The Effects of Anthropogenic Electromagnetic Fields on the Behavior of Geomagnetically Displaced Skates

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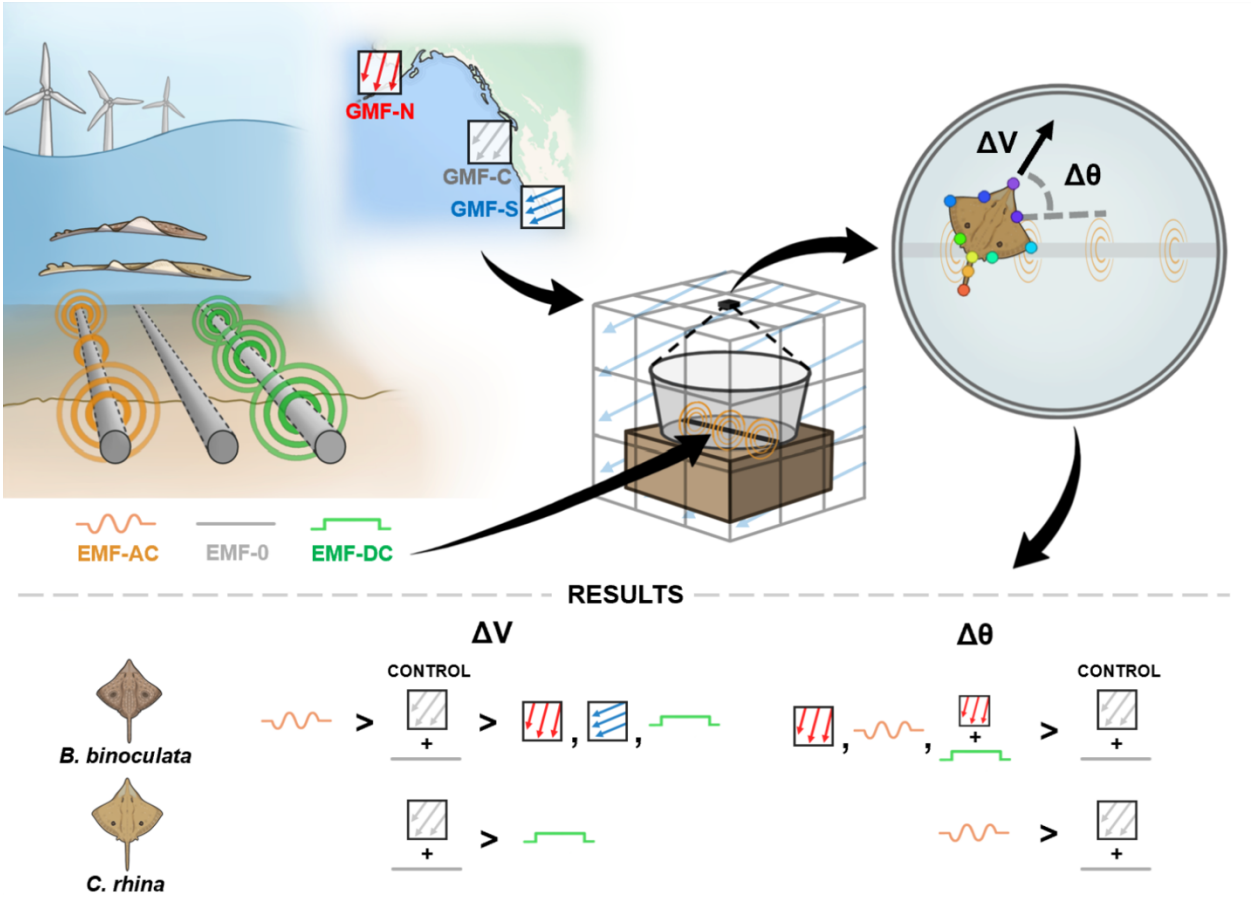
GRAPHICAL ABSTRACT



