OCS Study
BOEM 2023-005

Supplemental Data Regarding the Behavioral Response of Rock Crabs to the EMF of Subsea Cables and Potential Impact to Fisheries

US Department of the Interior
Bureau of Ocean Energy Management
Pacific OCS Region (Camarillo, CA)

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by

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DISCLAIMER

Study collaboration and funding were provided by the US Department of the Interior, Bureau of Ocean Energy Management (BOEM), Environmental Studies Program, Washington, DC, under Agreement Number M21AC00001. This report has been technically reviewed by BOEM, and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the US Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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ABOUT THE COVER

Cover image is a still from a film about this project ("Can Crabs Cross Submarine Cables?": https://youtu.be/dZWCQctUNS4) created by Shaun Wolfe of *Shaun Wolfe Photography*.

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List of Abbreviations and Acronyms

α	alpha [significance threshold level]
AC	alternating current
ADV	acoustic doppler velocity meter
AIC	Akaike information criterion
AICc	Akaike information criterion for small sample sizes
B-field	magnetic field
BOEM	Bureau of Ocean Energy Management
CDFW	California Department of Fish and Wildlife
cm	centimeter
DC	direct current
df	degrees of freedom
E-field	electrical field
EMF	electromagnetic field
GLM	generalized linear model
h	Cohen's *h* [a measure of effect size for chi-square proportions tests]
iE-field	induced electrical field
kV	kilovolt
LCI	lower 95% confidence interval
m	meter
M	Hodges-Ajne test statistic for circular uniformity
MRE	marine renewable energy [includes both wind and wave energy sources]
µT	microtesla
NOAA	National Oceanic and Atmospheric Administration
p	p-value
PVC	polyvinyl chloride
s	second (time)
T	tesla
UCI	upper 95% confidence interval
VIF	variance inflation factor
VRG	Vantuna Research Group at Occidental College
w	Cohen's *w* [a measure of effect size for chi-square tests of independence]
w_i	Akaike weight
χ^2	chi-square
z	z-score for model averaging

1 Introduction

1.1 Marine Renewable Energy

The need for diversity and flexibility in sources that support the energy grid while combating climate change has amplified the need for renewable energy sources (Jacobson et al. 2015; Johnson et al. 2021). Marine renewable energy (MRE) planning has increased pace in the United States in recent years with the Biden Administration's focus on counteracting the climate crisis (The White House 2021), along with many states issuing goals for net neutral carbon (e.g., State of California 2018). Development of MRE devices, such as ones that harness offshore wind and wave energy, contributes to state and national economic development, and is predicted to create jobs and increase cumulative gross domestic product through both construction and operation (Speer et al. 2016). MRE has shown to be an effective supplement to traditional energy sources, though socio-economic and ecological impacts are expected as more MRE devices are constructed (Nelson et al. 2008). Although these structures will be an integral component of our energy security (Borthwick 2016), there are potential impacts that MRE devices can have on marine organisms and their environments, such as collision and entanglement, sound pollution, change in natural flow patterns, energy removal from the system, physical habitat disturbances, chemical pollution, sediment resuspension, heat emission, and change in electromagnetic fields (Borthwick 2016; Copping et al. 2016; Taormina et al. 2018). As MRE development continues, it will be increasingly important to understand and anticipate the results of these infrastructure projects on the marine environment.

1.2 Electromagnetic Fields

One potential impact of MRE development is a localized change in electromagnetic fields (EMF). Naturally occurring EMF is pervasive in the marine environment through the Earth's geomagnetic field and local EMF distortions within the surrounding environment. Anthropogenic EMF interacts with the ambient field, potentially disrupting the natural behavior or physiology of marine organisms that can detect these anomalies, particularly when those organisms rely on the magnetic field to guide their movements through a region (Taormina et al. 2018). Many marine species are sensitive to EMF, primarily for navigation and orientation purposes (Gill et al. 2014). The flow of electrical current through a transmission cable generates EMF in the form of electrical fields (E-fields) and magnetic fields (B-fields), as well as weak electrical fields induced by alternating magnetic fields from AC cables (iE-field) (Taormina et al. 2018). EMF from power cables can affect a variety of marine organisms, causing behavioral (e.g., Hutchison et al. 2020; Westerberg and Lagenfelt 2008), developmental (e.g., Woodruff et al. 2012), and physiological changes (e.g., Jakubowska et al. 2019; Scott et al. 2018). Though sub-lethal behavioral effects of EMF on marine organisms have been documented, this area of research is still in its infancy (Claisse et al. 2015; Kaplan et al. 2010).

Strong conclusions about how EMF affects organisms, especially invertebrates, are lacking (Taormina et al. 2018). Most studies on EMF effects have focused on the responses of fishes. However, due to differences in sensory organs and other physiological and life-history characteristics, it is difficult to extrapolate current knowledge of EMF effects on fishes to other animal groups. Thigmotropic organisms that traverse the sea floor, such as crabs, may be subject to stronger and more direct EMF currents. Of the few studies on the effects of EMF on crustaceans, behavioral responses have been noted. For example, Hutchison et al. (2020) found that American lobsters (*Homarus americanus*) explored the seabed more when exposed to EMF. In other studies, edible crabs (*Cancer pagurus*) spent more time in shelter when exposed to EMF and were attracted to EMF in a strength-dependent manner (Scott et al. 2021; Scott et al.

2018). Additionally, Dungeness crab (*Metacarcinus magister*) had greater activity variability when exposed to EMF (Woodruff et al. 2012). However, other studies have found no effect of EMF on crustaceans (e.g., Bochert and Zettler 2004; Love et al. 2017a; Taormina et al. 2020). Not only are there contradicting conclusions, but some studies have problematic study designs, such as not controlling for confounding factors (e.g., Love et al. 2017a; Taormina et al. 2020; Woodruff et al. 2012), not having an appropriate number of replicates (e.g., Hutchison et al. 2020), or using EMF treatment levels that are orders of magnitude greater than what may be expected for offshore renewable energy cables to emit (e.g., Scott et al. 2021). Furthermore, very few studies have been conducted *in situ*, leaving gaps in our understanding of how the effects of artificial EMF translate to an environment with natural EMF signatures that will also be encountered by marine organisms.

Because the US West Coast is both a hot spot for emerging MRE development as well as home to the largest crab fisheries in the nation (NOAA 2020), there is an obvious concern on the potential impact development will have on fisheries. Crab fishers are particularly concerned that EMF from subsea cables may reduce catch by creating de facto "electrified fences" that deter crabs from crossing over cables to get to baited traps. To address this potential impact, the BOEM funded a study conducted by Love et al. (2017a) to investigate the effects of EMF on the behavior of two commercially important crab species, and they found that crabs did cross an energized cable to get to a baited trap. The study did not control for stimuli other than EMF, such as the current (i.e., water velocity/direction), which may transport olfactory and chemosensory cues. Crabs often use rheotactic and chemical information for orientation and navigation (Weissburg and Zimmer-Faust 1994) and chemoreception has been shown to be the predominant sensory modality used by Atlantic rock crab (*Cancer irroratus*) to detect prey (Zhou and Rebach 1999). Because the study performed by Love et al. (2017a) did not control for environmental conditions impacting these other sensory modalities, in particular current direction and experimental setup relative to nearby reefs, further investigation was needed to build upon their study design and findings. This report builds upon the goals, experimental design, and findings of Love et al. (2017a).

1.3 Study Goals

Information is currently incomplete on how EMF from power cables affects crab harvest. Crab fishers and coastal communities along the West Coast rely on fisheries, with the total national value of Dungeness crab at more than $235,000,000 (NOAA 2020)and the red rock crab (*Cancer productus*; **Figure 1**) fishery valued at over $587,000 in the Santa Barbara, California area alone (CDFW 2020). This study is critical to making informed and sustainable policy decisions about renewable energy development and ensuring that this technology can coexist with local fisheries as MRE development continues.

Figure 1. Red rock crab, *Cancer productus*.
All crabs used in this study were red rock crabs caught in the Santa Barbara Channel by local commercial fishermen.

