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The effects of electrified submarine cables on movements of two commercially important crustacean species

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ABSTRACT

Submarine energy infrastructure is expanding rapidly as offshore energy extraction and transport intensifies. Power transmission through submarine cables creates anomalies in the Earth's geomagnetic field, potentially affecting marine species that use natural electromagnetic fields (EMF) to navigate and forage. Most research on EMF effects on marine animals use laboratory or mesocosm experiments that constrain subject animal movements. The artificial nature of these studies limits their extension to real-world environments, creating uncertainty in predicting impacts of important infrastructure projects. We use hyperbolic positioning acoustic telemetry to assess the impacts of the Maritime Link submarine transmission line on the movements of commercially important Snow Crab and American Lobster. Our results show that crossing rates were not affected by the presence and operation of the submarine cables, nor was the movement velocity different in the cables' proximity. In contrast, we found effects of temperature and diel period on movement speeds of both species. The methods used here could be useful to future research on EMF effects in other species and in areas with more extensive underwater infrastructure.

1. Introduction

Submarine energy infrastructure is rapidly expanding across the world's oceans and is expected to grow as the extraction and transportation of energy from marine environments intensifies (Normandeau Associates et al., 2011; Klimley et al., 2021; Bueger and Liebetrau, 2023; Smyth and Kregting, 2023). This infrastructure can have immediate and varied impacts on ocean habitats within its footprint. On the positive side, it may provide new substrates and associated reef effects, thereby benefiting marine life (e.g., Love et al., 2017a). However, it also has the potential to cause localized environmental changes, ecosystem disruption, or effects on fisheries, which may include reduced fishing access to these habitats or declines in target species.

When power transmission infrastructure, such as offshore wind turbines or high voltage direct current (HVDC) transmission submarine cables are integrated into marine development, it can have significant consequences for marine ecosystems. HVDC submarine cables generate electromagnetic fields (EMF), which if strong enough can cause local magnetic anomalies in the Earth's natural geomagnetic field. Many marine species rely on this field for critical behaviors such as navigation, locating conspecifics, and detecting prey (Hutchison et al., 2020a; Hermans et al., 2024). Species like salmon, turtles, and Spiny Lobsters use natural EMF to guide their oceanic migrations (Lohmann et al., 1995; Lohmann and Lohmann, 2006; Lohmann et al., 2007; Putman et al., 2013), while others, such as elasmobranchs, rely on the EMF fluctuations caused by prey to forage (Hermans et al., 2024).

Our understanding of how species respond to anthropogenic changes in EMF is limited, particularly in real-world conditions (Boehlert and Gill, 2010; Woodruff et al., 2013). This knowledge gap not only fuels resistance to infrastructure projects but also hinders the development of effective mitigation strategies for potential ecological impacts (Woodruff et al., 2012).

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In Atlantic Canada, Snow Crab (*Chionoecetes opilio*) and American Lobster (*Homarus americanus*) are amongst the most important commercial fishery species (Fisheries and Oceans Canada, 2022). While not known to exhibit migrations at the scale of other known EMF-sensitive species, they do undergo more regional seasonal migrations and dispersal (e.g. Pezzack and Duggan, 1986; Mullowney et al., 2018) that could be affected by EMF anomalies. Accordingly, when a major submarine HVDC transmission line was proposed to link southwestern Newfoundland to Cape Breton, Nova Scotia (Canada), effectively bisecting the Cabot Strait and the important American Lobster and Snow Crab fishing grounds within, concerns regarding the potential for the cables to impact movements of these species were expressed by harvesters and regulators alike (DFO, 2012).

EMF has the potential to impact benthic organisms by distorting navigational fields, obscuring the signatures of potential prey (Hutchison et al., 2020a), or attracting predators (e.g. Gill et al., 2009). While studies have looked at these effects for American Lobster under tank (Woodruff et al., 2013) and mesocosm (Hutchison et al., 2020b) conditions, detecting these effects under natural conditions is much more challenging and requires expectations of how change in movement might deviate in the presence of EMF anomalies. Reductions in successful passage rates over HVDC cables could indicate the potential for the cable emissions to act as a barrier. Other more subtle effects such as changes in movement velocity, turn angles, or movement behavior states may affect changes in feeding, refuge seeking or the ability to navigate. For example, increased tendencies toward elevated movement velocities in the vicinity of the submarine cables might indicate an avoidance of the cable area, even if it is not acting as a complete barrier. Alternatively, slower movement velocities might reflect disorientation in the vicinity of the submarine cables or an increase in feeding/searching behavior. While assessing the ability of tagged animals to cross a HVDC cable can be done with mark-recapture techniques (e.g. Love et al., 2017b), assessing smaller scale effects requires precision data on movement tracks that can only be acquired in deep water by telemetry positioning systems (Westerberg and Lagenfelt, 2008; Gill et al., 2009; Normandeau Associates et al., 2011; Klimley et al., 2021).

Here we use hyperbolic positioning acoustic telemetry to assess the impacts of two HVDC submarine cables on the movements of two commercially important species, Snow Crab and American Lobster. Specifically, we use data collected from tagged Snow Crab and American Lobster before and after the installation of the submarine cables to assess whether the EMF anomalies generated by HVDC submarine cable operation impede the frequency of movements across the cables or affect the movement velocity of animals as they approach them. We also assess if the electrical load has any effect on crossing success. Unlike previous fine scale movement behavior assessments of EMF, this research was done as a real-world manipulation, in open ocean habitats with industrial scale EMF exposures.

2. Methods

As part of the Maritime Link Project's environmental assessment (EA), an Environmental Effects Monitoring Program (EEMP) was developed to evaluate the potential impacts of the 500 MW submarine cables on the behavior of Snow Crab and American Lobster. To minimize artifacts and confounding factors, the study was designed to closely replicate real-world conditions. To this end, an acoustic telemetry approach was chosen, utilizing hydroacoustic receiver arrays with overlapping detection ranges. This setup ensures that tag transmissions are detected by multiple receiving hydrophones, enabling the triangulation of 2D positions within the arrays. The study included two consecutive years of monitoring (2014-2015) before the installation of the submarine cables (July–September of 2017) followed by one year of monitoring under steady state operation of the Maritime Link (2023), during which energy transfers fluctuate according to typical operational grid loads that are governed by commercial transactions.

2.1. Study area and the maritime link submarine cables

The final routing of the submarine cables was determined based on engineering solutions ensuring that cable technical properties were met during installation, as well as avoiding hazardous and sensitive areas, while minimizing overall cable length. The cables were protected by: 1) Horizontal Directionally Drilled (HDD) casing at transition locations from land-to-subsea in Cape Ray (Newfoundland) and Point Aconi (Nova Scotia), 2) rock berms at the submarine exit points of the HDD casings, 3) trenching in the seabed where possible, and 4) rock berms in locations where trenching alone could not achieve the required cable protection criteria.

The locations of the telemetry arrays were determined through consultations with local harvesters and regulators to ensure alignment with known Snow Crab and American Lobster habitats, which overlapped with the proposed submarine cables installation. Two distinct study areas were established, reflecting the differing habitat preferences of each species. The Snow Crab study area was located about 35 km from shore, at depths ranging from 102 to 110 m (Fig. 1), while the American Lobster study area was situated approximately 2 km offshore, at depths between 14 and 21 m (Fig. 1). Submarine cables within the study areas were embedded in the sediment using the trenching technique. To characterize and map habitat types within each study area, GIS-stamped video transects were conducted.

The American Lobster study area included a variety of habitats, such as sandy bottom, coarse substrate, and bedrock, with varying degrees of algal cover. For this study, the area was mapped based on the percentage of algal cover, as canopy presence is known to significantly influence American Lobster behavior (Jarrett et al., 2024; Konecny et al., 2024).