ABSTRACT

To mitigate the effect of climate change, the demand for marine renewable energy infrastructure is increasing worldwide. These facilities convert the kinetic energy of offshore wind, waves, tides or currents into electricity that is transported to shore through alternating current (AC), or direct current (DC), subsea cables. Energized cables emit magnetic fields radially into the surrounding seawater and induce secondary electric field artifacts. Thus, anthropogenic electromagnetic fields (EMFs) can alter the local geomagnetic landscape and may impact the behavior of EMF sensitive elasmobranchs that use the geomagnetic field (GMF) to navigate. We magnetically displaced big (*Beringraja binoculata*) and longnose (*Caliraja rhina*) skates to determine their response to GMF navigational cues. We then exposed skates to model AC and DC subsea cables to determine their response to fluctuating and constant EMFs. We then exposed skates to GMF and EMF to understand how EMF-AC and EMF-DC impacts GMF mediated behaviors. Experiments were recorded on video and 3D pose estimation software tracked the velocity, body angle, and spatial use of skates to quantify their behavioral response to magnetic stimuli. Big skates exposed to GMF and EMF were more active and showed the greatest changes in spatial use, velocity, and body angle. Conversely, longnose skates were less active but showed significant magnetic stimulus-specific changes in their movement kinematics. Thus, skates exposed to GMF and EMF showed stimulus- and species-specific changes in their behavior. Future studies will leverage these lab-based results to interpret the response of free-ranging elasmobranchs to EMF.

INTRODUCTION

To mitigate climate change, the demand for the development and implementation of marine renewable energy (MRE) projects is growing worldwide (Albert et al. 2020, Gill and Desender 2020). These installations convert the kinetic energy of offshore wind, waves, tides, or currents into electricity that is transported back to shore through high voltage subsea cables (HVCs). Depending on the length (typically < 100 km) and purpose of the HVC (e.g., inter-array, export), it will carry electricity in the form of alternating current (AC) that fluctuates back and forth, or direct current (DC), that is constant over time. As electricity is conducted through an HVC, it can emit a current-dependent magnetic field with a calculated intensity ≤ 5000 μT (*reviewed in* Albert et al. 2020) radially from the cable for several 10s of meters, which could induce secondary electric fields (1-700 μV/m) around animals that swim through them (Figure 1; Newton et al. 2019, Gill and Desender 2020).

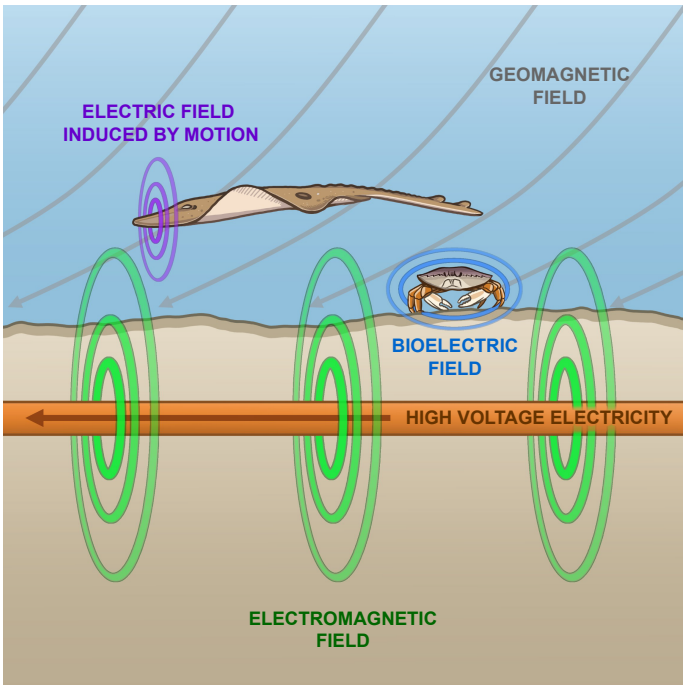


Figure 1. Depiction of natural and anthropogenic magnetic and electric fields encountered by an electroreceptive skate moving across the seabed. The buried subsea cable (orange) conducts electricity along its length. While it is electrically shielded, a magnetic field (green) is emitted radially into the environment. This electromagnetic field (EMF) can alter the local geomagnetic field (gray) and induce secondary electric fields (purple) around an animal (e.g. skate or crab) as it moves through electrically conductive seawater. Thus, EMFs could potentially impact magnetically based navigation behavior or mask bioelectric fields emitted by prey that skates use during foraging.

