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Letter

Female Crabs Are More Sensitive to Environmentally Relevant Electromagnetic Fields from Submarine Power Cables

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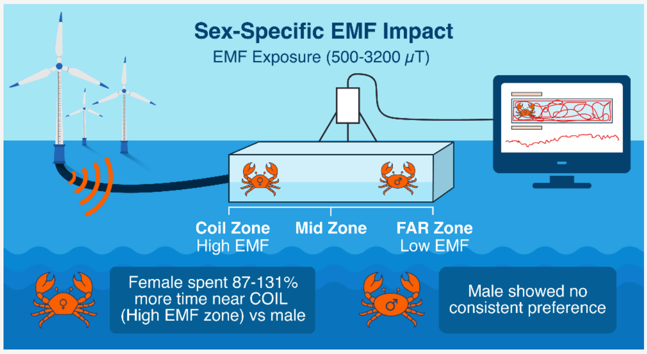

ABSTRACT: The expansion of offshore wind and marine renewable energy devices (MREDs) is increasing anthropogenic electromagnetic fields (EMFs) from submarine power cables (SPCs). SPC-generated EMFs can exceed 2700 μT, well above the geomagnetic field, and may affect benthic animal behavior. In decapod crustaceans, sex-specific habitat uses and seasonal migrations are well-documented, yet their role in EMF sensitivity remains untested. We exposed juvenile shore crabs (*Carcinus maenas*) (n = 120; 1:1 sex ratio) to EMFs of 500, 1000, and 3200 μT using a Helmholtz coil system and tracked behavior over 10 min trials. Females exhibited strong attraction across EMF levels, spending up to 131% more time in the EMF-exposed zone and significantly less time in the low-field zone. They also drove differences in distance moved, whereas males showed no consistent spatial preference and indifferent activity at the highest field strength. These sex-specific responses suggest SPC EMFs could disrupt female-driven reproductive behaviors like seasonal migrations and larval release. Attraction may cause disorientation, aggregation, or delays in migration, potentially altering sex ratios and reducing larval export. This study provides the first evidence of sex-specific EMF responses in crustaceans and highlights the importance of incorporating sex as a key variable in ecological risk assessments of offshore infrastructure.

KEYWORDS: *Electromagnetic Fields, Subsea Power Cables, Marine Renewable Energy Devices, Behavior, Crustacea, Sex*

1. INTRODUCTION

The accelerating shift to renewable energy is driving expansion of offshore wind farms (OWFs) and other marine renewable energy devices (MREDs).[1] This expansion requires increased deployment of submarine power cables (SPCs), which transmit electricity from offshore installations to terrestrial grids.[2,3] As capacity grows, SPC number, size, and voltage are increasing.[4]

SPCs introduce anthropogenic electromagnetic fields (EMFs) into marine ecosystems.[5] AC cables generate time-varying EMFs at 50−60 Hz, while DC cables produce stronger magnetic fields.[6−8] EMF intensities near cables can exceed 2700 μT,[9] decreasing to near-Earth's geomagnetic field (∼50 μT) depending on current load, burial depth, and sediment type.[10,11] For typical buried bipolar HVDC cables, fields at the seabed are only ∼10−20 μT above background directly over the route and decay to near-background within tens of meters.[6,7,11−13]

Many marine taxa rely on geomagnetic and electrical cues for navigation, foraging and reproduction.[3,14,15] Elasmobranchs, which detect prey using electroreceptive ampullae of Lorenzini, and migratory fish such as eels and salmonids both use geomagnetic cues for orientation.[16−18] Diverse marine invertebrates including crustaceans, molluscs, and annelids also respond to magnetic and electric fields,[19] which may be important during larval settlement, orientation, and predator avoidance but could be disrupted by anthropogenic EMFs.[2,13,20,21] Among crustaceans, spiny and American lobsters demonstrate geomagnetic orientation, suggesting magnetoreception supports benthic navigation and migration.[22]

Recent studies suggest EMFs from SPCs can influence locomotor activity, space use, and physiology in benthic invertebrates.[6] However, most focus on single species or lack analysis of sex-specific or state-dependent responses, despite evidence that susceptibility may be influenced by hormonal, metabolic, or behavioral traits.[23,24] In other taxa sensory processing and environmental sensitivity differ in sex and life stage,[25] and sex-specific foraging, escape behavior, or movement strategies occur in several crustacean species.[26] Sex and state dependent responses to EMF remain largely untested in