The Snow Crab study area consisted of uniform soft substrate with occasional rock or boulder emerging from the sediment. Unlike some other crab species, commercially targeted Snow Crab (terminal moult males) do not show a strong affinity for complex emergent benthic structures, instead settling in areas with little to no emergent structure (Ottmar et al., 2022). Snow Crab are highly stenothermic, favoring cold water (<2 °C) and fine, organically rich sediments such as mud or sandy mud, especially during early benthic stages. As such, the habitat of the of the Snow Crab study area was placed in uniform muddy bottom.

2.2. Array deployments

2.2.1. Snow Crab

The Snow Crab study area was situated within a section of the submarine cable corridor identified by local harvesters as supporting high densities of adult male Snow Crab (Fig. 1). Acoustic receiver moorings were deployed using a standard Ocean Tracking Network (OTN) configuration, incorporating a mix of 69 kHz VEMCO VR2w ($n = 9$) and VR2AR ($n = 7$) receivers (InnovaSea, Bedford, NS, Canada). Floatation was provided by a single syntactic foam float (40.6 cm diameter, 17.2 kg buoyancy, DeepWater Buoyancy, Biddeford, ME, USA), with all receivers positioned approximately 3 m above the seabed. For moorings using VR2AR receivers, which feature integrated acoustic release and sync tag, the flotation was tethered 1 m above the receiver. In contrast, VR2w receivers were positioned at the terminal end of the assembly, oriented vertically within a mounting cup to help ensure unobstructed signal reception. Acoustic releases (875-TD, Teledyne Benthos, North Falmouth, MA, USA) were employed on VR2w receivers, mounted on rope risers extending 1 m above the 80 kg steel mooring weight. Fixed-delay, time-synchronizing transmitters (sync tags) were integrated within VR2AR receivers and were externally mounted on VR2w receiver moorings using V16-5H transmitters. These were programmed to transmit at high power (160 dB) at 600-second intervals, allowing for precise calculations of receiver positions on the seabed. A V13-1H reference (sentinel) transmitter was attached to the rope riser of a central mooring assembly, 0.5 m above the bottom, to simulate a tagged animal and assess detection efficiency throughout the study. The

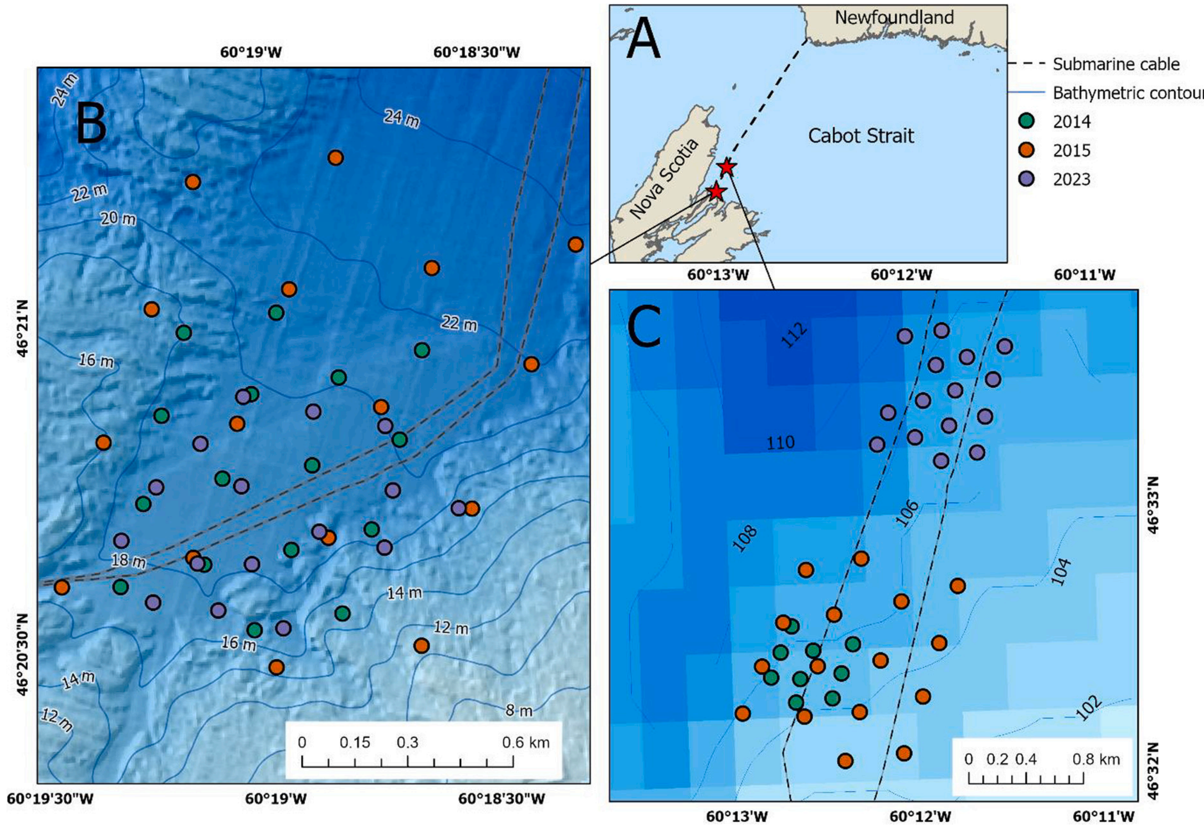

Fig. 1. Acoustic telemetry receiver array locations (red stars) along the Maritime Link submarine transmission line (A) used to assess the effects of electrified submarine cables on American Lobster (B) and Snow Crab (C) movement. Deployment-specific acoustic telemetry receiver locations are depicted by circles in panels B and C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

telemetry array of the initial deployment (2014; Table 1) consisted of a nine receiver VPS array using moorings spaced 250 m apart, covering approximately 0.25 km^2. The array configuration was informed by prior in-situ range tests to optimize receiver spacing. After the first season of data collection (Oct 23, 2014–Jan 22, 2015), the manufacturer reported that detection ranges exceeded those observed during range-testing trials. As a result, it was recommended that mooring spacing could be increased to 400 m without significantly affecting data quality. Based on this guidance, the array was redeployed using 16 receivers at 400 m spacing following the close of the commercial fishing season on September 13, 2015 (Fig. 1). In 2023, 16 receivers were spaced 250 m apart, and the location of the array was adjusted to best provide coverage of the installed submarine cables. Receiver locations spanned depths from 102 to 110 m. In all cases, the arrays were deployed before the release of tagged animals.

2.2.2. American Lobster

For the American Lobster study component, the array consisted of 16 independent acoustic receiver moorings (Fig. 1; Table 1), deployed from autumn through spring, thus avoiding the local commercial fishery season. Acoustic receiver moorings used the same technology as the Snow Crab array moorings. The array was initially deployed on October 21, 2014, prior to the release of tagged animals, and remained in place until January 15, 2015. It was then retrieved to prevent potential loss during peak winter ice conditions. The array was redeployed on February 23, 2015, and remained in the water until May 14, 2015, when it was removed to avoid risk of entanglement during the commercial American Lobster fishery. During the first deployment, receiver moorings were spaced approximately 250 m apart, covering an area of 0.65 km^2, with deployment depths ranging from 14 to 21 m (Fig. 1). As with Snow Crab, the array was redeployed following the manufacturer's recommendation using 400 m spacing after the close of the commercial fishing season on September 13, 2015 (Fig. 1, Table 1). In 2023, receivers were placed 250 m apart and the placement of the array was adjusted to provide balanced coverage of the installed submarine cables (Fig. 1).