The intensity of these anthropogenic electromagnetic fields (EMFs) could be up to 70-150X greater than that of the geomagnetic field (GMF: 20 - 70 μT). Measured B-fields from in situ cables range from 0.005 to 58.3 μT (Albert et al. 2020, Copping & Hemery 2020). Thus, EMFs can potentially alter the local GMF landscape, induce secondary electric fields that mask bioelectric cues, and impact electrically and magnetically mediated behaviors in EMF sensitive species (Albert et al. 2020, Bevelhimer et al. 2013, Gill and Desender 2020, Hutchison et al. 2020 & 2021, Klimley et al 2021, Scott et al. 2021, Woodruff et al. 2013).

Elasmobranch fishes (sharks, skates, rays) use their electroreceptors, the ampullae of Lorenzini, to detect the bioelectric fields of: prey during foraging (Bedore and Kajiura 2013, Kajiura and Holland 2002), conspecifics during the mating season (Tricas et al. 1995, Sisneros et al. 2000), predators during crypsis (Ball et al. 2005, Kempster at al. 2012, Sisneros et al. 1998), and likely use them to indirectly detect geomagnetic field cues during navigation (Anderson et. al 2017, Kalmijn 1974, 1978, 1988, 2000, Keller et al. 2021, Newton and Kajiura 2020a & 2020b). Physiological studies have shown that elasmobranch electroreceptors are best tuned to detect weak (< 20 nV/cm; Montgomery 1984, Murray 1962, Tricas and New 1998), low frequency (0.5-20 Hz; Adrianov et al. 1984, Peters & Evers 1985, Montgomery 1984, Tricas and New 1998), sinusoidal (AC) electric fields, which corresponds to the bioelectric field stimuli produced by marine organisms as they exchange of ions at the gills and ventilate (Bedore and Kajiura 2013). However, the morphological convergence of multiple receptor afferents onto ascending neurons results in lower behavioral thresholds (< 1 nV/cm) and greater sensitivity to a wide range of stimulus parameters (*reviewed in* Newton et al. 2019).

Similarly, though magnetic stimuli are not generally associated with biological systems and are not known to be naturally attractive to elasmobranchs, physiological studies have shown that their electrosensory system can detect the on- and offset of weak magnetic stimuli. This

response in the thorny skate (*Raja radiata*; Adrianov et al. 1984), common stingray (*Trygon pastinaca;* Adrianov et al. 1984, Akoev et al. 1976, Brown and Ilyinsky 1978), and thornback ray, (*Raja clavata*; Akoev et al. 1976, Brown and Ilyinsky 1978) rapidly attenuates in the presence of static magnetic fields. It has been hypothesized that elasmobranchs could use the GMF to navigate (Kalmijn 1978, 1981, 1982, 1984, 2000, Molteno and Kennedy 2009, Paulin 1995). Scalloped hammerhead sharks (*Sphyrna lewini*) are known to swim along the contours of the weak bathymetric magnetic stimuli produced by ferric compounds in the seafloor and perhaps navigate their environment by magnetic topotaxis (Klimley 1993). Bonnethead sharks (*S. tiburo*) can use experimentally manipulated GMF cues to derive a sense of their current location relative to that of a goal (e.g., a map sense) and maintain the correct heading (e.g., compass sense) to orient towards their home range (Keller et al. 2021). Such GMF-based navigation behavior has never been demonstrated in a batoid (skate or ray), but Uroliphid stingrays can detect the polarity (*Urobatis halleri*; Kalmijn 1978, *U. jamaicenis*; Newton and Kajiura 2020a), intensity and inclination angle (*U. jamaicenis*; Newton and Kajiura 2020b) cues of the GMF.