1.3.2 Specific Objectives & Hypotheses

This study supplements and builds upon the findings from Love et al. (2017a) on red rock crab behavior to increase our understanding of potential consequences that renewable energy projects may have to commercial harvest. Our primary objective was to verify the response of rock crab in the presence of energized cables associated with MRE installations, while also controlling for environmental conditions. To do this, we quantified and mapped local magnetic fields near an energized cable at the study site, determined if the energized cable altered crab responses, and described and quantified variables that were most likely to affect crab responses, including water current direction/velocity, magnetic field strength, and physical characteristics of each crab. Our experimental design specifically addressed three questions and the following null (H_0) and alternative (H_a) hypotheses:

1) **Will the requirement of crossing an artificial magnetic field from an energized power cable affect the rate at which crabs will enter a baited trap?**

   H_O: There is no difference in the rate crabs enter a baited trap with or without needing to cross an electromagnetic field
   H_A: There is a difference in the rate crabs enter a baited trap with or without needing to cross an electromagnetic field

2) **Does the presence of a submarine power cable and associated artificial magnetic field affect the direction of crab travel?**

   H_O: There is no difference in the direction of travel with or without the presence of a submarine power cable
   H_A: There is a difference in the direction of travel with or without the presence of a submarine power cable

3) **Does water current direction/velocity, magnetic field strength, or physical characteristics of the crabs influence the direction of travel or rate to which crabs will enter a baited trap?**

   H_O: There is no relationship between the rate crabs enter a baited trap or the direction they travel and water current direction/velocity, magnetic field strength, or physical characteristics of the crabs
   H_A: There is a relationship between the rate crabs enter a baited trap or the direction they travel and water current direction/velocity, magnetic field strength, or physical characteristics of the crabs

2 Materials and Methods

2.1 Study Setting

This study took place in southern California in the Santa Barbara Channel, offshore of Las Flores Canyon, where a 20.3-cm diameter submarine transmission cable lays partially exposed at a depth of approximately 9–11 m of water in a roughly north-south orientation (**Figure 2**). This alternating current (AC) cable operates at 34.5 kV and distributes power offshore from Las Flores Canyon to oil platforms Heritage, Harmony, and Hondo. Two similar, unenergized cables are completely buried a few meters to the east, and a 30.5-cm oil pipeline lays approximately 12 m to the west. These cables are similar in design and EMF character to those anticipated from ongoing MRE development (Normandeau Associates Inc. et al. 2011).

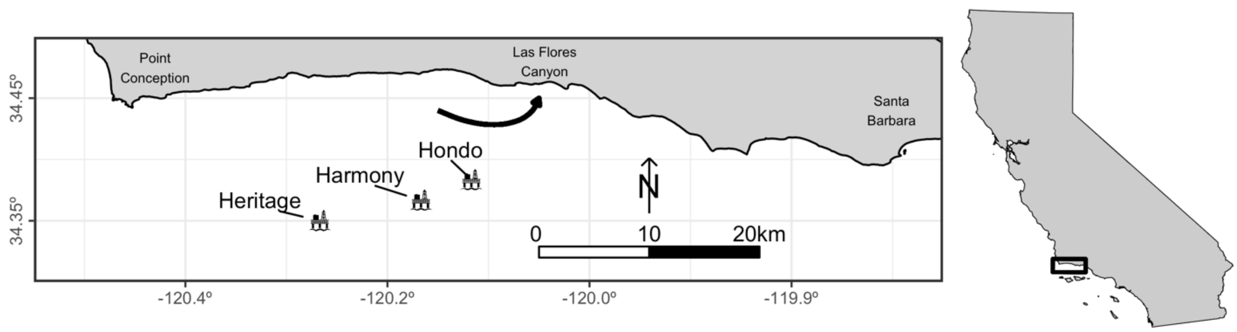

Figure 2. Map of the Las Flores Canyon study site.
The study site (indicated by the arrow near Las Flores Canyon) is approximately 35 km from Santa Barbara and 40 km from Point Conception, California, and is bisected by a power distribution cable that leads to oil platforms Heritage, Harmony, and Hondo.

2.1.1 Local Involvement

In addition to hiring an experienced crab fisherman to build the experimental cages, we collaborated with resident fishers and area experts who are knowledgeable about Santa Barbara Channel's fishing and marine community and incorporated their knowledge and expertise about the fishery environment and techniques into our study. In guided discussions, they identified specific concerns of the fishing industry with respect to MRE, including electrical and magnetic fields potentially altering crab behavior and physical obstructions posed by MRE installations, including the cables. Commercial crab fisherman also made suggestions about the type and quality of crabs to use in the study (larger crabs that have not recently molted), bait for the traps (locally caught mackerel cut up and hung in small mesh bags), and environmental variables that they believe affect crab behavior (specifically, current direction/speed). Stakeholders all strongly encouraged sharing the results with the Commercial Fisherman of Santa Barbara (CFSB), a non-profit organization which integrates regional efforts of fishing communities with the goal of improving both biological and economic sustainability of local fisheries.

We did not get a successful response after numerous attempts to contact the owner/operator of the Santa Ynez Unit facilities (ExxonMobil) to gather knowledge about cable power conveyance and operation.

2.2 Experimental Design

2.2.1 Cage Design

As in the previous study by Love et al. (2017a), each experimental cage consisted of two rectangular crab traps (similar to those used by local commercial crabbers, 0.9 m x 0.7 m x 0.3 m) connected by a 2.5 m x 0.25 m × 0.3 m mesh tunnel, and a small (0.25 m × 0.4 m × 0.5 m) cage (the chute) on top of the tunnel midway between the two traps (**Figure 3**). Traps, tunnels, and chutes were constructed of PVC-coated wire mesh with a steel frame and connected through aligned openings held together by bungee cords. Flexible PVC panels were installed on the sidewalls and ceiling inside of the tunnel at each trap opening to prevent crabs from climbing the walls or clinging to the ceiling of the tunnel, forcing a crab to enter either trap by walking on the bottom of the tunnel. Cages placed along the energized cable were situated on the substrate so that the energized cable was directly under the opening of one trap. The position of the chute with respect to the cable (chute east of the cable or chute west of the cable) was alternated along the cable. A local Santa Barbara commercial crab fisherman built 15 identical experimental cages and delivered them to the study site on 25 May 2021 (**Figure 4**), where Vantuna Research Group (VRG) divers assembled and installed them on the sea floor.

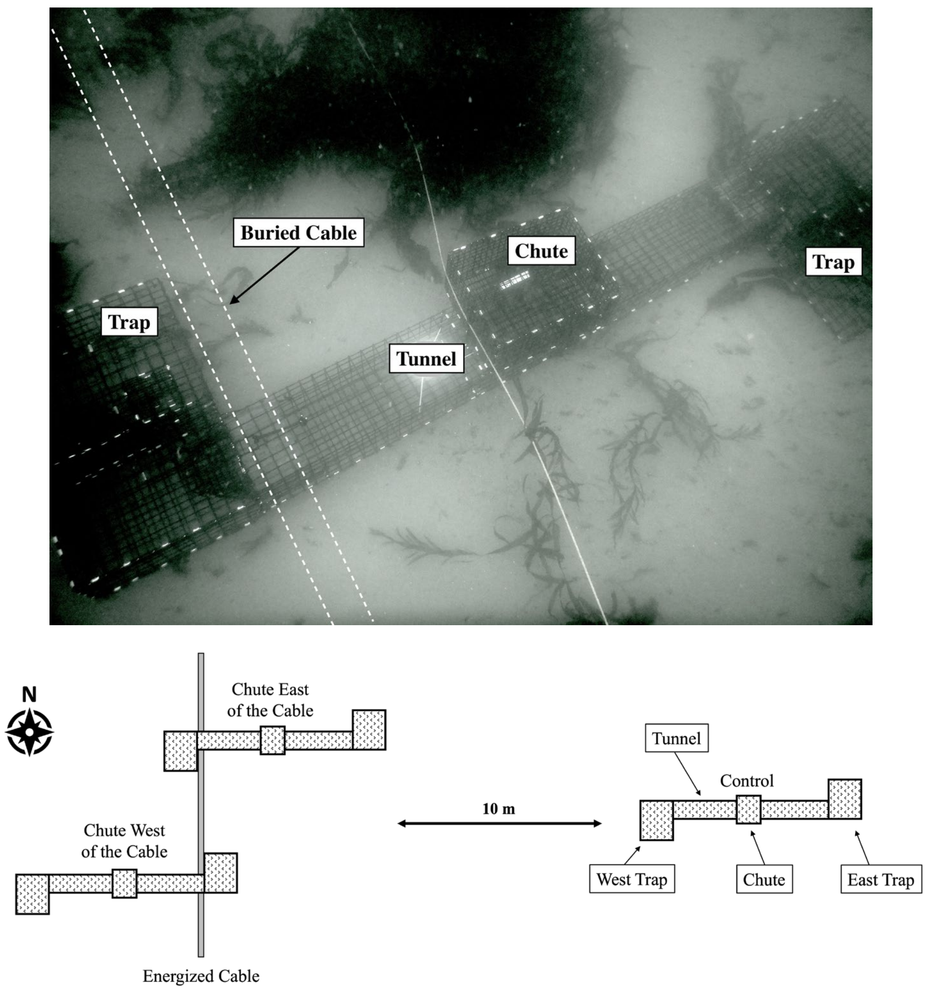

Figure 3. Experimental cage *in situ*, treatment positions, and cage diagram.
Two crab traps connected by a long tunnel, with a chute for introducing the crab to the cage attached to the middle/top of the tunnel. Entering one trap requires a crab to cross the energized cable, entering the other trap does not. Cages were installed along the cable by alternating the position of the chute with respect to the cable.