Table 1
Deployment summary of acoustic telemetry arrays used to assess movement behavior of Snow Crab and American Lobster before and after the installation and operation of the Maritime Link submarine transmission cables.

Species	Deployment	Number of receivers	Array configuration	Deployment depth	Deployment date	Recovery date
Snow Crab	2014/2015	9	~500 m × 500 m Array; 250 m Receiver Spacing	102–108 m	Oct 23, 2014	Jan 22, 2015
	2015/2016	16	~1200 m × 1200 m Array; 400 m Receiver Spacing	102–108 m	Sep 13, 2015	May 14, 2016
	2023/2024	16	~750 m × 750 m Array; 250 m Receiver Spacing	106–110 m	Oct 14, 2023	May 5, 2024
American Lobster	2014/2015	16	~750 m × 750 m Array; 250 m Receiver Spacing	14–21 m	Oct 21, 2014	Jan 15, 2015
					Feb 23, 2915	May 14, 2015
	2015/2016	16	~1200 m × 1200 m Array; 400 m Receiver Spacing	14–21 m	Sep 13, 2015	May 16, 2016
	2023/2024	16	~750 m × 750 m Array; 250 m Receiver Spacing	12–20 m	Oct 5, 2023	May 6, 2024

2.3. Animal capture and tagging

2.3.1. Snow Crab

Methods for capture, holding, and acoustic tagging of Snow Crab are described in Cote et al. (2019), which followed methods of Zisserson and Cameron (2016). Chartered commercial fishers used baited, 1.8 m diameter, top entrance traps to capture terminally moulted male Snow Crab. Female and juvenile male Snow Crab were collected using baited, rectangular, top entrance shrimp traps, which were modified for collection of small Snow Crab. Soak time of traps ranged between 12 and 36 h. Upon capture, Snow Crab were removed manually from the trap and inspected for physical damage or signs of decreased health or viability. Animals to be tagged were held temporarily in a 750 L insulated fish box. In 2014–2016 thermal conditions of deep water Snow Crab habitat were reproduced on deck by filling the fish box with approximately 300 L of ice which was then covered with a non-permeable membrane. Surface sea water was used to fill the remaining portion of the tank and was aerated and chilled to 1.5 °C. The holding box was covered to reduce light exposure and to maintain water temperatures. Whereas, in 2023, captured Snow Crab were placed in a 70 L fish tote (63 cm × 40 cm × 26 cm) and layered with salt water ice to maintain temperature of animals prior to tagging.

Two hundred and forty-four Snow Crab were tagged with either Vemco (Halifax, NS) V13 (diameter: 13 mm; length: 36 mm, weight in water: 6.0 g, 69 kHz, estimated tag life: 653 d, transmission frequency: 60–180 s), or V9 acoustic transmitters (69 kHz, diameter: 9 mm; length: 29 mm, weight in water: 2.9 g, estimated tag life: 347 d, transmission frequency: 60–180 s; Table 2). Snow Crab were individually selected for tagging and placed upright on a flat surface. To improve tag adhesion, the area of attachment on the dorsal surface of the carapace was dried with a paper towel, then lightly abraded using a rotary power tool with a flap-wheel sanding disc. A vinyl tubing, spaghetti-style tag (Floy Tag, Seattle, Wash., USA) was attached through a cap built into the transmitter and positioned around the animal's carapace between the second and third walking legs. A small volume of 3M® 5200 fast-cure marine adhesive was then placed on the carapace area prepared with the rotary power tool and the cap pressed into the adhesive. Once the acoustic tag was mounted in the adhesive, the spaghetti tag was tightened, and the aluminum sleeve was crimped to secure it in place and excess tubing trimmed. Thin wire pipe cleaners were then used to secure the posterior portion of the acoustic tag to further ensure tag position and adhesive contact throughout curing. These pipe cleaners were used as they corrode quickly and would fall off the animals soon after the adhesive cured. This curing process takes ~24 h but can occur while submerged in sea water.

Wherever possible, animals were released near their capture location to minimize the potential for alteration of natural behavior patterns. As no females or juvenile males were found within the habitats of the receiver array, they were captured and relocated within our monitored area from slope habitats (70–100 m depth) ~5 km to the southwest of the high resolution positioning system array.

Animals were released within 6 h of tagging in four equal sized groups at separate locations within the arrays (two release locations on each side of the proposed subsea cable area). Locations were selected to maximize the likelihood of animals interacting with the proposed subsea cable area and to avoid signal collisions which are typically associated with having too many tagged animals in one location. Each tagging group was released to the bottom at the prescribed location by ferrying them to the substrate in a custom-designed release cage that was opened by an acoustic release triggered from the surface. This release method minimized pelagic drift away from the study area and protected them from potential predation during transit through the water column.

Table 2
Summary of Snow Crab and American Lobster tagged to study movement behavior before and after the installation and operation of the Maritime Link submarine transmission cables.

Species	Total tagged	Male	Female	Date released	Submarine cables status
Snow Crab	48	48	0	Oct 31, 2014	Pre-installation (Before)
	116	101	15	Oct 5 & 7, 2015	Pre-installation (Before)
	80	80	0	Oct 14, 2023	Operating (After)
American Lobster	40	32	8	Oct 26, 2014	Pre-installation (Before)
	40	21	19	Oct 6, 2015	Pre-installation (Before)
	40	22	18	Oct 12, 2023	Operating (After)

2.3.2. American Lobster

Methods for capture, holding, and acoustic tagging of American Lobster were previously described in Konecny et al. (2024). Local commercial harvesters were chartered to set baited traps overnight within the study area to catch American Lobsters. Upon capture, American Lobsters were removed from the traps and inspected for physical damage or signs of decreased health and vitality and were banded and crated prior to being transferred to another chartered vessel for tagging. American Lobster catches comprised primarily males in both 2014 and 2015; however, enough females were captured in 2015 so that the tags were almost spread evenly across both sexes (Table 2). One hundred and twenty American Lobsters were tagged with VEMCO V13-1H (diameter: 13 mm; length: 36 mm, mass in water: 6.0 g, 69 kHz, estimated tag life: 653 d, transmission frequency: 60–180 s; Innovasea). Transmitter attachment methods were modified from those outlined by Bowlby et al. (2007), Morrison (2014), and Zisserson and Cameron (2016). Individual American Lobsters were measured (carapace length) and sexed. The area of transmitter attachment on the dorsal surface of the carapace was lightly abraded using a rotary tool with a flap-wheel sanding disc to improve tag adhesion. A vinyl tubing, spaghetti-style tag (Floy Tag) was attached through a cap built into the transmitter and positioned around the carapace between the first and second walking legs. A small volume of 3M® 5200 fast-cure marine adhesive was then placed on the carapace area prepared with the rotary tool and the cap pressed into the adhesive. Once the acoustic tag was mounted in the adhesive, the spaghetti tag was tightened, the aluminum sleeve was crimped to secure it in place, and excess tubing was trimmed. Thin wire pipe cleaners were used to secure the posterior portion of the acoustic tag to further ensure tag position and adhesive contact throughout curing. Like Snow Crab, tagged American Lobsters were released in 4 equal-sized groups within each quadrant of the array (Fig. 1). These locations were selected to safeguard against any bias due to directional currents, and to avoid signal collisions associated with having too many animals in one location.

2.4. Data pre-processing

Data preparation was conducted in a similar manner for both species with noted exceptions to account for species-specific behavior or array-specific positioning characteristics.

