static MFs that are superimposed on the ambient geomagnetic field
59 (Wei et al., 2017; Otremba et al., 2019), while AC cables are usually shorter and induce both a 50-
60 60-Hz MF and an induced electric field (Meißner et al., 2006; Gill et al., 2012; Kavet et al., 2016).
61 Currently, the values of cables' MF emissions are mostly estimated from modeling and theoretical
62 calculations (Albert et al., 2020). For example, it is estimated that a single-phase DC cable (15-cm
63 diameter, 1000 A) buried 0.5 m deep would emit the following MF intensities: 2700 μT at contact,
64 400 μT at seabed, 200 μT at 1 m, 100 μT at 2 m, and 20 μT at 10 meters distance. Due to a
65 compensation effect between their three electrical phases, AC cables (27-cm diameter, 12 cm between
66 the cores) produce lower MFs with faster decline: 2479 μT at contact, 80 μT at seabed, 24 μT at 1 m,
67 7 μT at 2 m, and 0 μT at 10 meters distance (formulas from Salinas et al., 2009). In either case, at
68 cable contact, artificial MFs can be 50 times higher than the geomagnetic field naturally experienced
69 by marine species. SPCs are generally buried between 0.3 and 3 m deep in soft sediment or covered
70 by thick and heavy structures on hard bottoms (Meißner et al., 2006). The exposure probability of a

71 species is thus highly dependent on its vertical distribution and motility. Accordingly, species living
72 close to the bottom, belonging to the demersal and benthic epi- and endofauna, should experience the
73 strongest MFs on a chronic basis (Albert et al., 2020). For example, large decapod crustaceans can
74 be prone to a reef effect and be observed on the foundations of offshore devices and SPC protective
75 structures (e.g., concrete mattresses, rocks) (Langhamer, 2009; Krone et al., 2013; Taormina et al.,
76 2020).

77 Decapods are an important part of global coastal fisheries and play significant ecological roles
78 in benthic ecosystems (Boudreau and Worm, 2012). Some adult species strongly affect benthic
79 community structure through top-down control of other decapod and mollusk species (Quijon and
80 Snelgrove 2005a, b). Occasionally, decapods may also act as keystone predators by regulating grazing
81 communities, thus preserving the structural complexity and productivity associated with benthic
82 vegetation (Elner and Vadas 1990; Silliman and Bertness 2002). Decapods, particularly early life
83 stages, are subjected to high predation pressure (Eggleston et al. 1997; Palma et al. 1998). As a result,
84 many decapods forage at night and seek protective shelter during the day (Stevens et al., 2003; Hunter
85 and Sayer, 2009).

86 Stressful events, including anthropogenic pollution, can disrupt the frequency, duration, and
87 performance of one or more activities associated with feeding and anti-predator behaviors and thus
88 adversely affect crustacean fitness (Rosson et al., 2011; Wale et al., 2013, Roberts and Laidre, 2019).
89 For example, a decrease or cessation of locomotor behavior may lead to a decline in food encounters
90 and/or intake and reduce the chance of escape and shelter from predators (Wale et al., 2013). The
91 ability to access and use natural crevices or other shelters is known to be a limiting factor for
92 population growth and recruitment dynamics in several crustacean species (Lawton and Lavalli, 1995;
93 Vannini and Cannicci, 1995). In turn, prolonged anti-predator responses can result in significant
94 energetic costs (Lima and Dill, 1990). The burgeoning research effort on magnetic pollution has
95 indicated that the edible crab (*Cancer pagurus*), the European lobster (*Homarus gammarus*) (Scott et
96 al., 2018; 2019; 2021), the freshwater crab (*Barytelphusa cunicularis*) (Rosaria and Martin, 2010),
97 and the freshwater spiny cheek crayfish (*Orconectes limosus*) (Tanski et al., 2005) show a clear
98 attraction to MF-exposed shelters. In contrast, potential signs of repulsion were observed in the spiny
99 lobster *P. argus* (Ernst and Lohmann, 2018), while other works have recorded no changes in the
100 shelter-seeking behavior of the European lobster (*Homarus gammarus*) with MF addition. In line
101 with such results, MF induced no changes in the spatial distribution of the brown shrimp (*Crangon*
102 *crangon*), the estuarine mud crab (*Rhithropanopeus harrisi*), the American lobster (*H. americanus*),
103 the Dungeness crab (*Metacarcinus magister*), the red rock crab (*Cancer productus*), and the yellow

104 rock crab (*Metacarcinus anthonyi*) (Bochert and Zettler, 2006; Woodruff et al., 2012, 2013; Love et
105 al., 2015, 2017). This conflicting literature emphasizes the lack of understanding of crustacean
106 responses to artificial MF and suggests potential intensity-dependent effects, as most attraction
107 responses only occurred with very high-intensity MF (2.8 mT).

108 In this study, a series of laboratory tank-based experiments were carried out to explore whether
109 artificial magnetic fields affect foraging and shelter-seeking behaviors of a common crab of the
110 European coasts, the velvet crab (*Necora puber*) (Wilhelm, 1995). Velvet crabs are part of the
111 epibenthic fauna, being attracted to the hard substrate and artificial shelters associated with offshore
112 wind farms (Ter Hofstede et al., 2022). They are commercialized and a major predator and scavenger
113 species of the European intertidal and subtidal zones (at depths up to 80 meters) and are found on
114 rocky and sandy bottoms (Norman, 1989, Freire and González-Gurriaran, 1995). Our experiments
115 were designed under the assumption that artificial MF cues are a stressful signal for crustaceans. Both
116 AC and DC MF gradients were tested with a maximum intensity of 304 μ T, to mimic the emission at
117 seabed from an AC/DC three-phase cable powered with 1600 A and buried at 0.3-meter depth. In a
118 first experiment, we documented the exploratory/roaming behavior of velvet crabs and hypothesized
119 that they would be repelled by the highest MF intensities and reduce their locomotor behavior. In a
120 second experiment, we probed crabs' foraging behavior by adding food in the zone of highest MF
121 emissions. We predicted that exposed crabs would reduce both their locomotor behavior and progress
122 along the gradient, resulting in a decrease in food intake. Finally, we evaluated whether MFs interfere
123 with crabs' sheltering behavior by placing an artificial shelter at the end of the gradient. We expected
124 that MFs would stimulate shelter-seeking behavior, reflected by a rise in locomotor behavior. We
125 presumed that MF exposure could interfere with the use of the shelter.