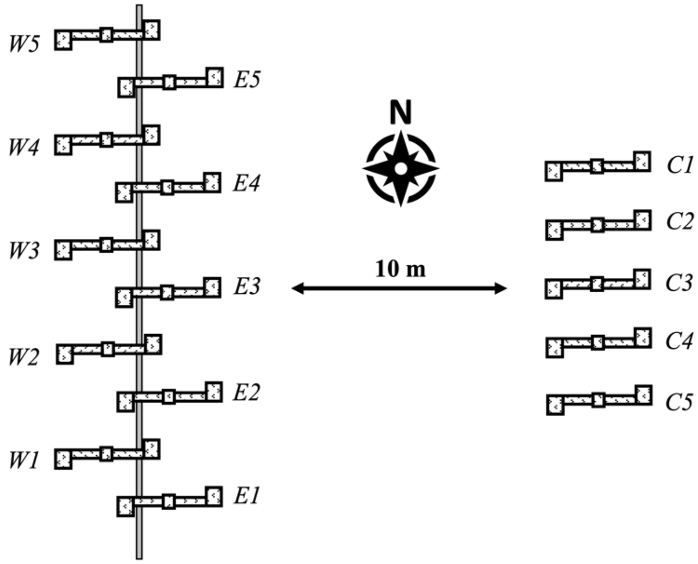

Figure 4. Experimental cage diagram and study area setup.
Five cages were placed in the control area (labeled C1-C5) and ten cages were placed across the cable – five with the chute to the west of the cable (labeled W1-W5), five with the chute to the east of the cable (labeled E1-E5). Cages in both areas were placed in approximately 4-m intervals.

2.2.2 Experimental Design

To assess each experimental hypothesis, experimental cages were placed in one of three positions (treatments):

- Across the energized cable, with the chute to the west of the cable so the crab would have to travel east across the cable to enter a trap
- Across the energized cable, with the chute to the east of the cable so that the crab would have to travel west across the cable to enter a trap
- In a control area that is free of any submarine cables and their associated magnetic fields

Five experimental cages were placed in each treatment position. The ten cable cages were alternated by treatment and evenly spaced along a 36-m long stretch of the energized cable. The five control cages were placed parallel to the cable cages approximately 10 m east of the energized cable (**Figures 3, 4**). Each cage was considered an independent unit and each crab placed in a cage for *in situ* experimentation was considered an independent replicate ("crab trial"). Care was taken during installation to avoid derelict traps from previous studies. This study was approved by the California Department of Fish and Wildlife (CDFW), and experiments were conducted under Specific Use Permit ID S-182750002-20352-001.

2.2.3 Pre-Experiment Power Analysis

We performed power analyses prior to experimentation using the 'pwr.p.test' and 'pwr.chisq.test' functions in the *pwr* package (Champely 2020) using R version 4.1.2 (R Core Team 2018). These analyses identified appropriate sample sizes to detect relevant and/or statistically significant effects in each experiment. We concluded that by running ~800 crab trials in the cable area, we would be able to detect as low as a 5% true effect size (the difference in cable crossing preference; $h = 0.10$) 80% of the time and as low as a 10% difference ($h = 0.20$) 99.9% of the time using a one-sample proportions test ($\alpha < 0.05$; **Figure 5**). For this study, a 5% true effect size would be reflected as 55% of crabs having chosen not to cross the cable to enter a baited trap while 45% chose to cross the cable to enter a baited trap, or vice versa. For reference, Love et al. (2017a) performed 495 crab trials and found a 54.5% to 46.5% proportion, respectively, which was not significantly different at $\alpha = 0.05$.

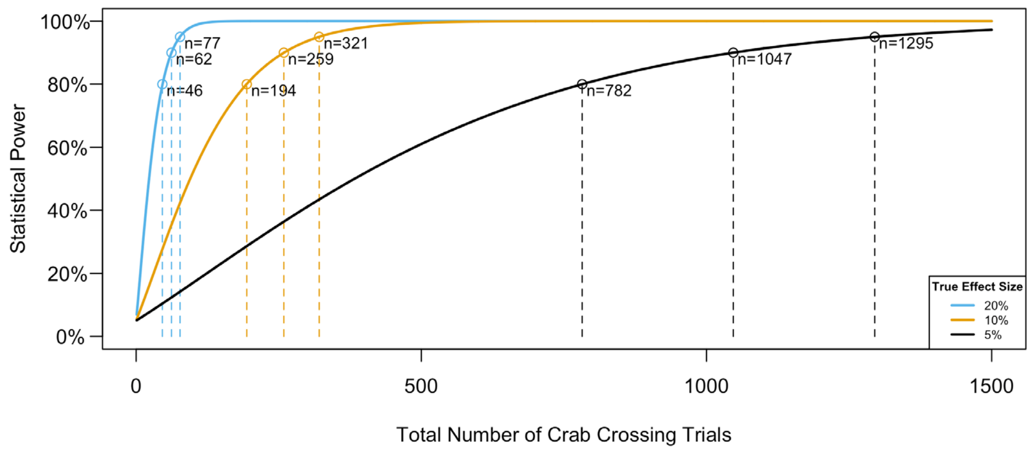

Figure 5. Pre-experiment power analysis for cable crossing preference.
The power analysis suggested that by running 782 crab trials we could detect as small as a 5% difference in cable crossing preference (i.e., 55% crossing the cable to enter a baited trap vs. 45% without crossing the cable, or vice versa) 80% of the time. By running 1,200 crab trials, we could detect a 5% difference in preference 95% of the time.

With respect to direction of travel (defined as traveling east to enter a baited trap, traveling west to enter a baited trap, or remaining in the chute or tunnel), we determined that with ~400 additional crab trials at the control area (1,200 crab trials total) we would detect a 'small' effect size (w = 0.1; Cohen 1988) 80% of the time and a slightly larger effect size ($w = 0.12$; still far smaller than a 'medium' effect size of 0.3) 99.9% of the time (**Figure 6**). For reference, Love et al. (2017a) detected a highly significant preferred travel to the west for crab trials on the energized cable. Overall direction of travel did not differ significantly between chute position relative to the cable, but no control was used to determine if that preference was related to the energized cable.

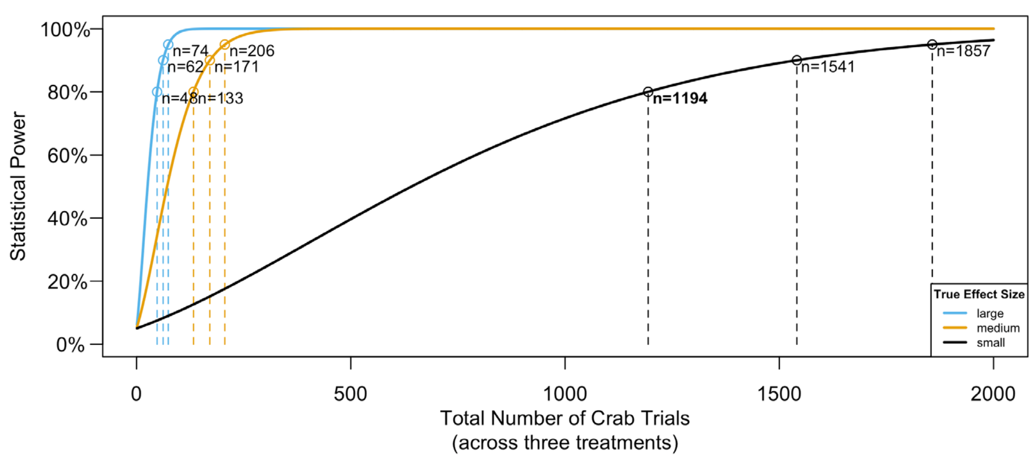

Figure 6. Pre-experiment power analysis for direction of travel.
The power analysis suggested that by running 1,194 crab trials we could detect a small difference in direction of travel (i.e., traveling west, traveling east, or remaining in the chute or tunnel) 80% of the time.