2.4.1. Before data

Individuals exhibiting no movement and remaining in the array for the duration of the array deployment were assumed to be dead or have shed their tag (Klinard and Matley, 2020). All such individuals were excluded from further analysis. Data were filtered to remove detections where HPE (Horizontal Positioning Error) was greater than the 75th percentile of values within each array. This percentile was selected as an appropriate threshold that balanced outlier removal (based on visual inspection) and data retention. As our goal was to understand fine-scale behavior, we avoided interpolating across long data gaps by splitting tracks whenever the time between subsequent detections exceeded 1.5 h. An exception was made for American Lobster when the detections bookending a data gap were in close proximity (<50 m). We considered such events to represent an animal sheltering in place rather than leaving the array (Konecny et al., 2024). A conservative speed filter was then applied to the tracks to remove any detections where the speed was greater than 10 m/min for Snow Crab and 5 m/min for American Lobster. The detections associated with such high speeds typically represent aberrant position estimates in the tracks which can bias downstream analysis. The speed filter was applied iteratively until the speed between all remaining detections within track segments did not exceed the defined threshold. An additional filter, using distance between successive points, was needed to clean Snow Crab data. It was applied in a similar manner to the speed filter, iteratively removing detections where the distance travelled exceeded 34.9 m (based on the 95th percentile of distance between detections in the 2023–2024 dataset) between successive locations. Track segments with ten or more detections were retained and these were run through a one-behavior first-difference correlated random walk state-space model. This procedure models the underlying movement process while accounting for the measurement errors (derived from sync tags), estimating the most likely position of an animal given the available information. This approach was also used in baseline assessments of telemetry data in our study area (Cote et al., 2019; Konecny et al., 2024). Examples of tracks resulting from the filtering process are provided in Figs. S1 and S2 for Snow Crab and American Lobster, respectively.

2.4.2. After data

After data was collected under real-world operating conditions of the Maritime Link transmission cables, which included hourly current loads that fluctuated between 1 and 234 kW (mean = 123 kW). These data were processed following the same methods as above, however instead of filtering based on HPE, points with an RMSE (root mean-squared error) > 1.3 were excluded from analysis. The RMSE measures detection time error (Shipley et al., 2024) and was not available from the manufacturer when Before datasets were collected. A threshold of 1.3 was selected based on the inflection point of RMSE vs speed. Visually, RMSE increases with speed after an RMSE value of approximately 1.3. Data were filtered based on this field as it appeared to be highly effective in removing outliers in the movement tracks. While this introduced differences in Before versus After processing, we prioritized having the best representation of movement tracks.

2.5. Analysis

2.5.1. EMF zone of influence

Alterations to the natural EMF, from Maritime Link submarine cable operations, vary according to cable installation methods (e.g. buried, shielding material), water depth, electrical current, and distance from cables. Of these, the electrical current running through, and the distance study animals were found from the submarine cables varied over time. In general, EMF intensity is proportional to the electrical current passing through the cables and is inversely proportional to the distance from the cables. For the purpose of the following analyses, we defined the cables' Zone of Influence (ZOI) as a 5 m buffer around each cable and putative cable location. This distance represented the point at which the cables' magnetic fields at full power were modeled to be of comparable strength to the Earth's natural magnetic field (50 μT; DFO, 2013; Fig. S3).

2.5.2. Crossing success

We evaluated whether the operating submarine cables acted as a barrier to our study species by enumerating submarine cable crossings by each individual in the 2023–2024 study period.

To evaluate if crossing success was affected by the operating cables, we identified tracks in both datasets where individuals entered and exited the ZOI (Figs. S5 and S6). Successful crossings were classified as segments of the tracks where a tagged animal started outside the ZOI, moved inside the ZOI, and crossed the cable before moving back outside the ZOI. Unsuccessful crossings were classified as segments where an individual moved inside the ZOI and back outside without crossing a cable. We fit a binomial generalized linear model (GLM) with a logit link to the number of successful and unsuccessful crossings by individual to determine whether there was an effect of the operating cables on the rate of successful cable crossings.

2.5.3. Cable electrical energy and crossing success

To determine whether crossing success varied with the electrical load of the operating cables, a weighted average of hourly current data (irrespective of current direction) was calculated for track segments intersecting the ZOI. A binomial generalized linear mixed model (GLMM, logit link) was fit to the After dataset to determine the effect of average current load on crossing success with a random effect of individual to account for multiple observations within individuals. The predictor variable (current) was scaled prior to analysis to improve model convergence.

2.5.4. Movement rates within and outside zone of influence

We compared movement rates within and beyond the ZOI as well as Before and After the cables were operating using the same track segments previously identified as interacting with the ZOI. For each track segment, detections from within the ZOI (that entered and exited the ZOI) were retained as well as detections outside of the ZOI recorded within 1 h prior to the Snow Crab entering the ZOI (see Figs. S4 and S5 for plot of included segments for Snow Crab and American Lobster, respectively). For American Lobster, we then further filtered the data to include only track segments where American Lobster were in known areas of open habitat (i.e. algal cover of 0%; see Fig. S5 for plot of included segments). This filter was applied as habitat has been shown to influence the behavior of American Lobster (Karnofsky et al., 1989a; Konecny et al., 2024) and the submarine cables only occupy areas of open habitat. Not all ZOI interactions had one full hour of detections outside the ZOI prior to entering the ZOI. Some track segments also had multiple interactions with the ZOI.

For each track segment, a time weighted average was calculated for movement rate (m/min), bottom temperature (°C) and time since release within and outside the ZOI. Diel period was taken as the mode across detections within and outside the ZOI. Time since release (TSR) was then transformed into a categorical variable (acclimation status) to identify segments where Snow Crab were in an acclimation period (average TSR $\leq$ 24 h) or post-acclimation period (TSR > 24 h) based on results from Cote et al. (2019) and Konecny et al. (2024), which showed elevated movement speeds for up to 24 h post release. A GLMM with a gamma distribution (log link) was fit to the movement rate across track segments. Only data from male Snow Crab were included in this analysis as there were no females present in the After dataset. Covariates of carapace length (cm), diel period, average temperature, and acclimation status were included in the model, as well as an interaction between time period (before cables were installed/while cables were operating) and ZOI (inside/outside). A random effect for individual was included to account for multiple track segments within individuals.

3. Results

3.1. Snow Crab

Of the 149 and 80 terminal moult male Snow Crab that were tagged in the Before and After study periods, data from 40 (26.8%) and 34 (42.5%) individuals were retained following the filtering process, respectively (Fig. S5).

In the two study years prior to the cables being installed, 15 of 40 Snow Crab entered and exited the ZOI. Across these individuals, there were 42 successful cable crossings out of 60 interactions (Fig. 2). When