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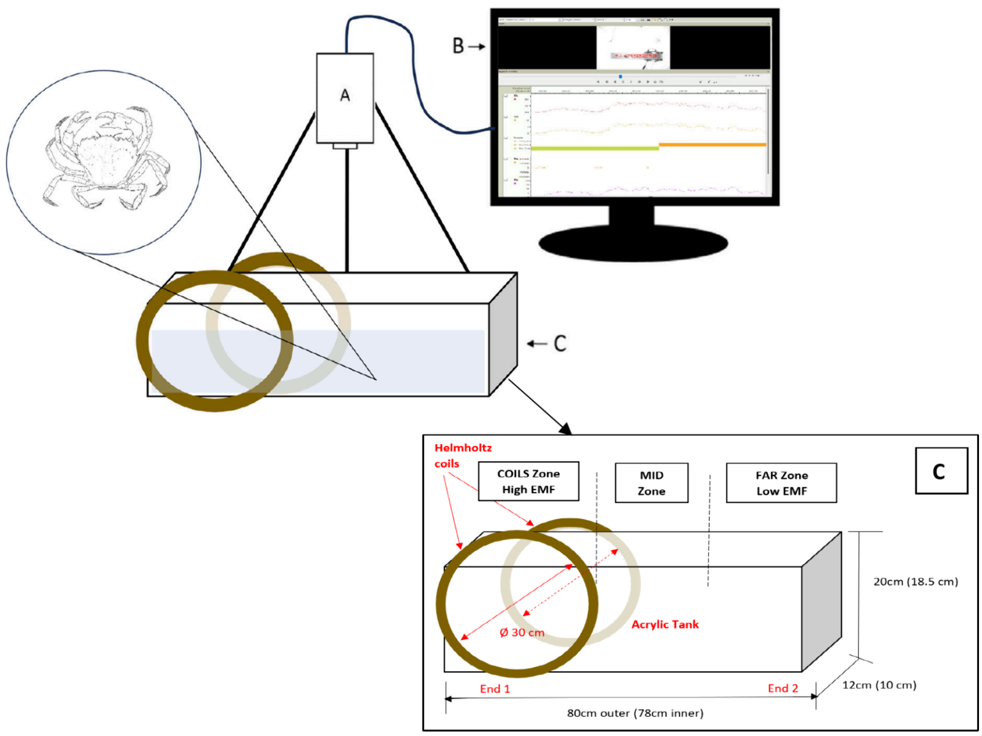

Figure 1. Schematic of the experimental setup: (A) Ethernet camera on tripod, (B) PC with EthoVision XT17, and (C) aquarium tank between two Helmholtz coils. The COIL zone generated the magnetic field, which decreased through the MID zone and to near-zero at the FAR zone.

crustaceans, risking incomplete risk assessments and ineffective mitigation.[27]

Crustaceans may detect EMFs via biogenic magnetite, electromagnetic induction, cryptochrome-based magnetoreception, or statocysts,[28,29] though evidence is extrapolated from other taxa.[30,31] The mechanisms underlying EMF sensitivity remain unresolved, and evidence for sex-based differences is lacking.[32,33]

Although direct evidence for sex-based magnetosensitivity in crustaceans is absent, other taxa show that magnetoreception and related behaviors can vary by sex or physiological state. Female sea turtles exhibit stronger geomagnetic orientation during nesting migrations than males,[22] and sex differences in migratory orientation occur in salmonids.[29] Such context-dependent sensitivity is plausible in crustaceans given behavioral and life history differences between sexes, particularly in migratory species.[16]