Elasmobranch magnetic field detection experiments have been conducted on a few species and have begun to describe their general sensitivity (Anderson et al. 2017, Meyer et al. 2005), natural and conditioned behavioral responses to the GMF (Kalmijn 1978, Keller et al. 2021, Newton et al. 2020a & 2020b), permanent magnets (Newton et al., 2017, Polpetta et al. 2021), and the EMF emitted by AC (Albert et al. 2021, Gill et al. 2009, Orr 2016) and DC cables (Albert et al. 2021, Hutchison et al. 2018 and 2020, Orr 2016). Despite inconsistent results across studies, strong permanent magnets (~2000X the GMF intensity) can initially repel sharks and rays from bait but they often become habituated in the absence of reinforcement (O'Connell et al. 2011, 2014a, 2014b, 2014c, 2015, Robbins et al. 2011, Siegenthaler and Jones 2016, Smith and O'Connell 2014, Stoner and Kaimmer 2008). Little skates (*Leucoraja erinacea*) spent more

time near an energized DC cable emitting constant EMFs compared to controls (Hutchinson et al. 2020) and were possibly engaged in unsuccessful foraging behavior. Juvenile thornback rays (*Raja clavata*) were attracted to DC but not AC cables (Albert et al. 2021) while adult thornback rays increased their movement and spotted catsharks (*Scyliorhinus canicula*) spent more time near AC cables (Gill et al. 2009). New Zealand carpet sharks (*Cephaloscyllium isabellum*) were attracted to DC, but not AC cables (Orr 2016).

The behavioral repertoire of an organism is its first line of defense against rapid environmental change, and these studies show that the behavioral responses of elasmobranchs to EMF stimuli can vary significantly depending on the species, life stage, ecological niche, and the quality, magnitude, and duration of stimuli (*reviewed in* Hutchinson et al. 2021, Hermans et al. 2024). Given the breadth of responses, it is possible that an elasmobranch that encounters a rapid and relatively significant (~10X) increase in the local GMF due to an anthropogenic EMF could stop to investigate, bite, turn away from, or ignore the anomaly as they progress along their migratory route (Klimley et al. 2021, Marra et al. 1989, Taormina et al 2018, Gill and Desender 2020).

Therefore, the imminent expansion of MRE infrastructure and HVC networks requires comprehensive research into the acute and chronic effects that EMF will have on the GMF-based behaviors, such as navigation, of receptive species (Gill and Desender 2020, Hutchinson et al. 2021, Klimley et al. 2021, Newton et al. 2019). The overall intensity (***F***) and inclination angle (***I***) of the GMF changes predictably with latitude such that unique combinations of ***F*** and ***I*** can be used to describe geographic locations on the Earth. GMF-based navigation behavior has been demonstrated in several species (Lohman et al. 1996, Keller et al. 2021, Naisbett-Jones et al. 2017 and 2020, Minkoff et al. 2019, Putman et al. 2014) by manipulating the ambient GMF to “magnetically displace” animals to a geographic location (treatment) that is within their normal distribution but different from their current physical location (control). Currently, there are several

knowledge gaps in quantifying the behavioral response of phylogenetically diverse elasmobranch species exposed to GMF displacement stimuli and EMFs from fluctuating AC and constant DC subsea cables, especially under conditions that test the impact of repeated encounters with HVCs over small spatiotemporal scales (Gill and Desender 2020, Klimley et al. 2021, Gill and Hutchison 2021, Hermans et al. 2024).

This project aimed to determine if the big (*Beringraja binoculata*) and longnose (*Caliraja rhina*) skates show a measurable behavioral response to EMF anomalies emitted by model HVCs. Because elasmobranch electroreceptors are well tuned to detect fluctuating stimuli, we predicted that the EMF emitted from AC cables would elicit stronger responses from skates than the constant EMF emitted from DC cables. However, as the AC output is expected to oscillate at 60 Hz (typical of US installations), it is possible that this higher frequency might make the emitted EMF's less attractive than if they oscillated at < 20 Hz, which might be more biologically relevant. As such, our hypotheses are that skates: (H1) can detect alterations to the ambient GMF, (H2) will alter their behavior in response to GMF displacement, (H3) can detect the EMFs emitted by an AC and DC model HVC, (H4) will alter their behavior in response to EMF cues, and (H5) will alter their GMF response (i.e., H2) with repeated EMF exposure. This work provides a foundation for future broad comparisons across phylogeny and ontogeny as well as longitudinal studies into the cumulative effects of chronic EMF exposure, including those with particular emphasis on vulnerable life history stages for each species (Gill and Desender 2020, Hutchinson et al. 2021, Hermans et al. 2024).