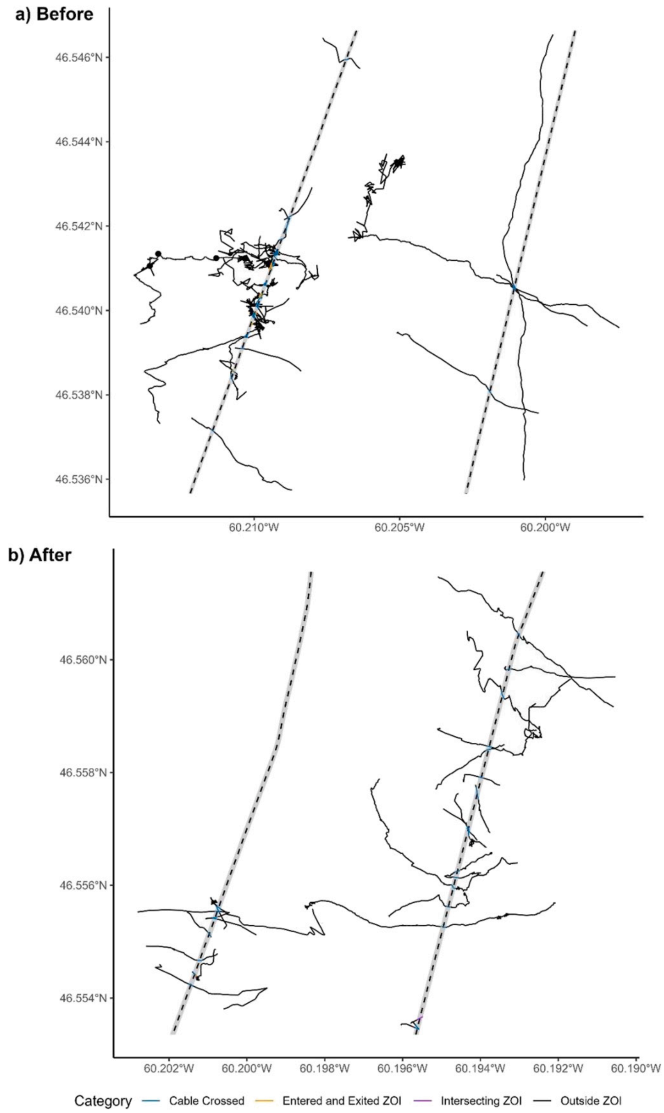

Fig. 2. Movement track segments of acoustically tagged Snow Crab that entered and exited the ZOI in the study periods before the cables were installed (a) and while the cables were operating (b).

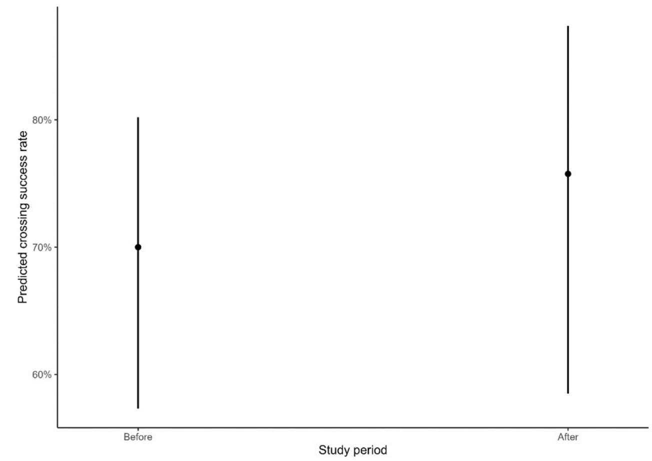

Fig. 3. Predicted cable crossing success rate of Snow Crab before the submarine cables were installed (before) and while the submarine cables were operating (after). Points represent generalized linear model (GLM) estimates and error bars represents 95% confidence intervals.

Table 3
Generalized linear mixed model (GLMM) model outputs evaluating the effect of carapace width, diel period, water temperature, acclimation status, Zone of Influence (ZOI) and the electrification of the submarine cables (Study Period) on Snow Crab movement rates. Statistically significant *p*-values are indicated in bold. The non-significant p-value for the interaction of ZOI and study period indicates the absence of a detectable effect of the electrified submarine cable.

Predictors	Movement rate (m/min)		
	Estimates	CI	*p*
Intercept	0.10	0.01–1.23	0.072
Width	1.03	0.84–1.25	0.795
Diel Period [night]	2.08	1.42–3.04	**<0.001**
Temperature	1.67	1.27–2.20	**<0.001**
Acclimation status [post-acclimation]	1.28	0.73–2.26	0.394
ZOI [Not intersecting]	0.92	0.69–1.23	0.582
Study period [After]	0.37	0.19–0.74	**0.005**
ZOI [Not intersecting] × Study period [After]	0.92	0.61–1.39	0.704
Random effects			
σ^2	0.19		
$\tau_{00\ Transmitter}$	0.60		
ICC	0.76		
$N_{Transmitter}$	27		
Observations	79		
Marginal R^2/Conditional R^2	0.258/0.824		

the cables were operating, 12 of 34 Snow Crab entered and exited the ZOI. Across the 12 individuals that entered and exited the ZOI while the cables were operating, there were 25 successful cable crossings out of 33 interactions (Fig. 2). GLM analysis showed no significant effect of cable operational status on the success rate of animals crossing the cable (p = 0.555; Fig. 3; Table S2).

3.1.1. Cable current load and crossing behavior

Within the After study period, when the cables were operating under load, GLMM analysis showed that there was no significant effect of current intensity (p = 0.275; Fig. S7; Table S3) on the success rate of Snow Crab crossing the cable.

3.1.2. Movement rates within and outside zone of influence

We found no effect of carapace width (GLMM, p = 0.795) on movement rate, but diel period (GLMM, $p \leq 0.001$) and temperature (GLMM, $p \leq 0.001$) significantly affected movement rates in Snow Crab with individuals moving faster at night and at higher temperatures (Table 3; Fig. 4). There was a non-significant trend of increased movement rates during the post-acclimation period (GLMM, p = 0.394; Fig. 4d). There were also significant effects of study period (GLMM, p = 0.005) on movement rates with Snow Crab moving faster in the period before the cables were installed both inside and outside the ZOI (p = 0.582; Table 3; Fig. 4e). The interaction however, between study period and the Snow Crab's location (inside or outside the ZOI) did not significantly affect movement rates suggesting that the operating cables did not impact Snow Crab movement rates (p = 0.704; Table 3; Fig. 4e).

3.2. American Lobster

Of the 80 and 40 adult American Lobster that were tagged in the Before and After study periods, data from 58 (72.5%) and 32 (80%) individuals were retained following the filtering process, respectively (Fig. 5a; Fig. S8).

In the two study years prior to the cables being installed, there were 27 of 58 (46.5%) individuals that entered and exited the ZOI. Across these 27 individuals, there were 102 successful cable crossings out of 112 interactions (Fig. 5a). For the 18 of 32 (56%) of American Lobster entered and exited the ZOI while the cables were operating, there were