Despite their ecological importance in nutrient cycling, sediment mixing, and food web dynamics,[34] crustaceans remain underrepresented in EMF research.[35] Sensitivity may vary with life stage or behavioral state, including reproduction, moulting, or migration.[36] One study highlighted that SPC risk varies across life stages and species ecology, emphasizing the need for species-specific assessment.[6] In *Carcinus maenas* (Linnaeus, 1758), females often migrate to subtidal habitats to spawn and may show stronger site fidelity during reproduction,[37−39] potentially influencing EMF encounter rates. This study focused on *C. maenas*, a widespread intertidal crab across the UK and temperate coasts worldwide.[37] Though not commercially harvested, it plays a key ecological role and is a robust bioindicator due to tolerance of laboratory conditions but sensitivity to anthropogenic stressors.[40] As a benthic forager, *C. maenas* exhibits strong thigmotaxis and exploratory movement, with juveniles dispersing within intertidal and shallow subtidal habitats.[35] Its suitability for controlled assays makes it an ideal model for evaluating EMF impacts.[41]

The study examined behavioral responses of juvenile *C. maenas* to environmentally relevant EMFs in a laboratory setting, focusing on sex-specific effects. We quantified spatial preferences, locomotor activity, and mobility to detect attraction or avoidance. We hypothesized that EMF exposure would alter behavior, and that females would respond differently to males, reflecting known sex-based differences in reproductive roles, movement ecology, and seasonal migrations.[39,42,43]

2. MATERIALS AND METHODS

2.1. Experimental Animals. Juvenile *C. maenas*, (35−60 mm carapace width)[37,44] were collected from Langstone Harbour, UK (50°47′22.8″N, 1°02′35.9″W) during low tide. Crabs were transported in aerated containers to the University of Portsmouth's Institute of Marine Science (IMS) and acclimated in 1000 L outdoor flow-through seawater tanks, at 12.1 ± 1 °C and ∼11 h light:13 h dark (October), and 32.5 ± 0.5 PSU, matching Langstone Harbour conditions. They were fed mackerel (*Scomber scombrus*) three times per week. Only healthy, undamaged individuals were selected. Sex was determined morphologically: males exhibit a narrow triangular abdomen and larger chelae, females broad rounded abdomen.[45,46]

2.2. EMF Experimental Setup. The exposure system used a Helmholtz coil pair (124 turns, 30 cm diameter) constructed from 116.8 m of 1.5 mm enamelled copper wire. The coils were aligned coaxially and spaced 150 mm apart to generate a uniform magnetic field,[47−49] powered by a 12 V, 5 A direct current (DC) source, producing a static magnetic field up to 3200 μT. Hereafter we use "EMF" for consistency with wider literature.