METHODS

Skates

Big skates (n = 4; DW = 30-40 cm) were either captured (n=2) using a 2 m wide benthic beam trawl (44.701, -124.143; 35 m depth) or donated (n=2) from local aquaria, and Longnose skates

168 (n = 3; DW = 50-60 cm) were caught using bottom set long line (43.317, -129.745; 310 m
169 depth). Skates were held on the boat deck in flow through seawater tanks then transferred to
170 oxygenated seawater tanks and transported to the laboratory at Hatfield Marine Science Center
171 in Newport, OR. Skates were housed in flow through seawater tanks (2 m dia.) on a 12:12 hr
172 light:dark cycle and fed a mixture of shrimp, clams, herring, and nutritional supplements (Shark
173 and Ray Supplement; Mazuri, SKU 0053065) every other day (7-10% BW / week). Once
174 subjects were feeding for a minimum of 30 days, they were deemed sufficiently acclimated to
175 captivity and healthy for behavioral testing. All procedures were conducted within the ethical
176 guidelines set by the Institutional Animal Care and Use Committee of Oregon State University
177 under protocol #2022-0257.
178
179 ***Experimental Apparatus***
180 The experimental apparatus (Figure 2A-B) was constructed in a magnetically uniform location
181 within the laboratory and consisted of a 1.8 m round polyethylene tank filled to 60 cm placed on
182 a level platform of wooden pallets (~ 1 m high, iron nails removed, topped with a layer of 5 cm
183 foam core) and a model HVC placed within a Merritt coil system (Merritt et al. 1983). The Merritt
184 coils were used to generate geomagnetic field (GMF) pseudo displacement stimuli, whereas the
185 model HVC generated EMF noise stimuli. The Merritt coil system was constructed with 38 mm
186 PVC pipe and fittings (3 x 3 x 3 m overall) and two continuous loops of 14 AWG wire were
187 secured to the PVC structure: one loop was a series of four horizontal loops and the other a
188 series of four vertical loops (26, 11, 11, and 26 windings) that were spaced 1.11, 0.78, and 1.11
189 m apart. The coils were positioned so that the horizontal and vertical coils were aligned with the
190 vertical and horizontal components of the GMF, respectively. Each loop of the coil system was
191 powered by a single channel 30 W DC power supply (30 V, 5A, Model #TP3005DM, TEK
192 Power, Montclair, CA). A customized configuration of switches and circuitry controlled the