126 2. MATERIALS & METHODS

127 2.1 Crustacean collection and maintenance

128 Velvet crabs (*Necora puber*, 250 individuals) were collected in November 2020 by scuba
129 diving in the bay of Brest, France. The individuals were kept in two 600 L flow-through tanks (length
130 \times width \times height of 1 \times 1 \times 0.6 m) supplied with 13 °C seawater (natural seasonal temperature), for
131 23 days. They were fed daily with a variety of frozen food (e.g., squids, mussels, shrimps, and fish)
132 and provided with artificial shelters (grey pipe pieces). To ensure the detection of the crabs during
133 video tracking analysis, a test pattern (a 2 \times 1 cm rectangular white piece of oil cloth) with a central
134 black cross design was glued to the center of each crab's carapace. Behavioral trials were carried out

135 in a thermally regulated (19–22 °C) and blind experimental room with a 10:14 h light: dark cycle that
136 matched the winter photoperiod. Before the trials, 220 crabs were distributed among five 100-L glass
137 tanks (44 crabs per 0.3 m²; water depth: 30 cm) for a 2-week acclimation period to the experimental
138 facilities, with two feedings a day. The tank surface was complexified using artificial shelters (PVC
139 pipes 63 mm in length, 125- and 200-mm diameter) both to reduce agonistic behaviors and
140 cannibalism and to accustom crabs to their use. All the room tanks were supplied by continuous
141 seawater flow (84 L h⁻¹) in a closed circuit (with freshwater supply of 151 L h⁻¹). The successive
142 filtering systems included mechanical polyethylene filtration followed by Biogrog biological
143 filtration and UV treatment. Throughout the study period, the temperature was maintained at 13.4 ±
144 0.42 °C by a cooling unit. Each acclimation tank was provided with an air pump to maintain >95%
145 oxygen saturation. The water was kept at a pH of 7.8 and other parameters were maintained below
146 the following threshold values: NH₄⁺ <0.1 mg/L, NH₃ <0.01 mg/L, NO₂ <0.05 mg/L, NO₃ <10 mg/L.

147 2.2 Experimental device

148 The artificial MFs were created using the Magnotron, a Helmholtz copper coil system (1.5 m
149 × 1.5 m, 2.5-mm² wire diameter) detailed in Albert et al. (2022). Briefly, two coils were deployed in
150 a vertical position and parallel to each other at 1 meter distance. With this configuration, the MF
151 strength was homogeneous between the coils (304 μT) and decreased to 72 μT in their periphery (Fig.
152 1). The coils produced both direct (DC) and alternating (AC) current magnetic field: in DC treatment,
153 they were connected in a branch circuit to a DC power supply (14.5 V; 4.6 A) and in AC treatment,
154 they were powered by the electrical current (60 V; 5 A) generated by an isolating transformer (model
155 CM3300/200/PT), with rheostat control. All the electrical parameters (voltage, electric intensity,
156 on/off switching, and coil temperature) were recorded in real time by purpose-built software
157 developed by MAPPEM Geophysics (<http://www.mappem-geophysics.com/>). The MF intensity
158 gradients were monitored using a magnetometer (Mag690 Three-axis, Bartington Instruments, and
159 0.1 Hz) placed within the area of homogeneous intensity. The whole system was isolated by black
160 curtains to avoid visual disturbance of the crabs during the behavioral trials.

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2.3 Behavioral trials

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A white opaque Plexiglas tank ($1.5 \times 0.45 \times 0.25$ m) was centered in each of the two MF gradients (Fig. 1), with one end under the coil ($\sim 304 \mu\text{T}$). Lengthwise, the experimental tanks were separated hermetically into three identical corridors (15 cm wide, 0.2 m water depth) with independent water inflows/outflows connected to the main water circuit. At the end furthest from the coil, a removable perforated and transparent section delimited an *initial zone* ($0.2 \times 0.15 \times 0.25$ m) associated with the lowest MF strengths ($72\text{--}78 \mu\text{T}$). For both tanks, the incoming water flows were directed towards the initial zones. Three distinct experimental scenarios (tests 1 to 3) were set up to study the potential effects of artificial MFs on the exploratory, feeding, and shelter-seeking behavior of crustaceans, respectively. Test 1 evaluated whether MFs induce repulsive responses in crustaceans and reduce their exploratory behavior ($N = 69$ crabs). Tests 2 and 3 investigated whether MFs modify velvet crab foraging ($N = 72$ crabs) and shelter-seeking behaviors ($N = 69$ crabs), respectively. For each test, three MF treatments were used: (1) ambient with the coils being turned off (i.e., $47 \mu\text{T}$) for the control treatment, CT; (2) direct current, DC ($72\text{--}304 \mu\text{T}$), and (3) alternating current, AC ($72\text{--}304 \mu\text{T}$). All individuals were tested once, and the magnetic treatments were randomly assigned. Due to technical constraints, the initial zone was exposed to $72 \mu\text{T}$ during the MF treatments, which was 1.5 times higher than the ambient field of the room. However, the control treatment group was included in the experimental design to monitor the potential effects associated with such exposure in the initial zone.

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In all three tests, each magnetic treatment was simultaneously applied to three individuals and replicated eight times ($n = 24$), except for DC in Test 1 and CT in Test 3, which were replicated 7 times ($n = 21$). Before each trial, the corresponding magnetic field was launched, and one crab was placed in each of the 6 initial zones for a 30-minute acclimation period. Prior the transfer of the crabs, a fixed quantity of frozen shrimps or a shelter (a 63-mm diameter PVC pipe section), for Test 2 and Test 3 respectively, were placed in the zone of highest MF strength of each corridor. Individual behavior was recorded using two GoPro HERO 5 black cameras located 1 m above each experimental tank (2.7-K resolution, linear screen, 30 frames per second). These were remotely launched 5 minutes prior the end of the acclimation phase. The behavioral trial was then started for a 30-minute period when the partition walls were removed. At the end of each trial, the individuals' carapace width (cm) was measured. Since *N. puber* forages predominantly at night, all trials were nocturnal and performed from 18 h 30 to 23 h 00 pm. Although the vision of the velvet crab has not been thoroughly studied, there is evidence that blue crabs (*Callinectes sapidus*), which belong to the same super family

194 (*Portunoidea*), are visual predators (Hines, 2007). Some behavioral experiments have suggested that
195 the blue crab can discern blue, yellow, and red colors (Baldwin and Johnsen, 2009). Accordingly, as
196 vision may assist the nocturnal exploratory behavior of *N. puber*, a weak light source (a dim white
197 LED tape between of 7.7–10.7 $\mu\text{mol. photons.m}^{-2}\text{s}^{-1}$) was added one meter above each corridor. In
198 addition, the use of LED rails ensured light homogenization along the MF gradient.

199 2.4 Behavioral analyses

200 The exploratory, foraging and shelter-seeking behaviors of the velvet crabs were described
201 using a set of seven variables. First, activity budgets were described by three behavioral variables that
202 were common to the three tests: the time spent stationary ($T_{station}$), the time spent walking (T_{walk}), and
203 the time spent trying to exit the tank (T_{escape}). In Test 2 and Test 3, respectively, the times spent
204 feeding (T_{food}) and inside the shelter ($T_{shelter}$) were also measured. Crabs' activity budgets were
205 compiled from 30-min video footages using the focal sampling method on BORIS software
206 (Behavioural Observation Research Interactive Software v. 7.9.7). Then, all videos were analyzed to
207 compile the crabs' x and y coordinates in each frame (29.97 fps) by use of Kinovea video-tracking
208 software. The *trajr* R package was used to draw the trajectory of each crab. As the tank's
209 configuration forced the crabs' movement path to one dimension (x-axis), their trajectories were
210 simply described by the *Total distance traveled* and *Maximal distance reached* in the corridor, in cm.
211 In addition, the crabs were divided into three groups according to their progression in the MF gradient:
212 *i*) reached the end of the corridor (*complete crossing*); *ii*) remained in the initial zone (*no crossing*);
213 or *iii*) moved through the corridor without reaching the opposite end (*incomplete crossing*) (see
214 trajectory examples in **Error! Reference source not found.**).