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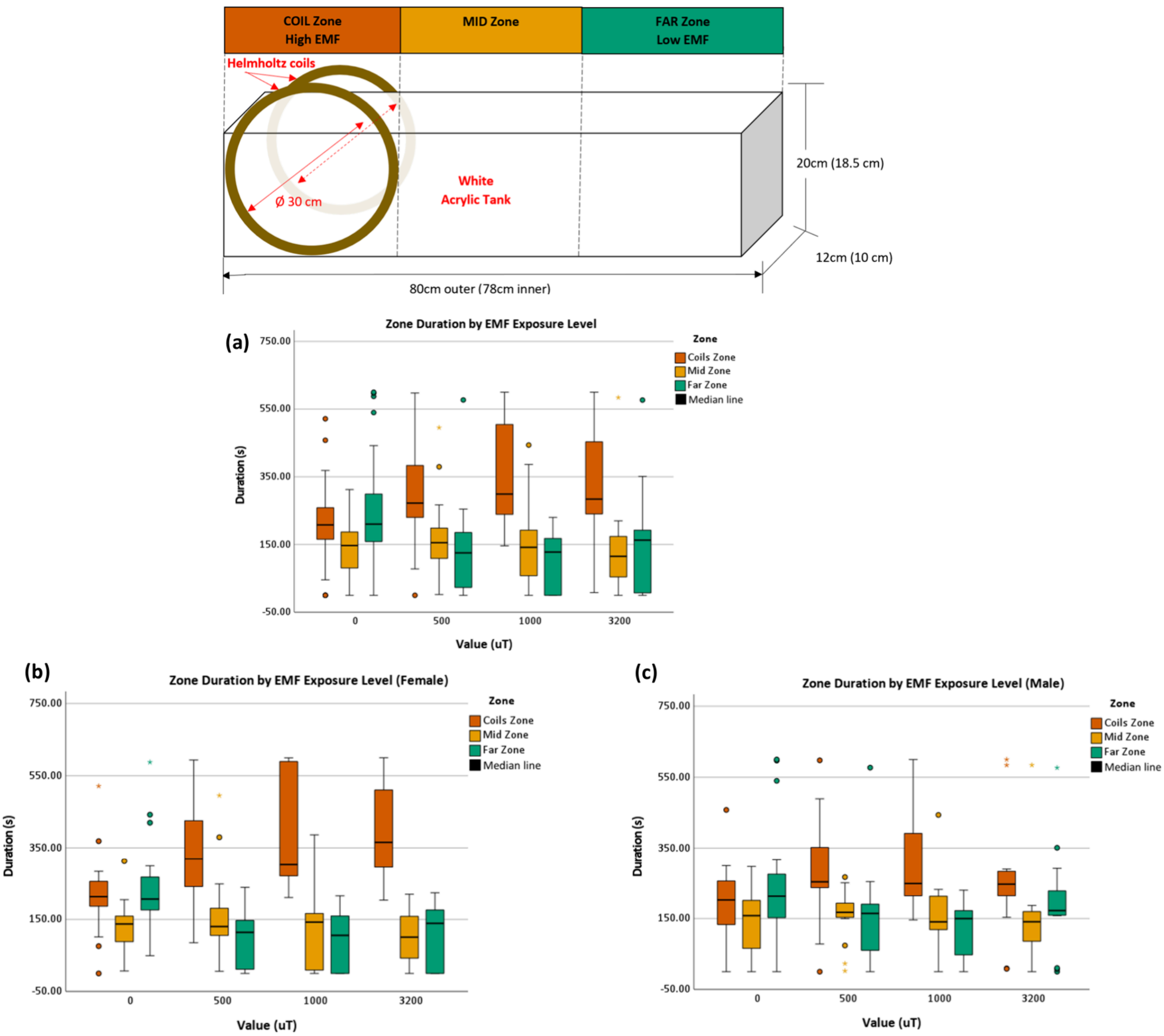

Figure 2. Aquarium tank setup showing zone EMF strength areas with resulting boxplots of *C. maenas* across EMF conditions (OFF; 500 μT, 1000 μT, 3200 μT) and zone duration for (a) all crabs (N = 120), (b) females (N = 60), (c) males (N = 60).

Field strengths were verified and mapped using a Magnet-Physik FH55 G/Teslameter. Peak intensities occurred at the COIL zone, decreasing toward the FAR zone. For the three EMF treatments (500, 1000, 3200 μT at COIL), average MID zone fields were ~330, 530, 750 μT, and FAR zone fields ~40, 40, 42 μT. The behavioral tank (80 × 12 × 20 cm, L × W × H, 10 mm white acrylic) was filled to 10 cm water depth, and centered within the coils to ensure consistent exposure.

An overhead Basler acA1300-60gc GigE color camera (Basler AG, Germany) recorded plan view movement, analyzed with EthoVision XT17 (Noldus) (Figure 1).

2.3. Behavioral Trials. Crabs (N = 120; 60 males, 60 females) were tested individually under four conditions: Control (OFF) and EMF ON at 500, 1000, and 3200 μT, with 15 males and 15 females per condition. Trials were conducted on isolated crabs in randomized order. Individuals were fasted for 24 h prior to testing.[50] Each crab was placed under an opaque plastic cylinder (10 cm diameter) in the center of arena for 10 min acclimatization (EMF OFF) period, then released for a 10 min tracked trial. The tank contained 10 L of aerated seawater at 12.1 ± 1 °C and 32.5 PSU, consistent with ambient harbor conditions and maintained via the flow-through seawater system, was divided into three zones: COIL (high EMF), MID, and FAR (low EMF). Crabs could move freely throughout.

EthoVision XT17 recorded mobility (% time active), total distance traveled across the arena and time spent in each of the three zones (zone duration) to assess attraction or avoidance. Additional metrics (meandering and zone entry frequency) were exploratory and are reported in the Supporting Information.