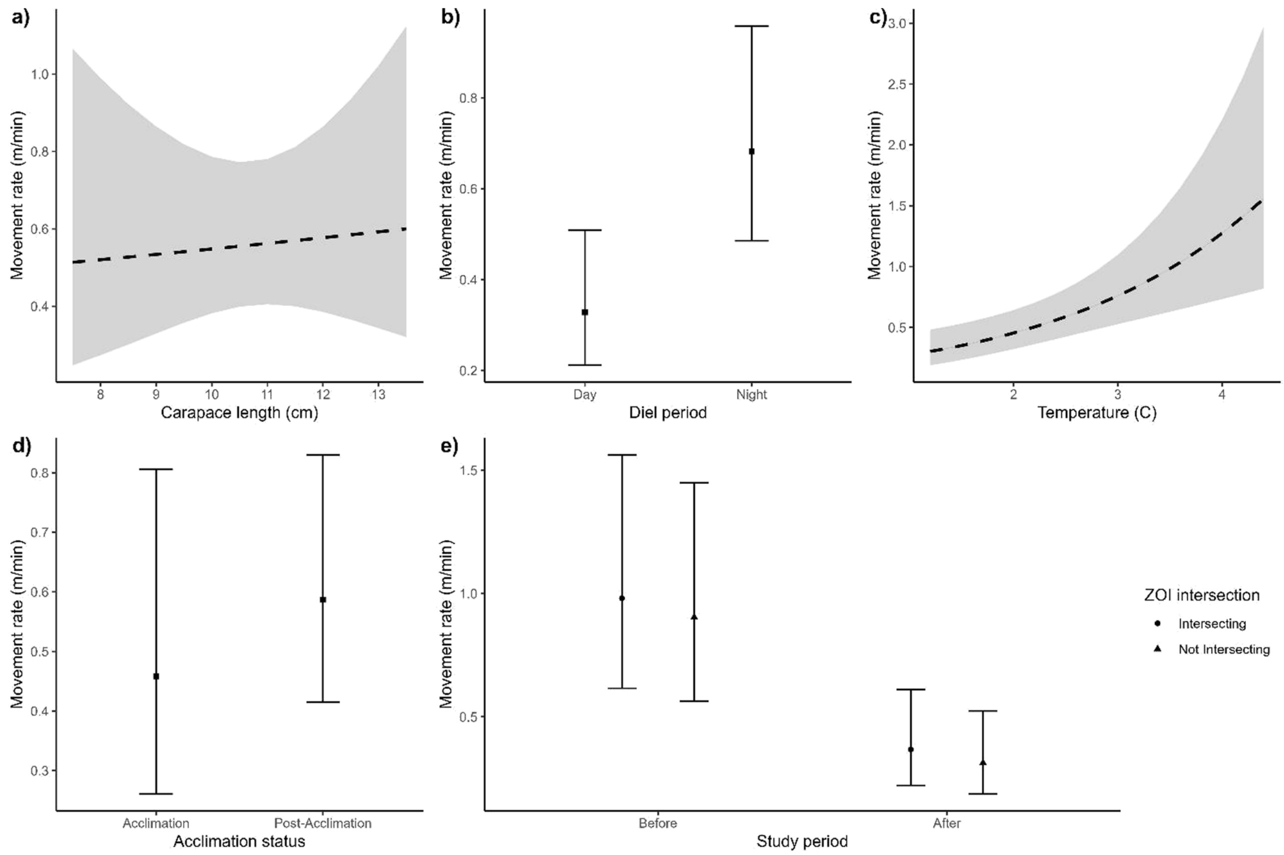

Fig. 4. Marginal effects plots from the fitted generalized linear mixed model (GLMM) that show the effect of carapace length (a), diel period (b), temperature (c), acclimation status (d), and the interaction between study period and location (e) on Snow Crab movement rates (m/min). Marginal means are shown (dashed lines and points) as well as 95% confidence intervals for the predicted values (shading and error bars).

60 successful cable crossings out of 64 interactions (Fig. 5b). GLM analysis showed no significant effect of the cables' operational status on the success rate of animals crossing the cables (p = 0.530; Table S4; Fig. 6).

3.2.1. Cable current load and crossing behavior

In the study period while the cables were operating under load, GLMM analysis showed that there was no significant effect of current intensity (p = 0.347; Table S5) on the success rate of American Lobster crossing the cables (Fig. S9).

3.2.2. Movement rates within and outside zone of influence

We detected significant effects of diel period (p = 0.002; Table 4) and temperature ($p < 0.001$; Table 4) on movement rates in American Lobster with individuals moving faster during the day and at higher temperatures (Fig. 7b, c). In contrast, sex (p = 0.271; Table 4) and carapace length (GLM p = 0.680; Table 4) were not significant (Fig. 7a, d). During the post-acclimation period, American Lobster moved significantly faster (p = 0.004; Table 4; Fig. 7e). There was no effect of study period (p = 0.237; Table 4) on movement rates or location (inside vs outside the ZOI; p = 0.886; Table 4; Fig. 7f). There was also a non-significant interaction between study period and location (inside or outside the ZOI) suggesting that the operating cables did not impact American Lobster movement rates (p = 0.757; Table 4).

4. Discussion

We were unable to detect effects of operational submarine electrical cables on either Snow Crab or American Lobster behavior, as barriers to movement, or as drivers of more subtle behavioral responses such as movement velocity or directionality. This is in contrast to other measured environmental or methodological variables which influenced various aspects of movement behavior.

The absence of an EMF-related response is not surprising given the limited EMF field anomaly generated by the cables under load and the low sensitivity and high variability observed in lab and mesocosm studies conducted on one of our species, American Lobster. Laboratory exposures of EMF on American Lobster showed no effects on activity, willingness to cross high EMF zones or to use high EMF habitats (Woodruff et al., 2013). In a mesocosm experiment, Hutchison et al. (2020b) showed American Lobster had an increased likelihood of conducting large turns (interpreted as exploratory behavior) and were marginally closer to the seabed in the EMF exposed enclosure compared to a control enclosure, but no differences were observed within the treatment enclosure between high and low EMF zones. Speed and distance travelled were not observed to differ in response to EMF in these experiments. These results were in contrast to more pronounced differences observed in the electrosensitive Little Skate, *Leucoraja erinacea*. To our knowledge, there are no available data on EMF effects for Snow Crab but other studies on Brachyurid crabs showed no influence of electrified cables when responding to baited traps (Love et al., 2017a). Many known EMF sensitive species (e.g. Spiny Lobster, Pacific Salmon, marine turtles) undertake much longer oceanic-scale migrations and benefit from homing over the course of their lifecycles (Lohmann et al., 2007; Putman et al., 2013). As such, navigation adaptations are likely critical to the survival of those species. Snow Crab and American American Lobster do migrate and disperse over moderate distances (Pezzack and Duggan, 1986; Taylor, 1992; Moriyasu et al., 2001; Bowlby et al., 2007; Cook et al., 2015; Mullowney et al., 2018; Hanley et al., 2024), but typically in the 10s of kms to low 100s of kms for

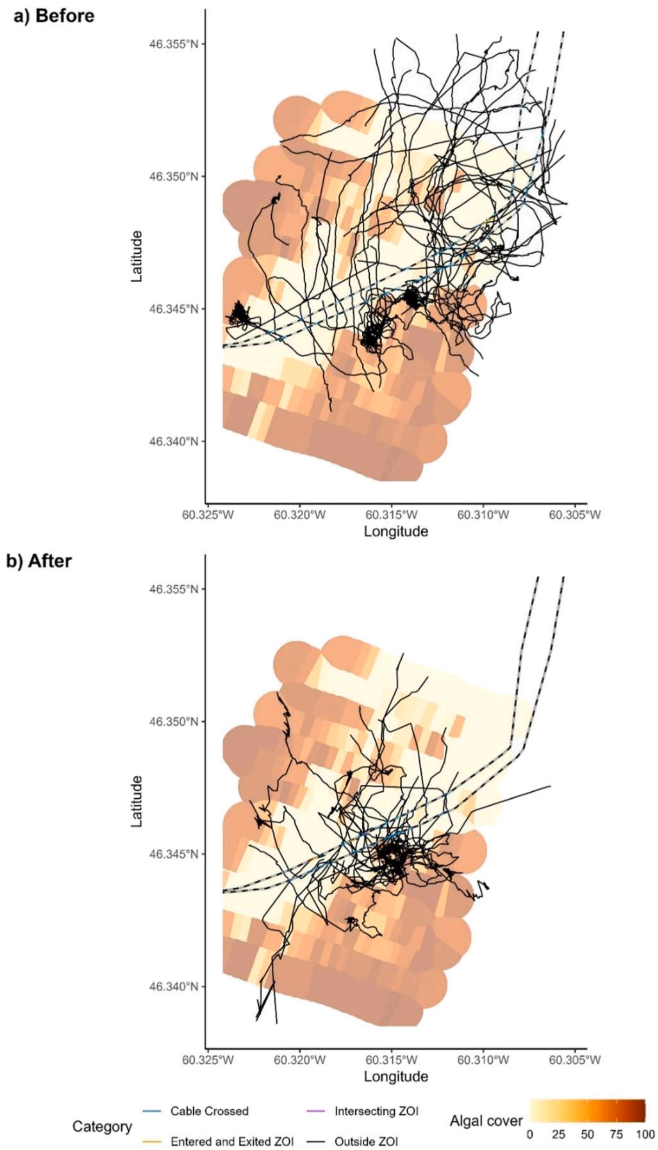

Fig. 5. Movement track segments of acoustically tagged American Lobster that entered and exited the ZOI in the study periods before the cables were installed (a) and while the cables were operating (b). Algal cover (percent cover) is shown for reference.