215 2.5 Statistical analyses

216 First, the mean carapace width (cm) of the crabs was compared across the MF treatments using
217 the single-factor ANOVA test, with Tukey's post-hoc tests. The effects of the MF treatments on the
218 crab's behavioral variables were investigated using models that account for the excess of sampling
219 zeroes (or one in some cases) that was caused by stationary individuals. Zero- or one-inflation models,
220 GAMLSS (generalized additive models for location, scale, and shape), were used for proportional
221 data (e.g., time fraction spent in the different behavioral categories). GAMLSS allowed the fitting of
222 a zero/one-inflation parameter using a mixed parametric distribution (i.e., both continuous and
223 discrete) on the interval [0, 1]. The magnetic treatment was used as the linear predictor of the response
224 variable (either $T_{station}$, T_{walk} , T_{escape} , T_{food} , $T_{shelter}$, or *Maximal distance reached*). The

225 GAMLSS models were performed using the “FactomineR” and the “gamlss.inf” packages
226 (Stanisopoulos et al., 2017) in R version 4.1.0 (R Core Team, 2021). Then, a binomial-gamma hurdle
227 model (a generalized linear model) was used for zero-inflated continuous data (i.e., *Total distance*
228 *traveled*). The relevance of the MF treatment predictor was assessed with likelihood ratio tests
229 (“lmtest” package) that compared the fit of the observed data of the null model (without any predictor)
230 and the full model (with the MF treatment as predictor). When the p-value was lower than an alpha
231 level of 0.05, pairwise comparisons between the three modalities of the MF treatment variable (i.e.,
232 CT, AC and DC) were performed (“emmeans” package). Model goodness-of-fit was assessed by the
233 graphical analysis of normalized quantile residuals. Finally, the effects of the MF treatments on crabs’
234 progress through the gradient (i.e., type of trajectory) were assessed using Fisher’s exact test (in the
235 “stats” package).

236 3. RESULTS

237 The mean carapace width of the crabs tested was equal to 5.26 ± 0.77 cm (mean \pm standard
238 deviation SD) and was not significantly different between the three MF treatments (ANOVA: $F =$
239 2.01 , $df = 2$, $p = 0.14$). During the acclimation phase, the crabs sheltered inside the PVC pipes
240 provided. However, due to high agonistic behaviors during the first few days of acclimation, 7 crabs
241 died, and 5 crabs lost a leg. Among the injured crabs, two individuals with unimpaired locomotor
242 ability were used during the experiment.

243 3.1 Activity budgets

244 In Test 1, designed to characterize the exploratory behavior of crabs, the individuals remained
245 motionless most of the time regardless the MF treatment, ($86.8 \pm 4.3\%$, mean \pm standard error) (Fig.
246 3). In particular, 37.7% of the crabs remained stationary inside the initial zone throughout the 30-min
247 trial. Active individuals spent $9.1 \pm 2.8\%$ of the time walking and $4.1 \pm 1.6\%$ trying to escape the
248 tank. The crabs' activity budgets did not vary significantly in DC and AC treatments in comparison
249 with the control group, demonstrating no alteration of their exploratory behavior (Table 1).

250 In Test 2, which explored the crabs’ foraging behavior, *Tstation*, *Twalk*, *Tescape*, and *Tfeed*
251 occurred $84.5 \pm 5.6\%$, $5.8 \pm 2.1\%$, $1.7 \pm 0.7\%$, and $8.0 \pm 4.5\%$ of the time, respectively. In total,
252 36.1% of the individuals remained motionless in the initial zone. The DC and AC treatments caused
253 no changes in the activity budgets of the crabs tested compared to control group. The locomotor
254 behavior and food intake were not affected by the MF treatments (Table 1).

255 Test 3 aimed to evaluate whether MFs interfere with the crabs' shelter-seeking and sheltering
256 behavior. During the behavioral trials, crabs spent $88.9 \pm 3.9\%$ of the time stationary, and among
257 them, 42% remained strictly in the initial zone. In active individuals, $6.2 \pm 2.1\%$ of the time was spent
258 walking, $0.9 \pm 0.5\%$ on escape attempts, and $4.1 \pm 2.3\%$ inside the shelter (Table 1).

259 3.2 Progression through the MF gradient

260 Crabs' progress along the MF gradient was classified as either *complete crossing*, *incomplete*
261 *crossing*, or *no crossing*. In Test 1, 56.5% of the crabs remained in the initial zone (*no crossing*),
262 15.9% performed *incomplete crossings*, and 27.5% reached the end of the corridor (*complete*
263 *crossing*) (details in supplementary data). With food addition (Test 2), a higher proportion of crabs
264 (33.3%) initiated an *incomplete crossing*, 20.8% a *complete crossing* and 45.8% did not cross the
265 corridor at all. Finally, in Test 3, 55.1% of the crabs performed *no crossing*, 15.9% an *incomplete*
266 *crossing*, and 29.0% a *complete crossing*. Across these three experimental scenarios, the MF
267 treatments (CT, AC, and DC) caused no changes in the crabs' trajectory (Test 1: $p = 0.63$, Test 2: p
268 $= 0.94$, Test 3: $p = 0.28$; with χ^2 test).

269 One critical ambition of the behavioral trials was to evaluate the effects of an MF gradient on
270 the crabs' locomotor behavior. As stated earlier, a significant proportion of the crabs did not move in
271 the MF gradient, which resulted in a zero-inflated data distribution of the continuous variable *Total*
272 *distance traveled*. To consider this large number of zeros and fit the data distribution, a binomial-
273 Gamma hurdle model was used to model the zero and non-zero data as two separate processes. First,
274 the binomial model questioned the effects of MF on the probability that crabs would travel a non-
275 null distance. Then, a gamma glm model evaluated whether the average of the non-zero distances
276 covered by the crabs, differed significantly from those of the control group over AC and DC
277 treatments. On average, regardless of the treatment, the crabs traveled 504.03 ± 166.91 cm in Test 1;
278 313.93 ± 135.31 cm in Test 2, and 304.02 ± 101.79 cm in Test 3. In Test 1 and 2, the AC and DC
279 treatments did not change the ratio of moving and non-moving crabs (Table 2) and had no influence
280 on their mean total distance traveled compared with that of the control group (Fig. 4, Table 2). In test
281 3, the null hypothesis that the null and full models were equally effective was rejected at the 5% level.
282 However, pairwise comparisons indicated that the variability explained by the MF treatment was due
283 to a significant difference between the AC and DC treatments, but not between these treatments and
284 the control group.