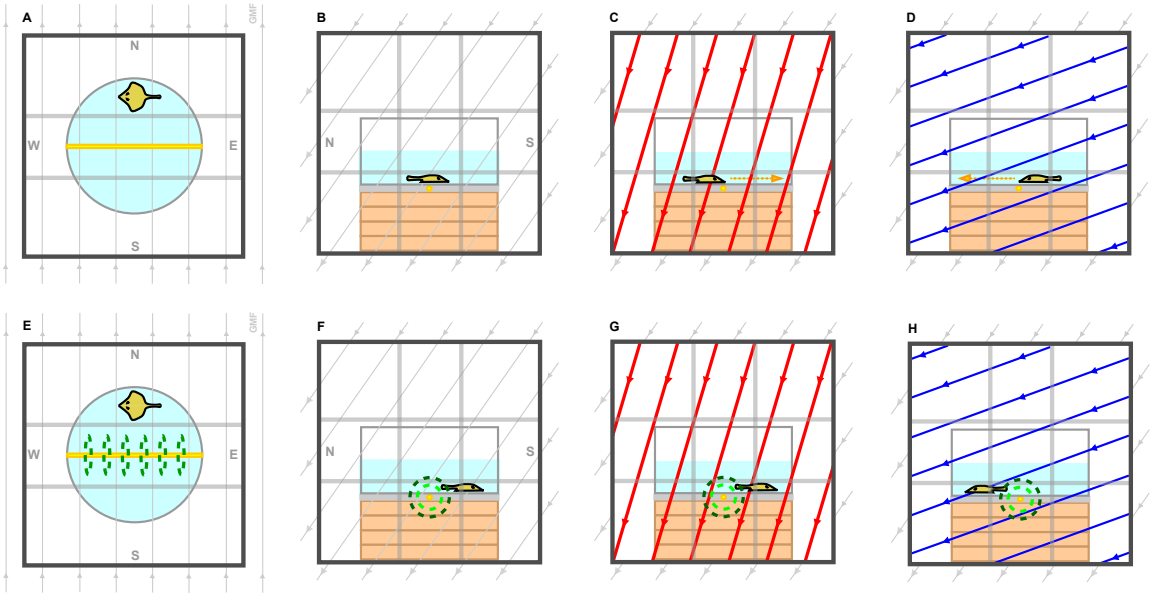


Figure 2. Experimental arena, Merritt Coil system, and mock subsea cable used to conduct geomagnetic field displacement and electromagnetic field exposure trials on big and longnose skates. A) Overhead and B) lateral views of skate in a tank (2 m diameter), direction of ambient geomagnetic field (GMF; light gray arrows), Merritt Coil system (thick gray lines; 3 x 3 x 3 m), mock subsea cable (yellow) emits electromagnetic field noise (EMF; green dotted circles) along west-east axis underneath tank. Mock subsea cable (yellow) located directly under the tank conducted either alternating (AC) or direct (DC) current and emitted fluctuating or constant EMF (green dotted circles), respectively. Cardinal directions indicated with capital letters. Tank was placed on top of wooden pallets to ensure it was within the uniform portion of the altered GMF produced by Merritt Coils during magnetic displacement trials. C) GMF-North displacement trial conditions without EMF noise. Red arrows within Merritt coils indicate altered GMF to match that of geographic location within the northern portion of species distribution. Orange arrow indicates expected southward movement pattern of skate magnetically displaced to the north if it demonstrated a GMF-based bicoordinate map sense. D) GMF-South displacement trial conditions without EMF noise. Blue arrows within Merritt coils indicate altered GMF to match that of southern geographic location within species distribution. Orange arrow indicates expected northward movement pattern of skate if it were magnetically displaced to the south and demonstrated a GMF-based bicoordinate map sense. E) Overhead and F) lateral views of skate during exposure to EMF (dotted green circles) emitted by mock cable. G) GMF-North displacement trials with EMF noise (green dotted circles). H) GMF-South displacement trials with EMF noise (green dotted circles).

direction and amount of electric current flowing through the coils. The model HVC was constructed of 10 AWG single conductor wire then placed on top of the layer of foam core directly underneath the east-west axis of the tank. A single conductor was chosen because it is the simplest to model for this initial study and creates a foundation for future work with multiple conductors (e.g., three phase AC). Depending on the experiment, the model HVC was connected to an AC (Variac Variable Transformer, model # TDGC2-3D, Circuit Specialists) or DC (60 V, 24A; model #RD6024, AVHzY) power supply. A tri-axial magnetometer (model

#3AMG, Alphalab Inc.) and the Physics Toolbox Sensor Suite (www.vieyrasoftware.net) for mobile devices were used to confirm the uniformity of the ambient GMF within the arena, the overall intensity (***F***) and inclination angle (***I***) of the resultant GMF pseudo displacement and EMF noise magnetic stimuli.

Geomagnetic and Electromagnetic Field Stimuli

We monitored the changes in spatial use and orientation angle of individuals exposed to altered GMF conditions, to discern if (1) skates can detect GMF cues (H1: e.g., ***F*** and ***I***), (2) alter their behavior, such as: use the GMF to derive a sense of their current location with respect to a goal (H2), and (3) maintain the correct heading to achieve that goal during navigation (H2). If subjects do not respond, it could mean that they either could not detect the stimuli, or that the stimuli were not sufficient motivation to elicit a navigation response. GMF control (GMF-C) stimulus exposure consisted of trials conducted at the ambient GMF in Newport, OR, [***F*** = 51.1 μT (horizontal = 20.6 μT, vertical = 46.9 μT), ***I*** = 66°); Figures 2A-B, E-F]. Geomagnetic north (GMF-N; Figure 2C, G) and south (GMF-S; Figure 2D, H) pseudo displacement stimuli were chosen to mimic the northern (***F*** = 54.6 μT, ***I*** = 73.0°; AK, USA) and southern (***F*** = 41.0 μT, ***I*** = 49.2°; Baja, MX) ends, respectively, of the estimated distribution for both species (Fishbase.se).