2.3 *In Situ* Measurement Instrumentation

2.3.1 Magnetic Fields

Divers measured magnetic fields using a Sper Scientific 3-axis EMF meter housed inside a 10-cm diameter, 30-cm long watertight enclosure manufactured by Blue Robotics (**Figure 7**). The small size instrument and housing size allowed us to measure within 5 cm of the seafloor, giving a record of the magnetic fields experienced by crabs as they walk across the seafloor.

Figure 7. Sper Scientific EMF meter inside the Blue Robotics waterproof enclosure.
The 3-axis EMF meter was used throughout the study to measure magnetic fields within 5 cm of the seafloor. Bottom image credit: Shaun Wolfe of Shaun Wolfe Photography.

2.3.2 Water Current Speed and Direction

To determine whether the direction of travel was influenced by water-borne olfactory cues, we measured current speed and direction *in situ* using a SonTek Argonaut acoustic doppler velocity meter (ADV). The ADV measures water movement at a single 1-cm^3 point approximately 5 cm in front of the sensor. The ADV mounting bracket was separated from the seafloor attachment (a pair of sand screws) by a 2-m horizontal arm to prevent interference from the anchoring hardware while maintaining stability (**Figure 8**). It was mounted vertically with the sensor at a height of 10 cm and pointed toward the seafloor to monitor water movement 5 cm above the seafloor. While deployed, the ADV continuously recorded three-dimensional water motion data for 1 minute at 5-minute intervals.

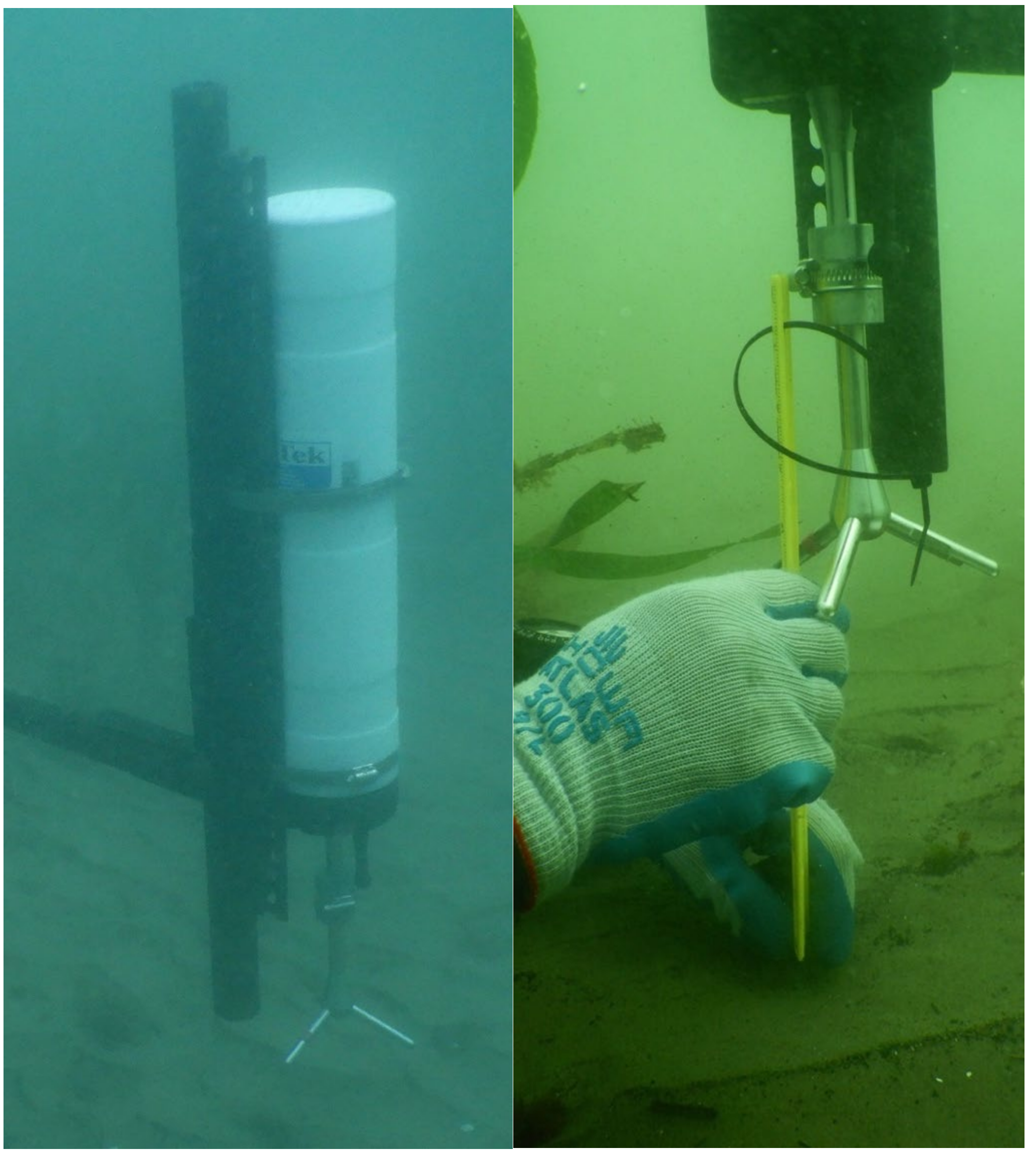

Figure 8. Sontek Argonaut ADV mounting bracket and installation.
The ADV was mounted to a bracket that was anchored to the seafloor about 1 m away from the ADV to avoid interfering with water current measurements (left). The ADV was mounted 10 cm above the seafloor to measure the currents at 5 cm above the seafloor (right).

2.4 Field Experiments

2.4.1 Local Magnetic Field Mapping

On 23 April 2021, VRG divers measured local magnetic fields at the seafloor every 3 m along the 36-m running length of energized cable where the cages were later installed, and perpendicular out to 1.5 m on either side of the cable in 0.3-m increments (**Figure 9**). Where the cable was buried and not visible to divers, a 2-m long, 5-mm diameter hollow air probe with integrated measurement gradations was used to determine the depth of the cable.

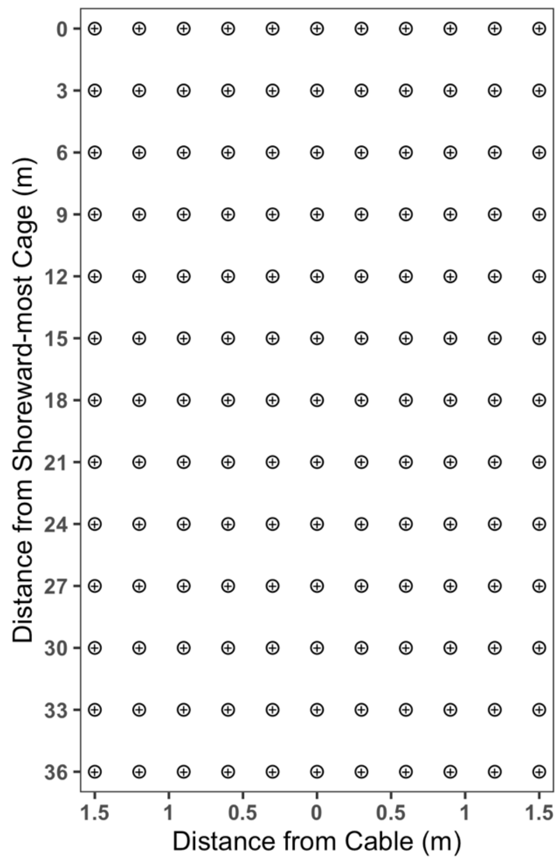

Figure 9. Magnetic field measurement grid. Divers measured the strength of the magnetic field on the seafloor along and parallel to the energized cable. Each point represents a measurement location.

2.4.2 Crab Trials

Divers visited the study site intermittently from 25 May 2021 to 21 July 2021 aboard the R/V *Neoclinus* or D/V *Obscurus*. Each morning, the ADV was deployed, magnetic field measurements were taken to ensure the cable was energized and operational, and both traps on every experimental cage were freshly baited with ~0.5 kg of previously frozen Pacific Mackerel (*Scomber japonicus*) from Cal Marine Fish Company of San Pedro, CA. Red rock crabs of legal size, obtained from one of two local Santa Barbara commercial crab fishermen, were selected haphazardly, measured (carapace width), sexed, macroscopically examined for anomalies (including gross pathology and missing legs or claws), and placed in the chute. Divers noted the time each crab was placed in the chute and estimated or measured surge, visibility, current speed/direction, water temperature, and magnetic field strength on the cable adjacent to the tunnel. Once all cages had a crab inside, the divers inspected each cage for crabs that were immediately trapped. Any trapped crabs were removed, the time and location of the crab (east trap or west trap) were recorded, and a new, naïve crab was placed in the chute. Following inspection of each experimental cage, divers surfaced. A new dive team inspected the cages approximately 30 minutes after the initial dive, removed all crabs while noting time and location of the crab (east trap, west trap, or tunnel/chute), placed new, naïve crabs in each cage, inspected for immediate trappings, and removed and replaced as necessary.