285 Before the trials, we assumed that while moving on the x-axis of the tank, a crab would be
286 exposed to increasing MF intensities that could potentially interfere with its locomotor behavior and

287 stop its progression. This hypothesis was tested by measuring the *maximal distance reached* (cm)
 288 through the MF gradient. However, this value did not vary significantly between the MF and the
 289 control treatments in any test (Fig. 5, Table 1).

290 Table 1. Summary of the likelihood ratio tests evaluating the effects of the MF treatments on the activity budgets and the
 291 *Maximal distance reached* of the velvet crab (*Necora puber*).

Response variables ~ predictors	AIC	LRT($\chi^2_{(2)}$)	P-value
TEST 1			
<i>Tstation</i> ~ 1	43.6		
<i>Tstation</i> ~ MF treatment	40.3	0.73	0.69
<i>Twalk</i> ~ 1	16.0		
<i>Twalk</i> ~ MF treatment	12.9	0.95	0.62
<u><i>Tescape</i></u> ~ 1	0.7		
<u><i>Tescape</i></u> ~ MF treatment	-2.1	1.24	0.54
<i>Maximum distance reached</i> ~ 1	52.1		
<i>Maximum distance reached</i> ~ MF treatment	49.8	1.68	0.43
TEST 2			
<i>Tstation</i> ~ 1	50.7		
<i>Tstation</i> ~ MF treatment	46.9	0.25	0.88
<i>Twalk</i> ~ 1	-14.4		
<i>Twalk</i> ~ MF treatment	-17.2	1.27	0.53
<u><i>Tescape</i></u> ~ 1	0.7		
<u><i>Tescape</i></u> ~ MF treatment	-20.1	1.24	0.54
<u><i>Tfeed</i></u> ~ 1	77.9		
<u><i>Tfeed</i></u> ~ MF treatment	74.5	0.60	0.74
<i>Maximum distance reached</i> ~ 1	56.4		
<i>Maximum distance reached</i> ~ MF treatment	53.4	0.98	0.61
TEST 3			
<i>Tstation</i> ~ 1	50.0		
<i>Tstation</i> ~ MF treatment	47.1	1.09	0.58
<i>Twalk</i> ~ 1	8.4		
<i>Twalk</i> ~ MF treatment	7.8	3.45	0.18
<u><i>Tescape</i></u> ~ 1	0.7		
<u><i>Tescape</i></u> ~ MF treatment	-2.1	1.24	0.54
<i>Tshelter</i> ~ 1	59.3		
<i>Tshelter</i> ~ MF treatment	56.9	1.66	0.44
<i>Maximum distance reached</i> ~ 1	45.9		
<i>Maximum distance reached</i> ~ MF treatment	42.2	0.25	0.88

293 Table 2. Summary of the likelihood ratio tests evaluating the effects of the MF treatments on the *Total distance traveled*
 294 by the velvet crab (*Necora puber*). The asterisks (*) indicate values under the 5% threshold. Pairwise comparisons
 295 between the modalities of the MF treatment predictor were performed for the binomial model that fitted the data observed
 296 in Test 3.

Response variables ~ predictors	df	Log Likelihood	Test statistic ($\chi^2_{(2)}$)	P-value	
TEST 1					
Binomial models (0 or 1):					
<i>Non null Total distance traveled ~ 1</i>	1	-46.2	0.10	0.95	
<i>Non null Total distance traveled ~ MF treatment</i>	3	-46.1			
Gamma models (only the non-null distances):					
<i>Total distance traveled ~ 1</i>	2	-290.1	0.10	0.95	
<i>Total distance traveled ~ MF treatment</i>	4	-290.0			
TEST 2					
Binomial models (0 or 1):					
<i>Non null Total distance traveled ~ 1</i>	1	-49.7	0.34	0.85	
<i>Non null Total distance traveled ~ MF treatment</i>	3	-49.5			
Gamma models (only the non-null distances):					
<i>Total distance traveled ~ 1</i>	2	-243.9	2.88	0.24	
<i>Total distance traveled ~ MF treatment</i>	4	-242.4			
TEST 3					
Binomial models (0 or 1):					
<i>Non null Total distance traveled ~ 1</i>	1	-47.6	8.68	0.01*	
<i>Non null Total distance traveled ~ MF treatment</i>	3	-43.3			
Pairwise comparisons:					
	estimate	standard error	df	z.ratio	p-value
CT – AC	0.79	0.62	inf	1.28	0.41
CT – DC	-1.00	0.64	inf	-1.56	0.26
AC - DC	-1.79	0.64	inf	-2.80	0.01*
Gamma models (only the non-null distances):					
<i>Total distance traveled ~ 1</i>	2	-239.3	1.41	0.49	
<i>Total distance traveled ~ MF treatment</i>	4	-238.6			

297

298

299 4. DISCUSSION

300 As a major colonizer of the artificial reefs associated with offshore wind farms, the velvet crab
301 (*N. puber*) is likely to undergo chronic exposure to cable induced MFs. This study investigated the
302 effects of an artificial magnetic field gradient (maximum intensity of 304 μT) on its exploratory,
303 foraging, and shelter-seeking behaviors.

304 4.1 Exploratory behavior

305 The first experiment investigated the effects of MFs on the exploratory behavior of crabs,
306 assuming they would be repelled by the highest intensities and would reduce their locomotor
307 behavior. The results show that the mean total distance traveled by *N. puber* individuals was
308 unaffected by the MFs, confirming the results obtained in other crustaceans, such as the American
309 lobster (*Homarus americanus*) (Hutchison et al., 2020) and the European lobster (*Homarus*
310 *gammarus*) (Taormina et al. 2020). Similarly, the time spent in *stationary*, *walking*, and *escaping*
311 behaviors was not modified by AC and DC MFs, as also reported in *H. gammarus* (Taormina et al.,
312 2020). From test 1 to test 3, the proportions of crabs performing *complete*, *incomplete*, and *no*
313 *crossings* were not related to the magnetic field exposure. Accordingly, though higher than the
314 ambient field (47 μT), the magnetic field recorded in the initial zone (72 μT) during MF treatment
315 did not cause any behavioral alteration in the crabs tested.

316 4.2 Foraging behavior

317 The second set of experiments explored the effects of MFs on the foraging behavior of *N.*
318 *puber*. We predicted that exposed crabs would reduce their locomotion along the MF gradient,
319 resulting in a decrease in their food intake. However, the addition of AC and DC magnetic fields did
320 not cause any behavioral changes in individual crabs, and both their average distance traveled and
321 maximal distance reached remained similar compared with values in the control conditions. Likewise,
322 the crabs' activity budget did not vary significantly with the addition of MFs. Although knowledge
323 of how MFs interact with crab foraging and feeding behaviors is very limited, the few available works
324 are consistent with the present findings. For example, AC MFs from both buried and unburied AC
325 cables (13.8–116.8 μT and 24.6–42.8 μT , respectively) did not prevent *Cancer productus* and
326 *Metacarcinus Magister*, from entering a baited trap (Love et al., 2017). Similarly, the freshwater crab
327 *B. cunicularis* did not alter its food consumption rate in response to an AC magnetic field (Rosaria
328 and Martin, 2010).