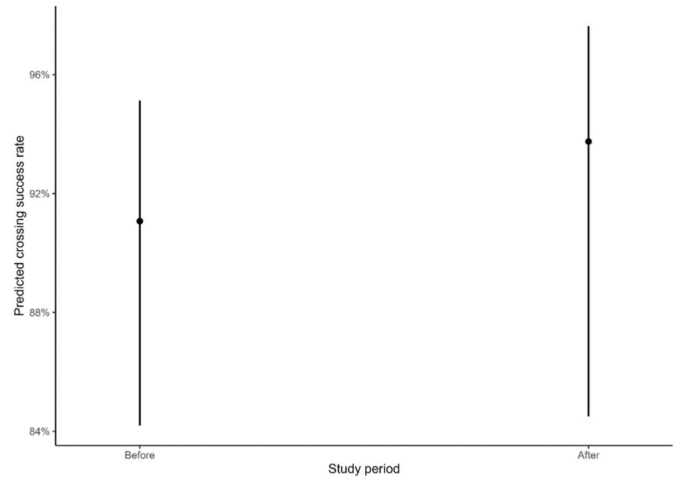

Fig. 6. Predicted cable crossing success rate of American Lobster before the submarine cables were installed (before) and while the submarine cables were operating under load (after). Points represent generalized linear model (GLM) estimates and error bars represents 95% confidence intervals.

Table 4
Generalized linear mixed model (GLMM) outputs evaluating the effect of carapace length, diel period, water temperature, sex, acclimation status, Zone of Influence (ZOI) and the electrification of the submarine cables (Study Period) on American Lobster movement rates. Statistically significant *p*-values are indicated in bold. The insignificant p-value for the interaction of ZOI and study period indicates the absence of a detectable effect of the submarine cables' operational status.

Predictors	Movement rate (m/min)		
	Estimates	CI	*p*
Intercept	0.84	0.18–4.02	0.829
Length	1.04	0.88–1.22	0.680
Diel Period [night]	0.70	0.56–0.87	**0.002**
Temperature	1.06	1.03–1.09	**<0.001**
Sex [Male]	1.20	0.87–1.66	0.271
Acclimation status [post-acclimation]	1.37	1.10–1.69	**0.004**
ZOI [Not intersecting]	1.01	0.88–1.16	0.886
Study period [After]	1.21	0.88–1.68	0.237
ZOI [Not intersecting] × Study period [After]	0.97	0.78–1.20	0.757
Random Effects			
σ^2	0.07		
$\tau_{00\ \mathrm{Transmitter}}$	0.17		
ICC	0.72		
$N_{\mathrm{Transmitter}}$	40		
Observations	95		
Marginal R^2/Conditional R^2	0.208/0.776		

both species. Homing has been suggested for American Lobster but the supporting data were studies that examined local-scale movements (Karnofsky et al., 1989b) or larger-scale studies that considered homing a return to a general area (Pezzack and Duggan, 1986). The ontogenetic and seasonal movements of Snow Crab (Mullowney et al., 2018) have not been attributed to homing behavior. The navigational cues that our study species use remain largely unknown but may be derived from other environmental information such as thermal or olfactory senses (Moore et al., 1991; Cote et al., 2019). Whether submarine cables, with only localized disruptions to EMF fields, would have biologically significant effects on the migrations of even sensitive EMF species remains unknown.

Our study appears to be the first to assess the effects of EMF on aspects of fine scale movement behavior using real-world exposures and unconstrained individuals. Even studies examining coarse-scale effects of electrified cables on unconstrained animals in open ocean environments are extremely rare (Normandeau Associates et al., 2011; Klimley et al., 2021). Two of these studies examined migratory responses of fish while in the vicinity of electrified submarine cables (Westerberg and Lagenfelt, 2008; Klimley et al., 2017). Westerberg and Lagenfelt (2008) examined the passage of tagged European Eels (*Anguilla anguilla*) across an electrified submarine cable and noted a small reduction in migration speed compared to migration corridor areas before and after the cable. The second (Klimley et al., 2017), noted successful migrations of Chinook Salmon and Green Sturgeon in the San Francisco estuary despite the presence of an electrified submarine cable that shared 85 km of their route and several bridges with EMF distortions an order of magnitude greater than the cable. Further study showed that Green Sturgeon exhibited slight delays in outmigration when the cable was powered vs. unpowered (Wyman et al., 2023). Slight delays in migration of Chinook Salmon, as well as small deviations in migration routes, were detected when submarine cables were electrified (Wyman et al., 2018). A third study (Love et al., 2017b) did not detect effects of an electrified cable on the willingness of two species of crab (*Metacarcinus magister* and *Carcinus productus*) to cross the electrified