2.4. Statistical Analysis. Raw behavioral data was exported from EthoVision XT17 was analyzed in IBM SPSS Statistics v29. Descriptive statistics were generated, and normality tested using Kolmogorov−Smirnov and Shapiro−Wilk tests. All variables violated normality ($p < 0.001$) and

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Table 1. Results Summary of Behavioral Metrics (Kruskal−Wallis and Post Hoc Dunn's Tests) for *C. maenas* with EMF Exposure Off/On (500 μT, 1000 μT, 3200 μT)[a]

group	Kruskal−Wallis χ^2 (df = 3)	*p*	outcome[b]	key finding	significant post hoc: Bonferroni	significant post hoc: FDR
				Zone Duration: Coil Zone		
Overall	**18.339**	**<.001**	**Significant**	**Highest at 1000 μT; all EMF > control**	**0 μT < 500 μT, 1000 μT, 3200 μT**	**0 μT < 500 μT, 1000 μT, 3200 μT**
Female	**14.572**	**0.002**	**Significant**	**Increased with EMF; greatest at 3200 μT**	**0 μT < 1000 μT, 3200 μT**	**0 μT < 500 μT, 1000 μT, 3200 μT**
Male	5.441	0.142	NS	No significant differences	N/A	N/A
				Zone Duration: Mid Zone		
Overall	3.628	0.305	NS	No significant differences	N/A	N/A
Female	1.985	0.575	NS	No significant differences	N/A	N/A
Male	2.365	0.5	NS	No significant differences	N/A	N/A
				Zone Duration: Far Zone		
Overall	**20.738**	**<.001**	**Significant**	**Shortest at 1000 μT; all EMF < control**	**0 μT > 500 μT, 1000 μT, 3200 μT**	**0 μT > 500 μT, 1000 μT, 3200 μT**
Female	**15.24**	**0.002**	**Significant**	**Shortest at 1000 μT; all EMF < control**	**0 μT > 500 μT, 1000 μT, 3200 μT**	**0 μT > 500 μT, 1000 μT, 3200 μT**
Male	7.625	0.054	NS*	Control >1000 μT trend	N/A	0 μT > 1000 μT
				Distance Moved		
Overall	**9.675**	**0.022**	**Significant**	**Highest at 500 μT; reduced at 1000 μT**	**1000 μT < 500 μT**	**1000 μT < 500 μT**
Female	**8.121**	**0.044**	**Significant**	**Peak at 500 μT; lowest at 1000 μT**	**1000 μT < 0 μT, 500 μT**	**1000 μT < 0 μT, 500 μT**
Male	4.071	0.254	NS	No significant differences	N/A	N/A
				Mobility		
Overall	**8.784**	**0.032**	**Significant**	**Highest at 500 μT; lowest at 3200 μT**	**1000 μT < 500 μT, 3200 μT**	**1000 μT < 500 μT, 3200 μT**
Female	6.27	0.099	NS	No significant differences	N/A	N/A
Male	4.934	0.177	NS	No significant differences	N/A	N/A

[a]Zone frequency, mean velocity, and meandering metrics are reported in the Supporting Information as exploratory data and were excluded from the main statistical interpretation due to limited ecological relevance and interpretability. [b]NS = Not Significant; NS* = Approached Significance (p = 0.054).

were analyzed using nonparametric Kruskal−Wallis tests. Analyses were first conducted across all crabs, then separately for females and males to identify sex-specific responses. Where significant effects were found, pairwise comparisons were conducted using Dunn's test with Bonferroni adjustment.

Zone duration, distance traveled, and mobility were selected as primary metrics based on prior EMF studies.[51,52] To address Type I error inflation, false discovery rate (FDR) correction was applied to Kruskal−Wallis and post hoc tests across primary comparisons. Statistical significance was set at $\alpha = 0.05$ after correction.

3. RESULTS

Behavioral responses of *C. maenas* were evaluated across four EMF exposures (OFF, 500, 1000, and 3200 μT), for distance traveled, zone duration, and mobility ($N = 120$; equal sex ratio). Tracking accuracy exceeded 99.5%(35). All variables violated normality (Shapiro−Wilk test, $p < 0.001$) and were analyzed with nonparametric tests and Bonferroni/FDR correction.