4.3 Shelter-seeking behavior

329

330 The bulk of the literature has exploited the shelter-seeking behavior of crustaceans to study
331 their attraction or repulsion to MFs. Here we evaluated whether MFs interfere with crabs' sheltering
332 behavior by placing an artificial shelter at the end of the gradient. We expected that MFs would
333 stimulate shelter-seeking behavior, reflected by a rise in locomotor behavior. However, we presumed
334 that MF exposure could interfere with the use of the shelter, resulting in a behavioral trade-off. We
335 found that the addition of magnetic fields did not modify the time crabs spent inside the shelter
336 (Maximum distance reached) nor change their locomotion through the MF gradient (*Total distance*
337 *traveled*). The current literature about the potential tropism of crustaceans to MF-exposed shelters
338 also provides heterogeneous findings. On the one hand, several studies have reported attraction
339 responses towards magnet-equipped shelters in the edible crab *Cancer pagurus* (2.8 mT DC, Scott et
340 al., 2018; 500 and 1000 μ T DC, Scott et al., 2021), the European lobster *H. gammarus* (2.8 mT; Scott,
341 2019), and the spiny cheek crayfish *Orconectes limosus* (800 μ T DC; Tanski et al., 2005). On the
342 other hand, a repulsive size-dependent behavior was observed in larger individuals of spiny lobster
343 (*Panulirus argus*), which selected control versus magnet-equipped dens (320 μ T DC; Ernst and
344 Lohmann, 2018). The sole study of Taormina et al. (2020) corroborates our findings since the
345 exposure of juvenile European lobsters (*H. gammarus*) to AC and DC gradients (51–200 μ T) did not
346 induce any temporal shifts in shelter-seeking and sheltering behaviors.

4.4 Success of the attractive stimuli

347

348 In this study, regardless of the treatment, only 25% of the tested crabs fed on the food items
349 provided. Since this proportion was lower than expected and unrelated to the MF treatment, we thus
350 questioned the experimental design. In each corridor, the water inflow used for water renewal was
351 located behind the food items and allowed the circulation of the chemical cues to the crab. Since
352 crustacean species use chemical cues to detect and locate food items at low concentrations (Weissburg
353 and Zimmer-Faust, 1993; Rebach et al., 1996), we immediately excluded the hypothesis that food
354 might be undetectable by the crabs from the initial zone. Furthermore, as crabs were starved before
355 the experiments, rejection of the food seemed unlikely. Accordingly, we assumed that a combination
356 of inter-individual behavioral plasticity and stress related to handling and environmental change were
357 causing these response variations (Guerarhdi et al., 2012).

358 A similar percentage (26% of crabs) was observed for the sheltering response, demonstrating a
359 rather moderate attractiveness of the refuge. In a natural environment, holding a shelter is generally
360 crucial for the survival of most crustacean species and takes place in predator defense and

361 reproductive behaviors (Nelson, 2005). In the laboratory experiments conducted so far, crustaceans
362 usually settled in the refuges provided. For example, *C. pagurus* and *H. gammarus* occupied the
363 refuge 48–66% and 32% of the time, over 7-hour and 45-minute experimental periods, respectively
364 (Scott et al., 2018, Taormina et al., 2020). Similarly, 49 out of 51 individuals of the spiny lobster (*P.*
365 *argus*) occupied a shelter during a 15-minute trial (Ernst and Lohmann, 2018). In the present work,
366 the low number of sheltering responses may have been a consequence of the species tested, the short
367 experimental duration (30 min), and/or the tank design. However, sheltering is known to be part of
368 the ecology of *N. puber*, which is usually found within crevices and under boulders (Norman, 1989).
369 In addition, Hinchliff et al. (2015) observed a very quick sheltering behavior within a 10-min period
370 in 18 velvet crabs. Moreover, as acclimating crabs were provided with artificial shelters like those
371 used in the trials, they were assumed to be accustomed to them. We cannot exclude that the 140-cm
372 distance to the shelter was too far to allow visual detection by stationary individuals. However, other
373 studies confirmed the absence of attraction to the MF gradients (230 μ T) despite shorter crustacean-
374 shelter distances (122.5 cm) (Taormina et al., 2020).

375 **4.5 Interaction of environmental cues**

376 The marine environment provides many signals that marine organisms can detect (e.g.,
377 chemical, physical, biological, and acoustical cues) (Bullock et al., 2008). Since variations in
378 environmental conditions can alter the availability and reliability of such signals, marine crustaceans
379 tend to orient using multiple cues, such as wave surge, sound, or the geomagnetic field (Herrnking
380 and MacLean, 1971). In the field, crustaceans extract redundant signals and combine and hierarchize
381 the information in them (Ugolini, 2002). Within that context, investigating the interaction between
382 such additional signals and magnetic fields should improve our understanding of the response
383 mechanisms occurring in natural conditions. The present work is a contribution to this approach as
384 the first to demonstrate that MFs gradient do not alter the natural behavioral response to chemical
385 cues from food items.

386 **5. CONCLUSION**

387 In conclusion, these results suggest that anthropogenic MFs of comparable intensity to SPC
388 emissions (300 μ T) induce neither attraction nor repulsion behavioral responses and do not alter
389 exploratory, feeding, and sheltering behaviors. Nonetheless, as crustaceans' magneto-sensitivity is
390 assumed to be level-dependent, dose response studies should be conducted to assess the effects of
391 cable emissions. In addition, since *in situ* scenarios presume chronic exposure, future studies should

392 also question the temporal component of the MF response mechanism to detect potential habituation
393 or resilience.
394

Journal Pre-proof

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409

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FIGURES CAPTIONS

Figure 1. Side view of the experimental facilities

Figure 2. Examples of *Necora puber* crabs' trajectories within the MF gradient. The magnetic field strength (μT) is minimal (75.8–96.7 μT) within the initial zone (x axis = 0–20 cm) and maximal (304 μT) at the opposite end of the tank (x axis = 140–150 cm). MF intensities are averaged on the 3 corridors measurements. Crabs were confined to the initial zone for 30min before opening the gate. *Complete crossing* corresponds to the crabs that reached the end of the corridor; *no crossing* is for those that remained in the initial zone and *incomplete crossing* for the crabs that moved through the corridor but did not reach the opposite end.