This dive plan was repeated up to three times, followed by a final dive to remove all crabs (noting time and location), bait, and the ADV. All experimental crabs were tagged to avoid potential reuse and released away from the study site, and southeast of Point Conception and outside of any Marine Protected Areas as per CDFW requirements. Following completion of the experiment, all cages were dismantled by VRG divers on 17 Sep 2021 and retrieved by a local fisherman on 30 Sep 2021.

2.5 Analyses

All analyses were performed using R version 4.1.2 (R Core Team 2018).

2.5.1 Magnetic Field Mapping

The initial magnetic field measurement survey of the energized cable created a grid of 143 equally spaced points across the seafloor (**Figure 9**). A thin plate spline surface was fit to magnetic field measurements and magnetic field strength was interpolated across the study area using the 'Tps' and 'predictSurface' functions in the *fields* package (Nychka et al. 2021). This smoothed and interpolated surface was plotted to visualize magnetic field strength experienced on the seafloor in the study area. Similarly, magnetic field measurements taken at the beginning of each crab trial were used to create time-series illustrations of magnetic field strength over both space and time at the energized cable and in the control area.

Cable burial depth was integrated into measurements to describe and model the relationship between magnetic field strength and distance from the energized cable. Distances from the cable along the parallel (east-west) lines of the measurement grid were calculated as either the depth of the cable under the sand (in the case of measurements taken directly above the cable) or the length of the hypotenuse of a triangle, where the two known sides of the triangle are cable depth and distance away from the cable along the seafloor. Data were fit using nonlinear least squares to an asymptotic regression model using the 'nls' and 'SSasymp' functions and an exponential decay model using 'nls' and the 'NLS.expoDecay' function in the *aomisc* package (Onofri 2023). To determine which model best fit the data, model parameters were constructed and ranked according to second-order Akaike Information Criterion (AICc, AIC for small samples). Model parameters were constructed using the 'AICc' function in the *MuMIn* package (Bartoń 2022) and Akaike weights (w_i) were calculated to assess the relative likelihood of each model. Akaike weights were interpreted as the weight of evidence in favor of each model (Akaike 1971; Burnham and Anderson 2002). For visualization, a 95% confidence interval for the selected model was calculated using the 'predFit' function in the *investr* package (Greenwell and Schubert Kabban 2014).

2.5.2 Water Current Speed and Direction

Data collected by the ADV is output as a pair of vectors—north/south water velocity and east/west water velocity—which can be geometrically translated to an overall speed and direction. Negative values for either vector indicate water flow in the opposite direction stated. For example, a north/south velocity vector with a value of -1.0 cm/s indicates a southward flow at 1.0 cm/s, and the combination of a north/south velocity vector with a value of -1.0 cm/s and an east/west velocity vector of 1.0 cm/s translates to a velocity of 1.41 cm/s towards a direction of 135º (due southwest). For visualization and summarization, speed and direction were plotted on a polar surface, and the Hodges-Ajne test was performed to provide a non-parametric measure of the uniformity of the directional data using the 'unif_test' function in the *sphunif* package (García-Portugués and Verdebout 2021). For hypothesis testing, we used both water velocity vectors to account for overall speed and direction while avoiding issues with circular variables.

2.5.3 Crab Hypothesis Testing

First, we assessed whether there was a significant difference in the rate crabs enter a baited trap with or without needing to cross an electromagnetic field by performing a one-sample proportions test of the number of crabs that were trapped after crossing the cable versus trapped without crossing the cable in all non-control cages. Second, one-sample proportions tests and chi-square tests of independence were performed to identify significant differences in direction of travel (i.e., traveling east to enter a baited trap, traveling west to enter a baited trap, or remaining in the chute or tunnel) and assess whether travel direction differed significantly between either of the cable treatments (chute west of the cable vs. east of the cable) or the control group. Lastly, we used a generalized linear model (GLM) approach to determine which explanatory variables (including experimental treatments—chute position and cable/control) most influenced the response variables of cable crossing preference and travel direction (**Table 1**). We tested for potential collinearity among potential explanatory variables using Pearson correlations and variance inflation factors (VIF) of variables included in the confidence model set for both response variables (Zuur et al. 2009). As treatment type and magnetic field are intrinsically related and therefore inappropriate to include in the same GLM, travel direction was modeled twice—once including magnetic field strength at the cable area only and once including treatment type in both the cable and control areas.

Table 1. Explanatory variables examined for influence on response variables using GLM.

Explanatory variables (individual crab characteristics, experimental treatment, and environmental variables) examined using a GLM approach to determine their influence on response variable of cable crossing preference and travel direction. "**x**" indicates the explanatory variable was included in modeling for the response variable listed above it.

Explanatory Variable Type	Explanatory Variables	Cable Crossing Preference (Crossed/ Did Not Cross)	Direction of Travel All Treatments	Direction of Travel Cable Only
Crab Physical Characteristics	Sex (M/F)	**x**	**x**	**x**
Crab Physical Characteristics	Carapace Width (mm)	**x**	**x**	**x**
Crab Physical Characteristics	Missing Legs (#)	**x**	**x**	**x**
Crab Physical Characteristics	Claw Damage (Y/N)	**x**	**x**	**x**
Experimental Treatment	Chute Position Relative to the Cable (East/West)	**x**	**-**	**-**
Experimental Treatment	Cable vs Control	**-**	**x**	**-**
Environmental Variable	North/South Water Velocity (cm/s)	**x**	**x**	**x**
Environmental Variable	East/West Water Velocity (cm/s)	**x**	**x**	**x**
Environmental Variable	Magnetic Field Strength (μT)	**x**	**-**	**x**

We fit logit-linked binomial regression models using all, some, or none of the explanatory variables to predict the response variables. For each response variable, we used the information-theoretic approach for model selection, based on AICc (Burnham and Anderson 2002; Johnson and Omland 2004), with the 'dredge' function in the *MuMIn* package. We ranked each model by w_i and retained all models with a cumulative $w_i \leq 0.95$ to create a 95% confidence model set (Symonds and Moussalli 2011). We examined the relative importance of each variable using the 'importance' function in the *MuMIn* package. This gives the sum of model weights ($\sum w_i$) over all models included in the confidence model set (Burnham and Anderson 2002) and identifies variables that are present in a large proportion of highly ranked models. We also used full-model averaging (via the 'model.avg' function in the *MuMIn* package) to produce parameter estimates across the confidence model set as an alternative method of identifying important predictor variables (Galipaud et al. 2017; Lukacs et al. 2010).

3 Results

3.1 Magnetic Field Mapping

Magnetic field strength near the seafloor was variable along the length of the energized cable, peaking at about 1.2 µT at Ean exposed section of the cable near where experimental cage E2 was later placed, but measuring near zero (background level) in all locations ≥ 0.9 m from the cable (**Figure 10**). This pattern was seen along the cable through the entire experiment, with only minor variations in magnetic field strength over time; magnetic field strength was near zero in the control area (**Figure 11**). Magnetic field strength rapidly declined following an asymptotic regression model (w_i = 0.96; pseudo-R^2 = 0.925) (**Figure 12**).