3.1. Locomotor Activity. Distance traveled, represents the total movement across the entire arena, varied significantly across treatments (H(3) = 9.675, $p = 0.022$), highest at 500 μT and reduced at 1000 μT. Post hoc tests showed 1000 μT was significantly lower than 0 μT (Control) and 500 μT. Females showed significant variation (H(3) = 8.121, $p = 0.044$), with 1000 μT significantly lower than both 0 μT and 500 μT, whereas males showed no significant difference (H(3) = 4.071, $p = 0.254$).

3.2. Zone Preferences. COIL Zone: Duration differed significantly (H(3) = 18.339, $p < 0.001$), longest at 1000 μT (355.44 s vs 206.00 s Controls). This was driven by females (H(3) = 14.572, $p = 0.002$), with progressive increases across EMF levels significant versus Controls ($p = 0.021$, FDR-adjusted $p = 0.042$), 1000 μT ($p = 0.003$), and 3200 μT ($p = 0.014$). Males showed no significant effect (H(3) = 5.441, $p = 0.142$).

MID Zone: No significant differences were detected (H(3) = 3.628, $p = 0.305$) for either sex. This supports the interpretation that responses were specific to the coil zone and not indicative of a generalized attraction or avoidance of the tank midline.

FAR Zone: Duration was significantly reduced under EMFs compared to Controls (H(3) = 20.738, $p < 0.001$; control mean = 251.43 s vs EMF means = 102.54−145.58). Females showed consistent and significant reductions under all EMF exposures (H(3) = 15.240, $p = 0.002$; all $p < 0.015$ after Bonferroni). In males, a reduction was evident at 1000 μT ($p = 0.049$), although this did not remain significant following FDR adjustment ($p = 0.061$).

These results indicate reciprocal zone use with COIL increases mirrored by FAR decreased, especially in females. Zone duration distributions are shown in Figure 2. Mobility (% time moving) varied significantly across exposures (H(3) = 8.784, $p = 0.032$), peaking at 500 μT and lowest at 3200 μT.

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Posthoc tests showed higher mobility at 500 μT compared to 1000 μT and 3200 μT (significant after FDR adjustment, not Bonferroni). No EMF treatment differed from Controls, although the 0 μT vs 500 μT contrast approached significance. Females ($H(3) = 6.270$, $p = 0.099$) and males ($H(3) = 4.934$, $p = 0.177$) showed no effects, suggesting the overall result reflected pooled variance rather than sex-specific responses. The significance in the combined data set may partly reflect larger sample size.

3.3. Results Summary. Table 1 summarizes findings, showing consistent female attraction to the COIL zone and avoidance of the FAR zone. Figure 2 presents zone duration boxplots for all crabs and by sex.

4. DISCUSSION

This study shows that exposure to environmentally relevant EMFs significantly altered *C. maenas* behavior, with pronounced sex-specific responses. Females exhibited consistent attraction to EMF-exposed zones (500−3200 μT), with overall differences in distance moved and mobility driven by combined rather than sex-specific effects. The strongest female attraction occurred at 1000 μT, while males were largely stable. Results were robust to Bonferroni and FDR corrections, with FDR also detecting a marginal male FAR zone response at 1000 μT. These findings align with evidence that SPC-emitted EMFs alter movement and spatial distribution in marine invertebrates,[21,51] and emphasize sex as a critical biological variable in impact assessments. To our knowledge, this is the first sex-specific EMF attraction in crustaceans.

Zone-based analysis revealed a reciprocal pattern, with female attraction to the COIL zone mirrored by FAR zone avoidance. This may reflect sex-based differences in reproductive roles, where females invest in egg production and larval release and may show stronger site fidelity during reproductive periods.[37−39] Sexual dimorphism in movement patterns has been reported in other crustaceans,[25] and may contribute to differential environmental sensitivity. Males displayed limited responses, with no significant mobility or distance moved effects. More broadly, effects on distance moved and mobility were subtle and inconsistent, lacking a clear directional pattern, supporting that zone-use metrics provided the strongest evidence of EMF-driven behavioral change.