Figure 3. Average time fractions (%) spent by the velvet crabs (*Necora puber*) in the different behavioral categories (*Tstation*, *Twalk*, *Tescape*, *Tfeed* and *Tshelter*), according to the MF treatments. Tests 1, 2 and 3 were designed to study potential alterations of the exploratory, feeding, and sheltering behaviors, respectively. Each barplot is a mean obtained from 24 crabs except for the CT and DC treatments of Test 1 and test 3 respectively, where $n = 21$. Error bars are standard errors. The black bars group the variables that were statistically compared.

Figure 4. Average *Total distance traveled* (cm) by the moving crabs (*N. puber*) as a function of the MF treatments. Tests 1, test 2 and test 3 were designed to study potential alterations of the exploratory, feeding, and sheltering behaviors, respectively. Each barplot is a mean obtained from 24 crabs except for the CT and DC treatments of Test 1 and test 3 respectively, where $n = 21$. Error bars are standard errors. The asterisks “*” indicate statistical differences at the 5 % level.

Figure 5. Average *Maximal distance reached* (cm) by the moving crabs (*N. puber*) in the corridor (150 cm in length), as a function of the MF treatments. Tests 1, test 2 and test 3 were designed to study potential alterations of the exploratory, feeding, and sheltering behaviors, respectively. Each barplot is a mean obtained from 24 crabs except for the CT and DC treatments of Test 1 and test 3 respectively, where $n = 21$. Error bars are standard errors.

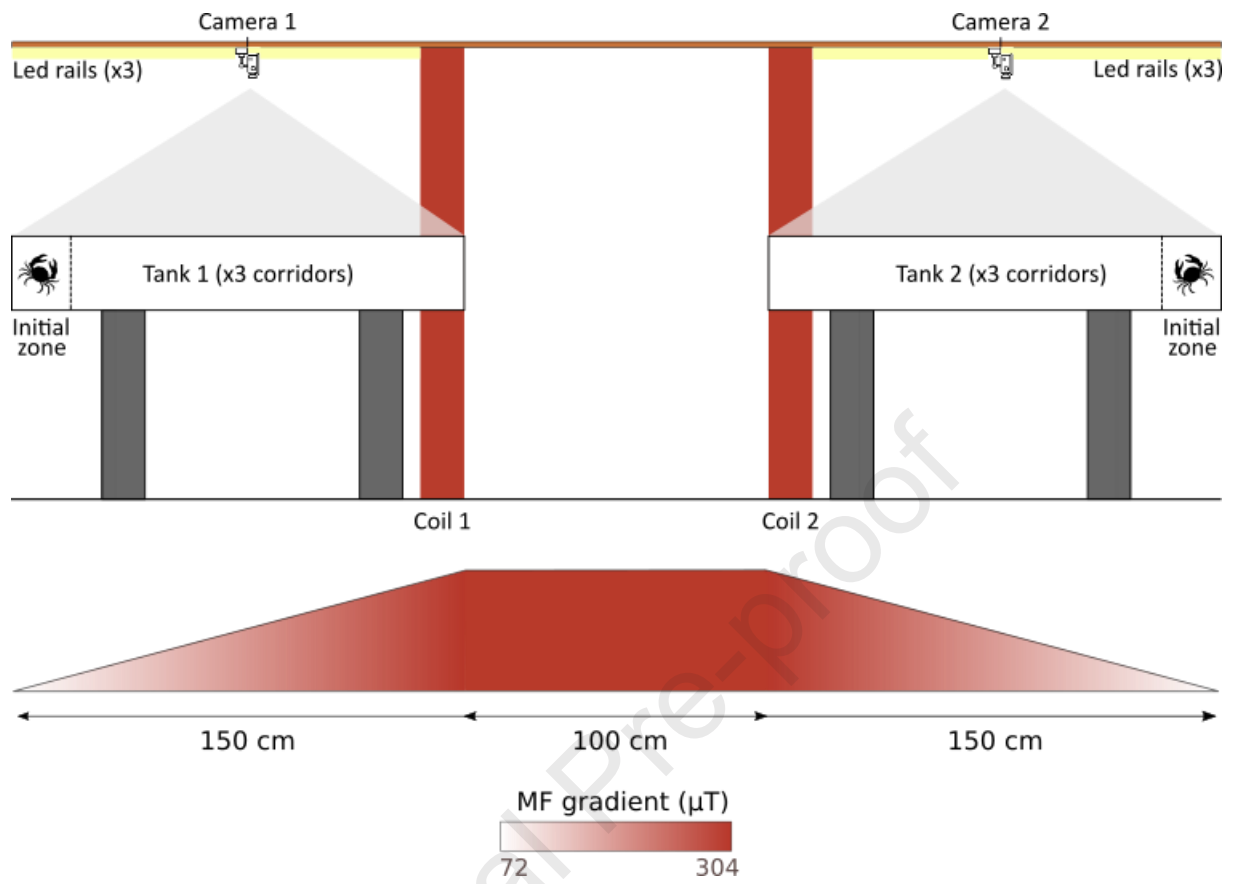
Figure 1 (should appear in color)

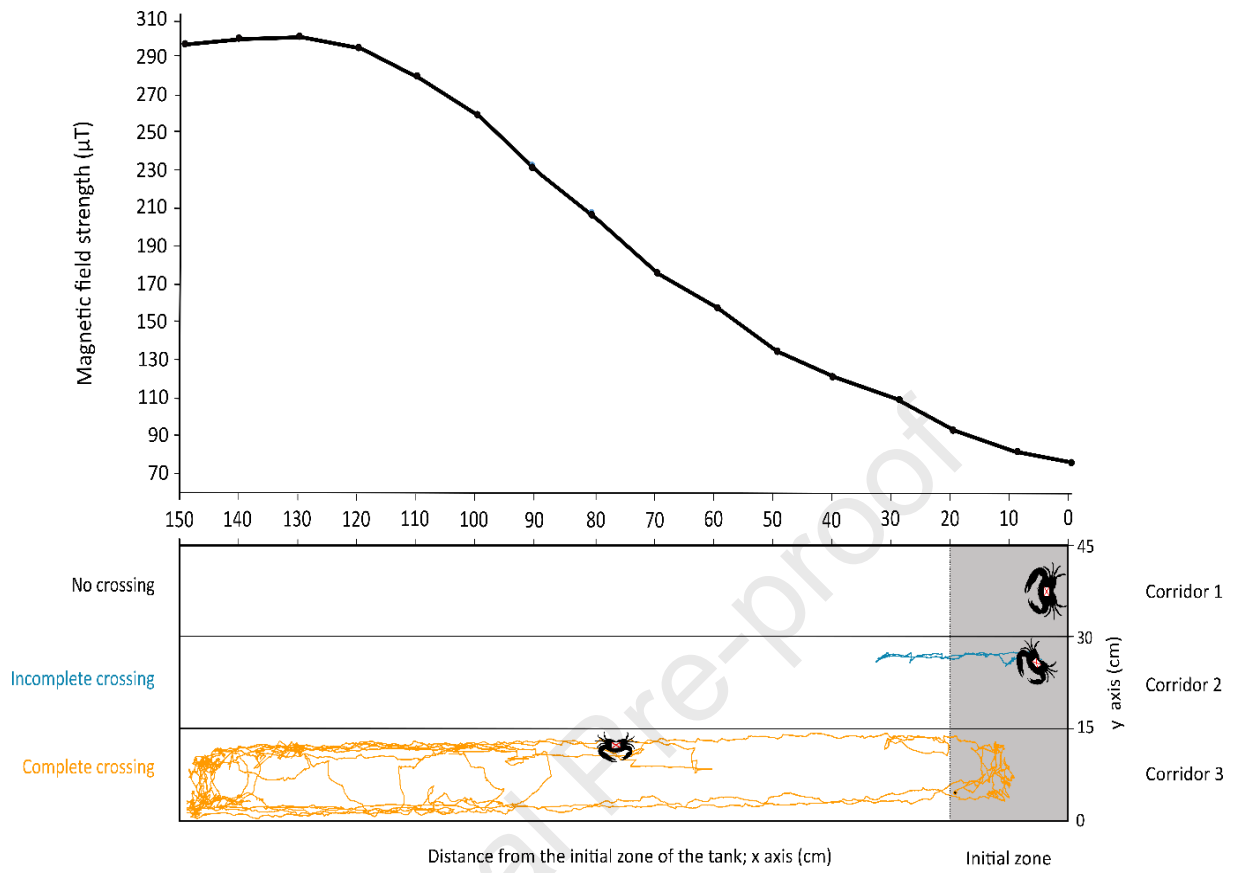
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Figure 3