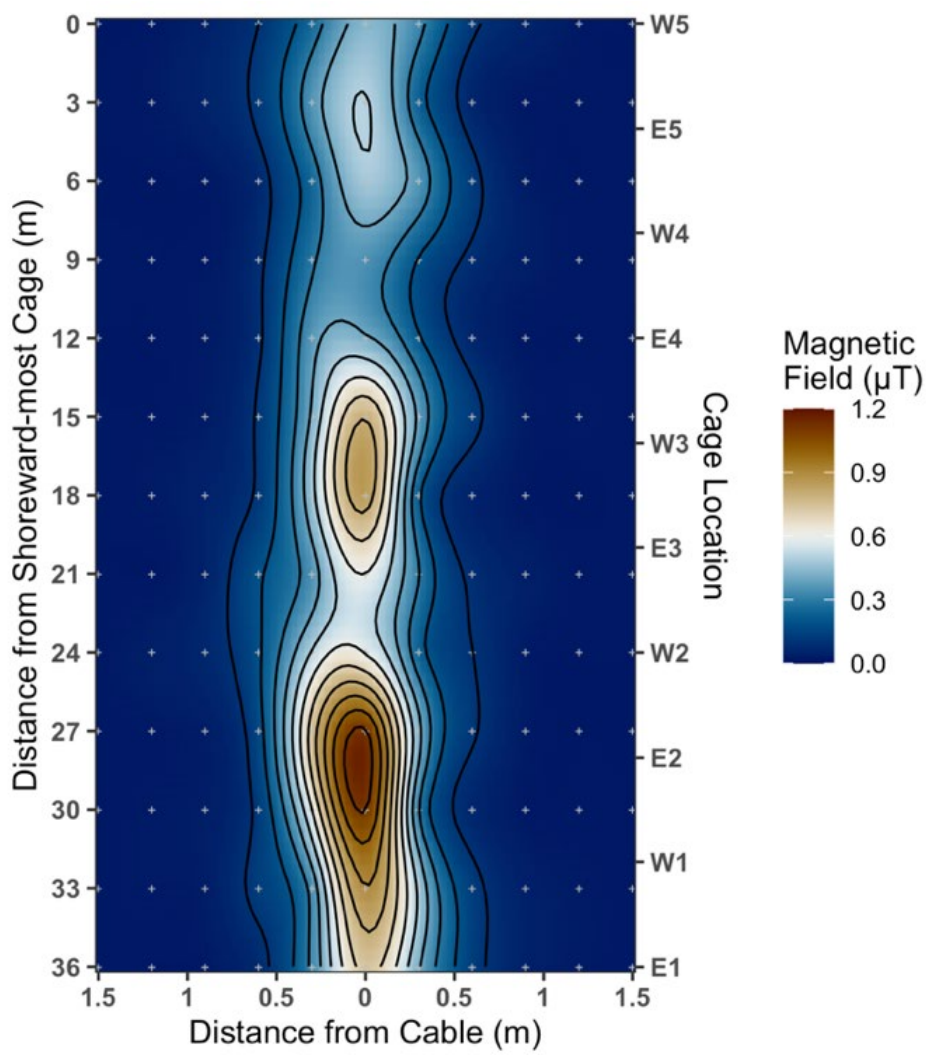

Figure 10. Map of magnetic field strength along and parallel to the energized cable.
Measurements were the highest at unburied sections of the cable and near zero at all measurements ≥ 0.9 m away from the cable. Figure not to scale.

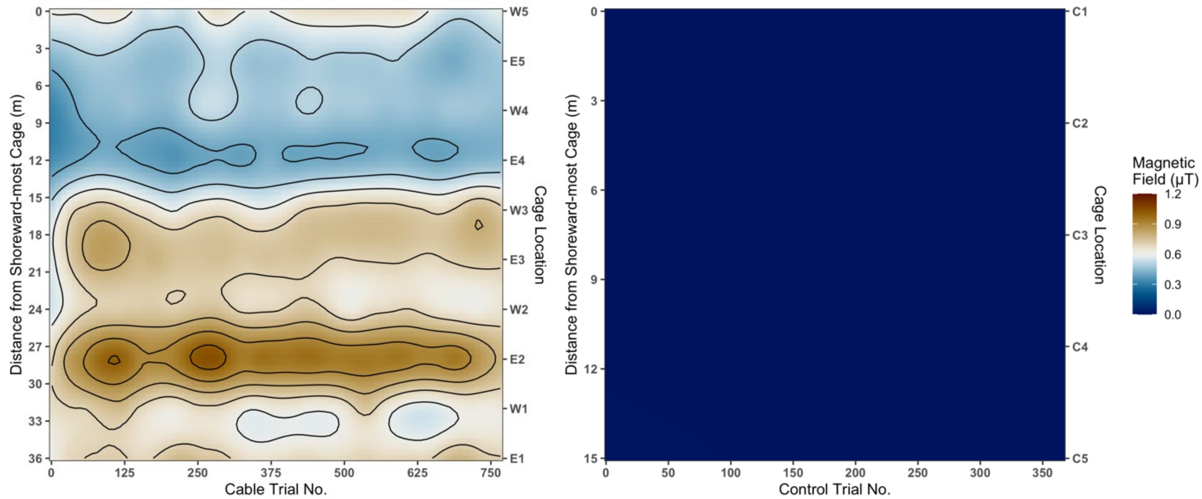

Figure 11. Magnetic field strength over time at the energized cable and in the control area.
Magnetic field strength was largely consistent over time (measured as Trial No., along the x-axis) and space (y-axis) along the energized cable (left), and there were no measurements over background levels in the control area at any time throughout the study (right).

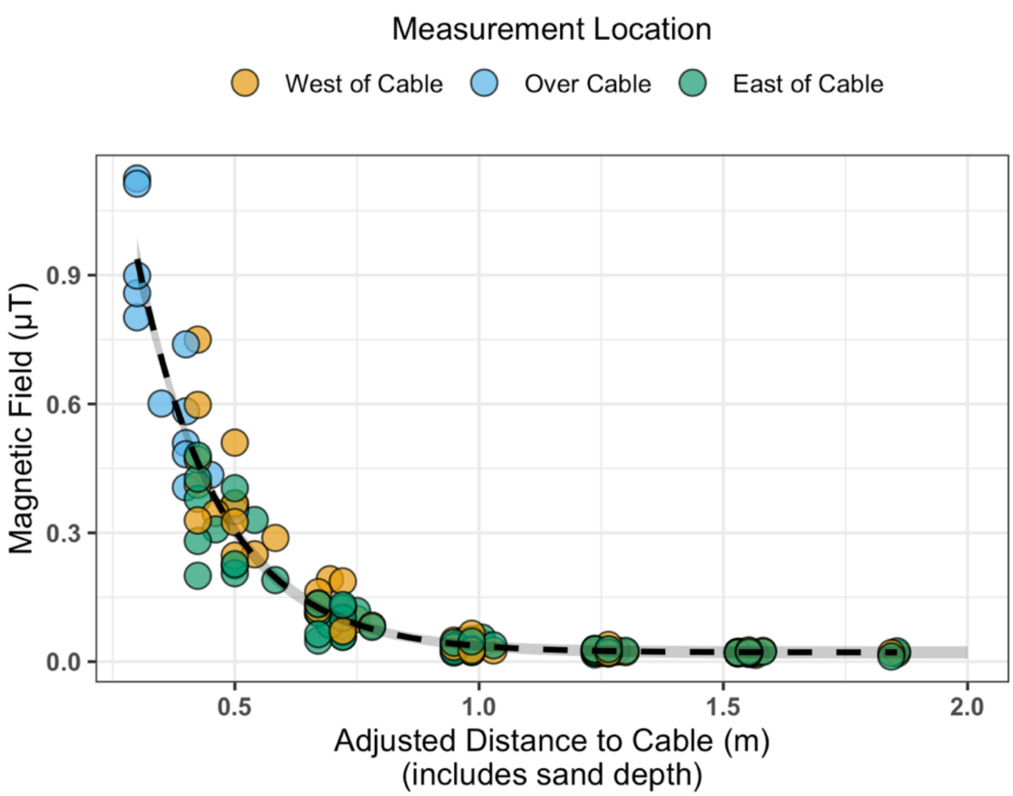

Figure 12. Relationship between magnetic field strength and distance to the cable.
Magnetic field strength decays rapidly to background levels by about 1 m distance away from the cable, including sand cover over the cable. The narrow gray ribbon indicates the 95% confidence intervals (1,000 permutations) of the selected asymptotic regression model (black dashes); pseudo-R^2 = 0.925.

3.2 Water Current Speed and Direction

The speed of water flow rarely exceeded 4 cm/s, averaging about ~1.5–2 cm/s, and was typically towards the east-southeast (~130˚) with less-frequent flow towards the west-northwest (~310˚; **Figure 13**). Directionality was not uniform ($M = 482$, $p < 0.001$).