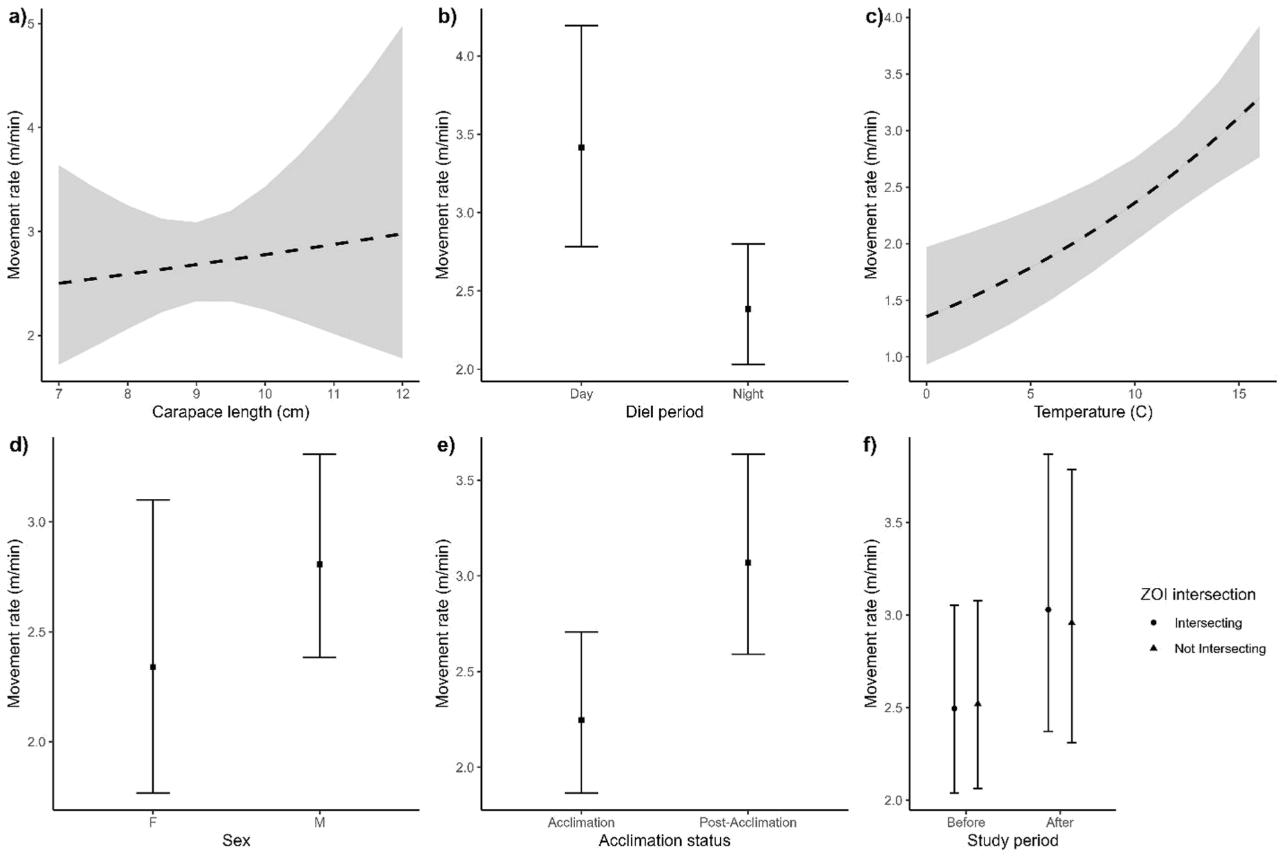

Fig. 7. Marginal effects plots from the fitted generalized linear mixed model (GLMM) to show the effect of carapace length (a), diel period (b), temperature (c), sex (d), acclimation status (e), and the interaction between study period and location (f) on American Lobster movement rates (m/min). Marginal means are shown (dashed lines and points) as well as 95% confidence intervals for the predicted values (shading and error bars).

cable to reach baited traps. Other studies using real-world exposures of EMF evaluated potential changes in distribution of fish (Bergström et al., 2013; Love et al., 2017a; Kilfoyle et al., 2017) and invertebrates (Love et al., 2017a; Donázar-Aramendía et al., 2025) in proximity to electrified submarine cables. No consistent significant responses were observed in these studies except in Bergström et al. (2013) that observed some local changes in distribution that were not specifically attributed to submarine cables, but rather the entire windfarm development. Such changes could have been related to the change in structural habitat complexity, as Love et al. (2017b) also noted higher densities of animals over submarine cables, irrespective of whether they were electrified.

Reviews on the subject of EMF effects have identified the need for Before-After assessments of EMF effects on biota caused by submarine cables (Boehlert and Gill, 2010; Klimley et al., 2021). Studying the effects of industrial activities in open ocean environments is impeded by study costs and the challenging environmental conditions (e.g. deep water, remote). More common are lab studies, which are logistically practical, and can isolate variables of interest (Calisi and Bentley, 2009). Unfortunately, the removal of confounding variables also means that the understanding of effects under complex real-world conditions remains largely speculative (Normandeau Associates et al., 2011; Woodruff et al., 2013). A few mesocosm studies (e.g. observing EMF responses in enclosures; Gill et al., 2009; Hutchison et al., 2020b) have improved inference of EMF effects under real-world conditions by conducting trials in enclosed, semi-natural environments where study animals are exposed to functioning submarine cables. The enclosures allow researchers to add replicate and control treatments and to avoid emigration losses that negatively affect statistical power (Hutchison et al., 2020a). However, the need for enclosures limits such approaches to shallow water habitats (Hutchison et al., 2020a) and prevents study specimens from expressing responses to important ecological processes (e.g. migration, predation) that often shape animals' motivation and associated movement behavior. These studies also had inconsistent results, suggesting they are not immune to confounding factors. Open ocean field studies, with unconstrained movement of study individuals, provide the best realism for EMF effects but are most costly and are vulnerable to misinterpretation if confounding effects are not managed. Typical safeguards to deal with confounding effects used in lab and mesocosm experiments (e.g. BACI designs) are challenging to implement at larger scales as there are almost always inherent differences amongst treatments in time and space at large scale field conditions (Underwood, 1992; Love et al., 2017a). In our study, telemetry detectability was not consistent in Before-After study periods, making direct temporal comparisons difficult. This could have been problematic had we detected cable-related differences between Control and Impact habitats within a single time period. Field observations of Snow Crab and American Lobster are also characterized by high natural variability (Cote et al., 2019, 2020; Konecny et al., 2024), which negatively impacts statistical power (Calisi and Bentley, 2009). However, variability in movement behavior appears to be an inherent characteristic of these species, a fact further supported by lab and mesocosm observations of American Lobster and Snow Crab (Foyle et al., 1989; Woodruff et al., 2013; Hutchison et al., 2020b). It is also uncertain whether responses of our study animals would change over time as they became acclimated to the presence of the electrified cables. However, the infrequent interactions we observed between study animals and the electrified cables, as well as the extended study period suggests that our results reflect long term responses to this infrastructure.

Environmental variables, while not an explicit focus of our study, were necessary to account for variation in behavior observed during baseline studies on our species (Cote et al., 2019; Konecny et al., 2024). Relative to Snow Crab, American Lobster occupy much more heterogeneous environments that are characterized by more variable substrates, thermal conditions, and light levels. It is therefore somewhat surprising that these species shared similar environmental (temperature, diel period, tide) and experimental influences (tagging effects) on movement behavior. Substrate was the only environmental driver on movement behavior that was unique across the two species. While American Lobster can take refuge in the structure created by kelp and coarse substrates (Konecny et al., 2024), Snow Crab have adapted to the uniform muddy habitats available to them in deeper waters, using soft substrate for burrowing/predator avoidance. Previous analyses of movement data in our study area also identified sex (Cote et al., 2019; Konecny et al., 2024) and lifestage (Cote et al., 2019) as influences on movement behavior but we found sex not to be an important factor in our models for American Lobster and we had insufficient data to analyze lifestage (for either species) and sex (for Snow Crab only).

Diel period affected both Snow Crab and American Lobster movement velocities but in opposing ways: Snow Crab moved faster at night whereas American Lobster moved faster during the day. The latter result is seemingly at odds with previous analyses of our American Lobster data (Konecny et al., 2024), that noted a tendency for American Lobster to be more active at night. This can be explained by the fact that movement tracks of study animals in this study were selected based on consecutive interactions with both impact and control habitats. This selection process biased sampled tracks to active behavior states. While American Lobsters remain less likely to move during the day, daytime movements have a tendency to occur at higher speeds. A tendency for more directed and faster movements was also observed by Konecny et al. (2024) in American Lobster crossing open habitats and therefore our observations of higher movement velocities could reflect the American Lobster's perception of risk of moving during daytime periods.

Energized submarine cables are becoming more prevalent as energy is increasingly produced and distributed through marine environments (Klimley et al., 2021; Bueger and Liebetrau, 2023; Smyth and Kregting, 2023). Our results on commercially important American Lobster and Snow Crab provide no evidence that electrified submarine cables will alter the movement ecology of these species. The methodological approaches applied here could be useful to future studies looking at electrified submarine cable effects on other potentially sensitive species or the cumulative effects that might be associated with much larger/denser installations.

CRediT authorship contribution statement

David Cote: Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Cassandra Konecny:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Jean-Marc Nicolas:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Jeremy Broome:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **James McCarthy:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Darrin Baker:** Writing – review & editing, Methodology, Investigation.

Declaration of competing interest

J-MN is an employee of Emera NL; the proponent of the Maritime Link project. J-MN had input into the study design of this research and provided review of the manuscript and the results therein. The remaining authors have no competing interests to declare.

The study design was approved by independent scientists from federal government regulators prior to the project's (and study's) conditional approval as part of the environmental assessment. The analysis and interpretation of the results reported in this manuscript were led by two scientists (DC, CK) with no competing interests, and the results of this paper are contributing to the final assessment of the environmental assessment that are being reviewed by independent government regulators.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2026.120087.

Data availability

Data will be made available on request.

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