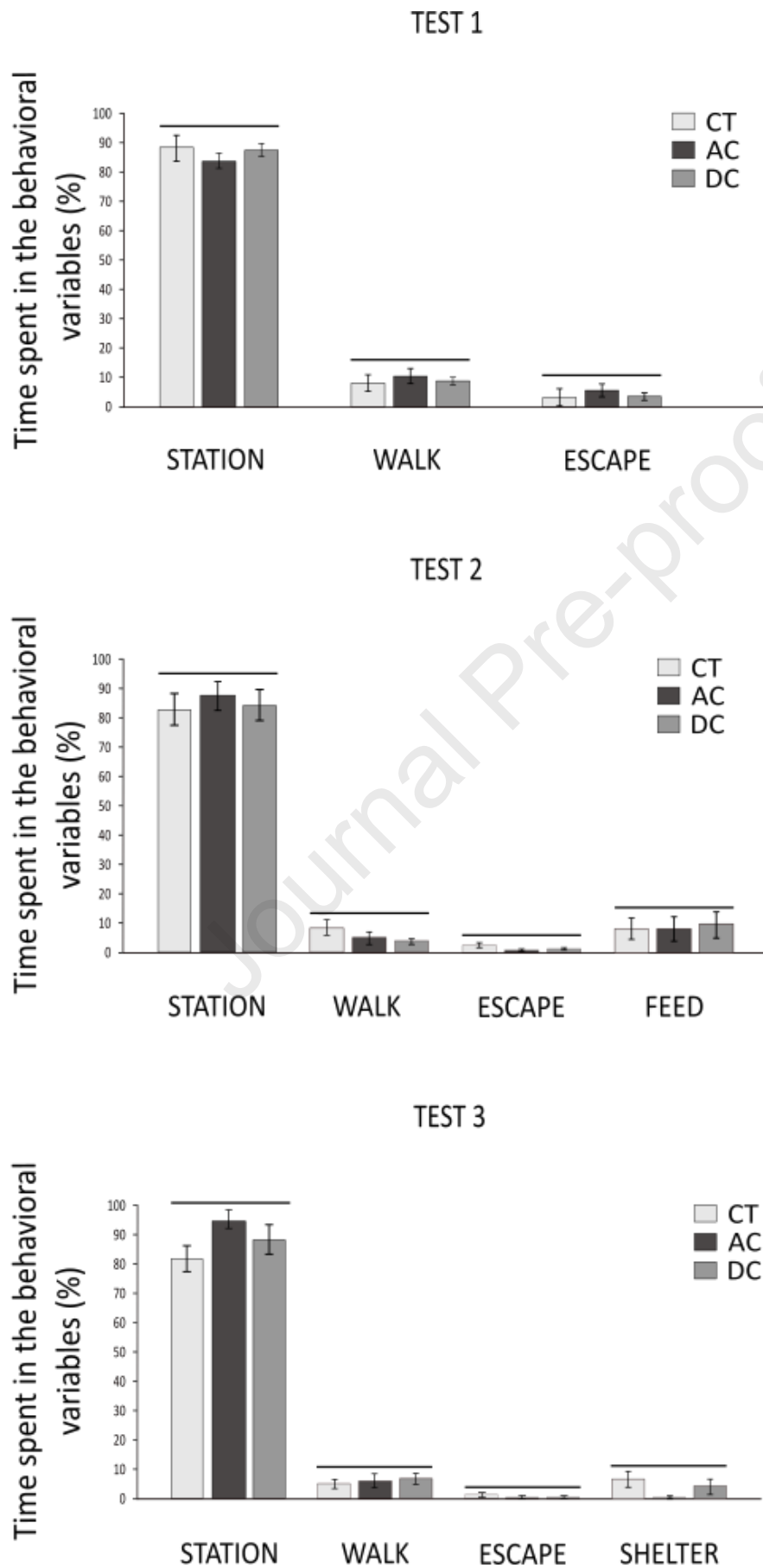


Figure 4

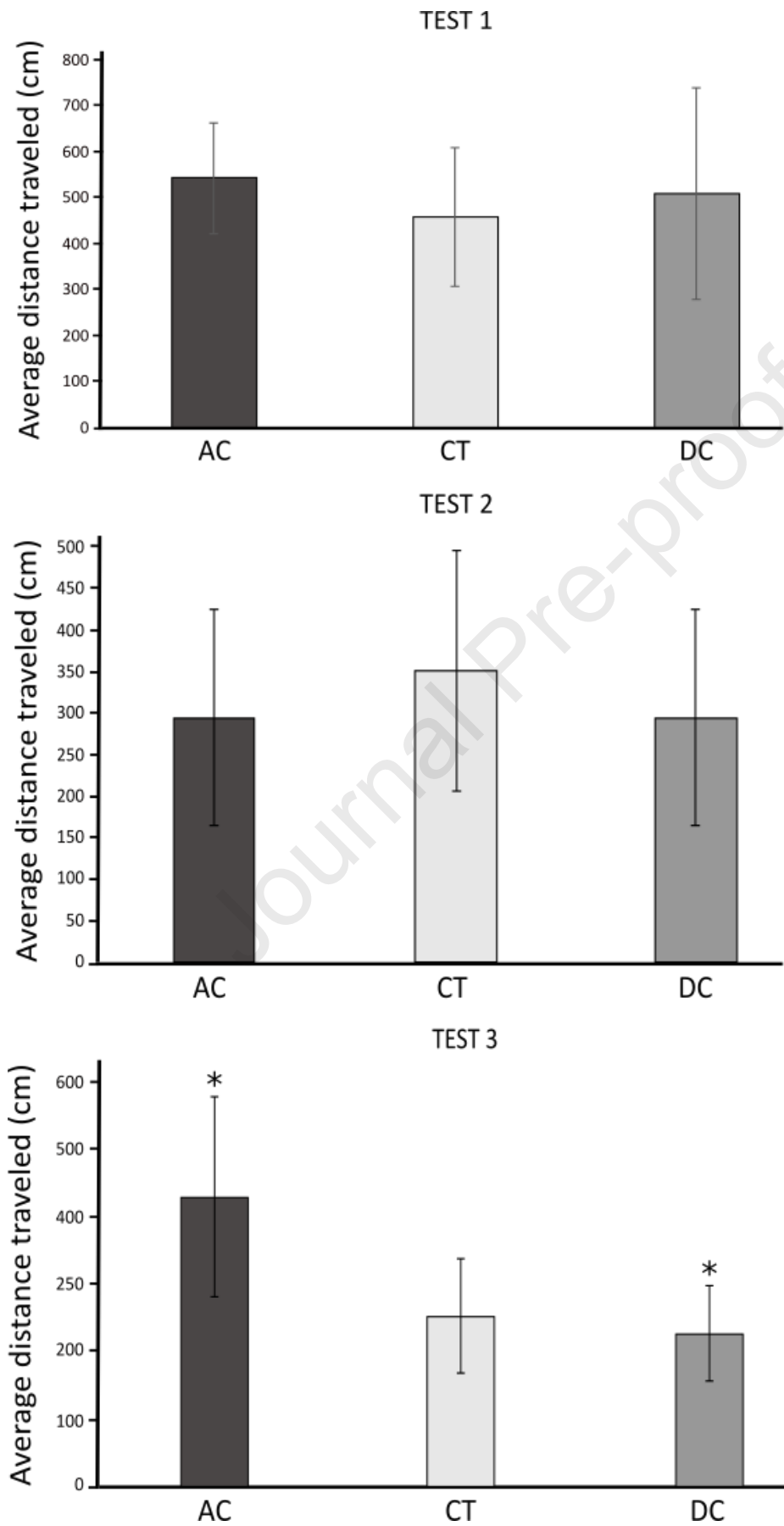
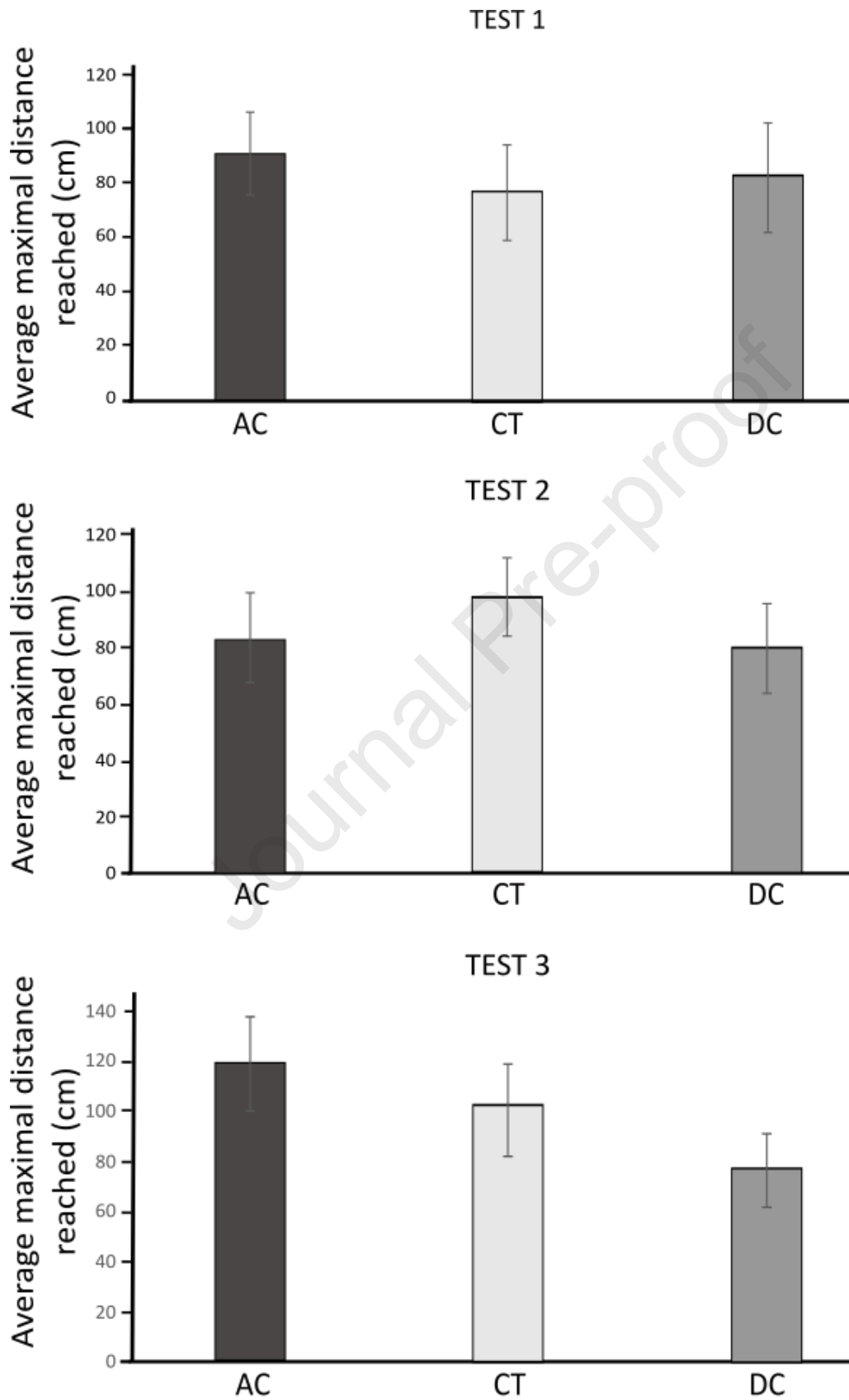


Figure 5



HIGHLIGHTS

- Submarine power cables emit high-strength magnetic fields in their vicinity
- Their protective rock cover can cause a reef effect and attract crustacean species
- *Necora puber* crabs were exposed to AC and DC magnetic field gradients (max. 304 μT)
- Exploratory, feeding and sheltering behaviors were studied across three scenarios
- *Necora puber* behavior was not altered by short -term magnetic field exposures

LA: conceptualization, methodology, validation, formal analysis, investigation, original draft writing, review and editing, visualization. **FO:** conceptualization, methodology, review and editing, supervision. **AJ:** conceptualization, methodology, review and editing, supervision. **LC:** conceptualization, project administration, supervision, funding acquisition. **SC:** conceptualization, project administration, supervision, funding acquisition.

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Declaration of interests

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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