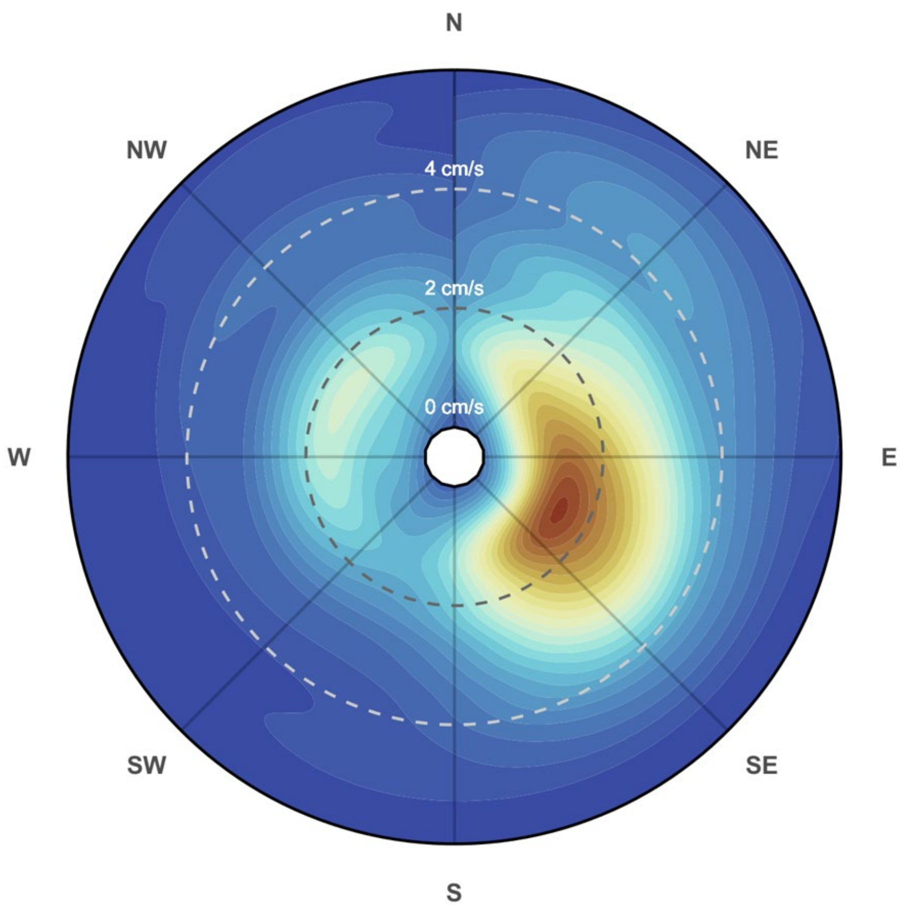

Figure 13. Cumulative frequency of water current speed and direction.
Warmer colors indicate more frequent speed/direction of water flow. The predominant current at the time of sampling was from the west-northwest to the east-southeast at about 1.5–2 cm/s.

3.3 Crab Hypothesis Testing

In most cases, crabs were trapped at either end of the cage within 15 minutes but were given at least 60 minutes before being replaced and counted as not having made a choice. Out of 750 crab trials performed on the energized cable, 30 remained in the tunnel or chute (‘Did Not Travel’), while 720 crabs entered either trap at the ends of the experimental cage. Of those 720 crabs, 49.2% (95% confidence interval: ± 3.7%) crossed the cable to enter a baited trap (**Figure 14**), and crabs showed no preference for crossing the energized cable or not ($\chi^2 = 0.168$, df = 1, $p = 0.682$).

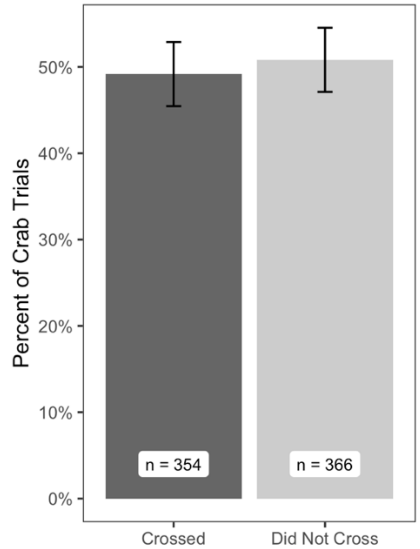

Figure 14. Cable crossing preference.
Crabs did not select a baited trap based upon the need to cross the energized cable. Error bars represent 95% confidence intervals.

An additional 459 crab trials were run in the control area, where no energized cables were present. Direction of travel differed significantly among the three treatments ($\chi^2 = 18.5$, df = 4, $p = 0.001$) (**Figure 15**). Across all three treatments combined, crabs traveled to the west a significant percentage of the time (68.0% ± 2.7%; $\chi^2 = 153.4$, df = 1, $p < 0.001$) regardless of whether trials were run in the cable area (63.9% ± 3.5%; $\chi^2 = 57.1$, df = 1, $p < 0.001$) or the control area (75.3% ± 4.1%; $\chi^2 = 109.8$, df = 1, $p < 0.001$), but crabs traveled west in significantly higher proportions in the control area ($\chi^2 = 17.0$, df = 2, $p < 0.001$). In the cable area, crabs traveled to the west a significant percentage of the time regardless of whether the chute was positioned east (62.5% ± 5.0%; $\chi^2 = 23.3$, df = 1, $p < 0.001$) or west (65.2% ± 5.0%; $\chi^2 = 33.8$, df = 1, $p < 0.001$) of the energized cable, and frequency of travel direction was not significantly different based upon where the chute was positioned ($\chi^2 = 1.37$, df = 2, $p = 0.504$).

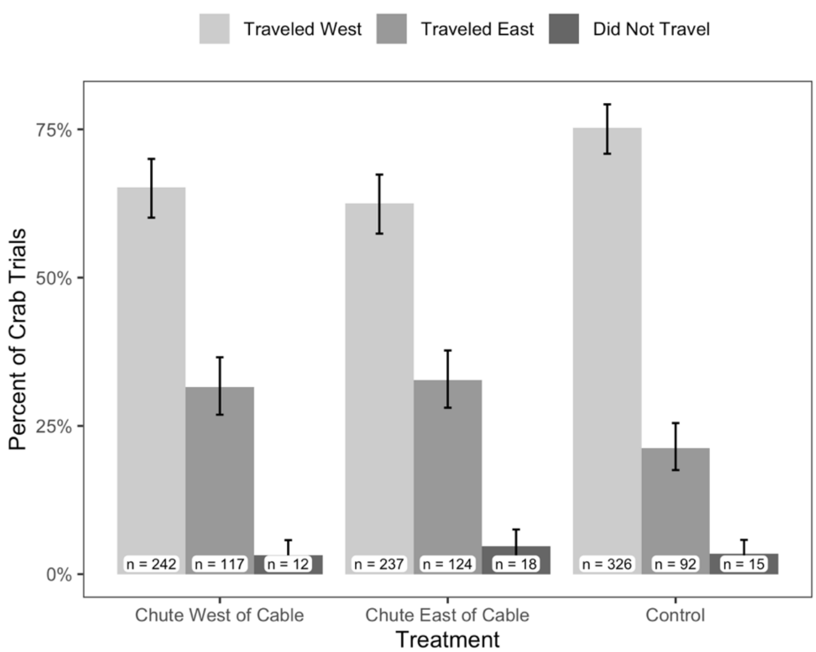

Figure 15. Direction of travel for all three treatments.
At both the cable and control areas, crabs traveled west at a significantly higher rate than either traveling east or staying in the chute or tunnel. Crabs at the control area traveled west more frequently than at the cable. There was no significant difference in travel direction between chute positions (east or west of the cable). Error bars represent 95% confidence intervals.

3.4 Generalized Linear Modeling

Using combinations of each potential explanatory variable (**Table 1**), we produced 256 models to explain crab cable crossing preference and 128 models for travel direction (e.g., response variables). No collinearity (maximum r = 0.19) or correlation (maximum VIF = 1.265) was detected among any variables in the confidence model sets.

The 95% confidence sets of models included 100 models for crab cable crossing, 41 models for travel direction at both the cable and control areas, and 83 models for travel direction at the cable only. Models not included in the 95% confidence sets mostly contain explanatory variables that are not influential to the response variables and therefore are not used in analyses. Consistent with the proportions test outcomes, only the experimental treatment variables were selected for the cable crossing (chute position relative to the cable; $\sum w_i = 1.0$; $p < 0.001$; **Table 2**) and travel direction (cable vs control; $\sum w_i = 1.0$; $p < 0.001$) response varables (**Table 3**). Magnetic field strength ($\sum w_i = 0.80$; $p = 0.176$) was the highest-ranking variable in terms of relative importance for travel direction in the cable area but was a poor predictor of travel direction, as were all other explanatory variables (**Table 4**). Water velocity vectors (and therefore water current speed/direction) were also non-significant predictors for cable crossing preference and travel direction.

Table 2. Relative importance and model selection table for cable crossing.

The position of the chute (east or west) relative to the energized cable was the only variable that was selected for and was the only variable that was in all 100 models in the 95% confidence model set. The intercept model describes the results when the values of all other variables are set to zero. * Indicates a significant variable in full-model averaging.