The observed EMF attraction is consistent with *Cancer pagurus* clustering near EMFs[21,51] and lobster studies reporting altered exploration, foraging and movement.[7,22,52] Other crab species also show EMF-linked behavior or physiology changes, including *Necora puber*,[53] and *Rhithropanopeus harrisii*,[54] as well as altered reflex response and condition in invertebrates, including crabs.[55] Laboratory work on crabs has shown magnetic field-driven attraction and altered movement,[21,56,57] though sex was not considered. In *Mytilus galloprovincialis*, EMFs exposure can trigger physiological stress.[58,59] Our findings extend this work by showing attraction in *C. maenas* is primarily female-driven, suggesting that omitting sex-based analysis may obscure meaningful variation.

Not all studies detect EMF effects. Some field and caging experiments report none or inconclusive results, including no changes in movement or catch rates in rock and red rock crabs near SPCs,[2,10,60−66] while others show variable distributional shifts.[56,66,67] A systematic review found that two-thirds of studies up to 3200 μT reported significant effects and a technical review highlighted diversity of EMF responses across taxa and the need for standardized experimental designs and cross-taxon comparisons.[67] Publication bias and lack of standardized methods may contribute to inconsistencies.

Positive thigmotaxis was evident across all treatments,[35] consistent with antipredator behavior, but COIL zone clustering, especially in females, plus increased overall movement at 500 μT, suggest active attraction rather than passive FAR zone avoidance.

Potential detection mechanisms include biogenic magnetite, electromagnetic induction, cryptochrome pathways, or statocysts.[22,29,68,69] In *Daphnia magna*, EMFs influence calcium signaling, oxidative stress, and hormonal pathways,[70,71] suggesting that endocrine modulation is possible, though sex-based mechanisms remain untested.

Magnetoreception is known in lobsters, fish, and turtles, and many crab species undertake sex-biased migrations.[38,42,72] In spider and blue crabs, females dominate long-distance reproductive migrations,[39,43,73] potentially predisposing them to stronger EMF responses. Our results support this, with females showing consistent attraction while males remained unresponsive.

Current regulations do not require sex-specific EMF assessments, but our findings indicate ecologically relevance. Ignoring sex differences could underestimate risks and weaken mitigation. Differential attraction may increase female exposure to EMF hotspots, altering reproductive and population stability.

While this study used a controlled laboratory setup, the EMF levels tested represent realistic values near SPCs, particularly in shallow or unburied cable sections. Nevertheless, the aquarium setting limits extrapolation to field conditions. The overall mobility effect may partly reflect larger sample size, as sex-specific analyses were not significant. In nature, crabs face complex stimuli, predators, and varied habitats. In addition, locomotor metrics (distance traveled and mobility) were calculated at the whole-arena level; future work could incorporate zone-specific movement analyses to reveal how activity varies with EMF intensity and location. Developing a standardized framework for EMF reporting, including spatial field decay profiles and biologically relevant thresholds, would improve cross-study comparability and support cumulative impact assessment. Field validation combining movement tracking with EMF mapping will be critical.

This study provides the first evidence that EMFs typical of SPCs elicit sex-specific behavioral responses in *C. maenas*. Females exhibited significantly greater attraction to EMF zones and avoidance of low-field zones, suggesting higher exposure risk. These differences could affect migration, mating, and larval release, with consequences for population dynamics. We recommend including sex as a biological variable in EMF research and environmental risk assessment. As offshore renewable energy grows, incorporating sex-specific behavioral data into impact assessments will improve our ability to predict and manage ecological impact, especially for species with complex life cycles and seasonal movements.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.5c00862.

Additional statistical analysis tables for zone duration, distance moved, mobility, descriptive statistics, Kruskal−

Wallis tests, Dunn's pairwise comparisons, sex-specific analyses, and exploratory variables as well as figures showing cumulative heatmaps of *C. maenas* spatial distribution under EMF conditions for both sexes, males, and females and boxplots of distance moved and of mobility across EMF exposure levels (PDF)

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Author Contributions

I, Elizabeth James, hereby declare that this paper, titled "Female crabs are more sensitive to environmentally relevant electromagnetic fields from submarine power cables", is the result of my coauthors and my original research and work. Experiments were conceived and designed by Elizabeth James, Mojtaba Ghodsi, and Alex T. Ford; all experiments were conducted by Elizabeth James; the paper was drafted by Elizabeth James and edited by Mojtaba Ghodsi and Alex T. Ford.

Notes

The authors declare no competing financial interest.

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