Explanatory Variables	$\sum w_i$	No. of Models	Estimate	LCI	UCI	z	p
Chute Position	1.00	100	1.406	1.079	1.733	8.424	< 0.001*
East/West Water Velocity	0.59	56	0.044	-0.056	0.144	0.870	0.384
Claw Damage	0.55	51	-0.182	-0.633	0.269	0.792	0.428
Magnetic Field Strength	0.44	48	-0.244	-1.036	0.548	0.604	0.546
Sex	0.36	42	-0.063	-0.324	0.199	0.472	0.637
Carapace Width	0.30	41	-0.001	-0.009	0.006	0.333	0.740
North/South Water Velocity	0.26	41	-0.005	-0.054	0.044	0.207	0.836
Missing Legs	0.24	40	0.004	-0.112	0.120	0.071	0.944
(Intercept)	-	-	-0.323	-1.552	0.905	0.516	0.606

Notes: LCI = lower 95% confidence interval; UCI = upper 95% confidence interval
$\sum w_i$ and No. of Models columns show relative importance; the other columns show full-model averaging parameters.

Table 3. Relative importance and model selection table for travel direction across treatments.

Treatment (cable vs control) was the only variable that was selected for and was the only variable that was in all 41 models in the 95% confidence model set. The intercept model describes the results when the values of all other variables are set to zero. * Indicates a significant variable in full-model averaging.

Explanatory Variables	$\sum w_i$	No. of Models	Estimate	LCI	UCI	z	*p*
Treatment (Cable vs Control)	1.00	41	0.555	0.266	0.843	3.769	< 0.001*
North/South Water Velocity	0.91	31	0.079	-0.005	0.164	1.833	0.067
Missing Legs	0.43	20	0.051	-0.118	0.220	0.588	0.556
Carapace Width	0.31	17	0.028	-0.007	0.005	0.311	0.756
Sex	0.30	17	0.028	-0.149	0.205	0.270	0.787
Claw Damage	0.28	17	-0.001	-0.175	0.230	0.337	0.736
East/West Water Velocity	0.25	17	0.000	-0.036	0.035	0.014	0.989
(Intercept)	-	-	0.798	-0.113	1.710	1.717	0.086

Notes: LCI = lower 95% confidence interval; UCI = upper 95% confidence interval
$\sum w_i$ and No. of Models columns show relative importance; the other columns show full-model averaging parameters.

Table 4. Relative importance and model selection table for travel direction in the cable area.

Magnetic field strength was the highest-ranking explanatory variable found in 55 of the 83 models in the 95% confidence model set but is a poor predictor of travel direction and was not a significant parameter using full-model averaging. The intercept model describes the results when the values of all other variables are set to zero. * Indicates a significant variable in full-model averaging.

Explanatory Variables	$\sum w_i$	No. of Models	Estimate	LCI	UCI	z	*p*
Magnetic Field Strength	0.80	55	0.789	-0.355	1.932	1.352	0.176
Sex	0.74	50	0.259	-0.166	0.685	1.194	0.232
North/South Water Velocity	0.70	45	0.064	-0.050	0.177	1.102	0.271
Carapace Width	0.27	34	-0.001	-0.008	0.007	0.144	0.886
East/West Water Velocity	0.26	32	-0.004	-0.053	0.045	0.158	0.874
Missing Legs	0.26	33	-0.009	-0.131	0.113	0.139	0.889
Claw Damage	0.25	32	0.013	-0.207	0.233	0.116	0.908
(Intercept)	-	-	0.182	-1.079	1.444	0.283	0.777

Notes: LCI = lower 95% confidence interval; UCI = upper 95% confidence interval
$\sum w_i$ and No. of Models columns show relative importance; the other columns show full-model averaging parameters.

4 Discussion

As with current MRE projects, future MRE development is likely to use cables similar to the one used in this study (Normandeau Associates Inc. et al. 2011). The presently operational Horns Rev and Nysted Offshore Wind Farms in Denmark use 33-kV 3-phase AC cables for inter-array transmission (Danish Energy Authority 2006). The long-planned NaiKun Wind Energy Project in British Columbia, Canada, proposes to use the same industry standard cables for inter-array power transmission, as well as power transmission to Haida Gwaii (Exponent Inc. and Hatch Ltd. 2009). Operating these cables at their maximum capacity would create magnetic fields on the seafloor no greater than ~1.5 µT (Gill 2005), a value that would be reduced to ~0.6 µT when buried 2 m below the seafloor (Danish Energy Authority 2006). We were not provided any information or data from ExxonMobil with respect to cable characteristics or operations, but since our maximum magnetic field measurements directly above an unburied section of the cable was ~1.1 µT, we can at least assume the cable was operational and likely running below full capacity throughout the study. The magnetic field readings of Love et al. (2017a) were upwards of 100 times higher than those presented here and one to two orders of magnitude beyond the modeled maximum for this cable.

We created two-dimensional maps of magnetic fields in the area along the energized cable showing variation in field strength strongly related to distance from the cable and burial under the seafloor, and demonstrated the that local magnetic anomalies produced by the submarine cable were fairly consistent over time. We believe this is the first time that magnetic fields produced by a submarine cable have been quantified and illustrated across the seafloor *in situ* and may indicate that (assuming consistent power transmission) measurements over a single time period may be sufficient for modeling the artificial magnetic field.

We were also able to model the magnetic field strength-distance to cable relationship as an asymptotic regression and determine the magnetic field decayed to background level just 0.9 m from the energized cable. Burial of submarine power cables to 1 to 2 m depth is often suggested as a way to reduce the magnitude that magnetic fields interact with the local environment, and our results suggest that this mitigation measure would be an effective strategy. Even directly over the energized cable, the magnetic field anomaly is at the lower end of what sensitive marine species can detect (Normandeau Associates Inc. et al. 2011).

Crabs did not show any preference or aversion to crossing the energized cable and showed a strong preference to travel to the west against the flow of the predominant measured current. Chute position was identified as the highest-ranking and only significant variable for whether a crab chose to cross the cable to enter a baited trap. This result is directly related to the overwhelming choice to travel west more often than traveling east (or staying in the chute or tunnel) regardless of all other variables and is essentially an artifact of sampling design.

Apart from measurements of magnetic field strength associated with the energized cable, our results were remarkably similar to that of Love et al. (2017a). Ideally, this is expected, but it is rarely observed *in situ* experimentation and is reassuring after a six-year gap between studies. Love et al. (2017a) hypothesized that the preferred western movement of crabs in this area may be due to environmental cues from the surrounding habitat, including olfactory (Grasso and Basil 2002), soniferous (Hughes et al. 2014), or acoustic cues (Kaplan and Mooney 2016) from nearby rocky reefs to the west and north of study area or the well-colonized oil pipeline to the west of the study area (Love et al. 2017b). It was also hypothesized that the crabs may simply be tracking the odor plume brought downstream from the bait bags in the western crab traps. Miller (1978)concluded that the orientation of the trap opening was important for catching red rock crabs. When the trap opening is perpendicular to the current, catch per unit effort increased significantly as crabs followed the olfactory cues delivered by the current. Indeed, the predominant current in the study area near the seafloor was generally from the west. Though specific direction and speed of water flow were not considered important or significant in GLM, the results generally support that hypothesis.

Treatment (cable versus control) was identified in the present study as the highest-ranking and only significant variable with respect to travel direction, though it did not appear to be related to the artificial magnetic fields produced by the energized cable. The general (non-significant) trend is of an increase in westward travel with an increase in magnetic field strength at the cable, though the preference for traveling west was even stronger in the control area (3:1) than along the cable—a paradoxical result if increased magnetic field strength had indeed caused increased westward travel. We are unable to identify any fundamental difference between the cable and control areas; both were on soft-bottom with patchy eelgrass (*Zostera* spp.) and were only a 10 m apart from each other. We do not have any specific hypotheses as to why there would be a stronger preference for travel to the west at the control versus the cable but note that the preference is overwhelmingly for travel to the west regardless of treatment.

This study suggests that the artificial magnetic field (the "electric fence") generated by 34.5 kV AC submarine power cables is unlikely to affect crab harvest rates because an energized cable did not prevent crabs from entering baited traps. Previous studies on commercially harvested crabs have noted both behavioral and physiological responses to exposure to magnetic fields above 250 µT (Scott et al. 2021; Scott et al. 2018); however, the magnetic fields induced by the energized cable at Las Flores Canyon do not approach that strength, and no behavioral responses were expected or identified. Crabs did not avoid crossing energized cables, and neither the cable nor the associated magnetic fields altered the direction crabs traveled. We mapped magnetic fields on the seafloor above and adjacent to the cable and in the control area over both time and space, and we quantified the strength and direction of water flow in the study area. While it was not a specific goal to pinpoint the environmental variable that causes crabs to have a strong preference for westward travel in the study area, we concur with Love et al. (2017a) that crabs are likely following environmental cues from nearby natural and artificial structures or odor plumes traveling in the predominantly eastward current along the seafloor.

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