The intensity of the EMF stimuli from our model HVC when powered by AC (EMF-AC) fluctuated ± 500 μT at 60 Hz with additional low band oscillations at frequencies of ~ 0.25 and 1 Hz (Figures SI1A, C). Conversely, the EMF stimuli emanated when powered by DC (EMF-DC) had a constant intensity of + 500 μT above the ambient GMF (Figures SI1B, D). The EMF-AC and -DC values were chosen to (1) standardize the relative change in magnetic field stimuli to 10X that of the ambient GMF, (2) remain within the range of magnetic stimuli possible from energized AC and DC HVCs in active MRE farms (Albert et. al 2020), and (3) be strong enough

to likely elicit an observable response, if detected. Control EMF stimulus conditions consisted of exposure to the non-energized model HVC that did not emit EMF noise (EMF-0; Figure 2A-D).

Behavioral Trial Procedure

An individual skate was transferred from its husbandry tank into the experimental tank via rubberized net and allowed to acclimate for 10 min. Acclimation time was determined from a minimum of three baseline activity trials (> 60 min) that allowed skates to return to baseline activity levels and align our study with prior work using similar methods on loggerhead sea turtles, *Caretta caretta* (Lohmann et al. 1991), Chinook salmon, *Oncorhynchus tshawytscha* (Putman et al. 2014), European eels, *Anguilla anguilla* (Naisbett-Jones et al. 2017), and bonnethead sharks, *Sphyrna tiburo* (Keller et al. 2021).

We tested whether skates had a behavioral response to EMF from AC and DC HVCs and if these stimuli might impact GMF-based navigation behavior. We used a nested block experimental design (Figure SI-2) to account for the variation of repeated measures exposure of individual skates to magnetic stimuli across multiple sessions. Sessions that tested the behavioral response of individual skates to EMF and GMF stimuli were conducted once per day. A session consisted of transferring a skate from its husbandry tank to the experimental tank, allowing it > 10 min to acclimate, then under one GMF condition (GMF-C, GMF-N, or GMF-S) we presented three separate 10-min EMF stimulus trials (EMF-0, EMF-AC, or EMF-DC) in random order (intertrial interval of 60-180 s). Once the three EMF trials were finished for a particular GMF condition, the skate was returned to its husbandry tank and the session concluded for that individual. Once all individuals were tested under that GMF condition, the session ended for that day and the skates were allowed to rest for 2-4 days until the next session of trials. This process was repeated so that individual skates were exposed to every permutation of EMF and GMF treatments (n = 9). Each permutation was conducted 5 times for

each animal (total number of trials per skate = 45) to simulate the scenario of a skate using GMF cues to navigate, then encountering an MRE array and being exposed to EMF multiple times over a relatively short time frame.

Behavioral Data Collection and 3D Markerless Pose Estimation

All trials were recorded onto a 256 GB micro-SD card at the “Standard” camera setting for the GoPro Hero 11 Black (4K resolution, 30 Hz frame rate, 4:3 aspect ratio, “linear” lens setting). Video recordings of trials included 15s before and after the onset and offset of GMF and EMF stimuli to discern if there were any observable immediate responses to magnetic stimuli. Video files were backed up, labeled according to subject and experimental conditions, and pre-processed (e.g., crop to 800 x 800 px, downsample to 1 Mbps without audio) in Adobe Media Encoder (2023). Despite the high video resolution and sampling rate, skates did not show any observable low latency (<10 ms) response to the EMF or GMF stimuli; thus these parameters preserved the integrity of the recorded behavioral responses and reduced computational load. Post-processed files were analyzed using DeepLabCut (DLC) v2.3.0. A curated set of seven videos had 20 frames extracted (automatic, k-means) from each so that 12 unique body parts (nose; anterior, tip, and posterior of left and right pectoral fins; left and right pelvic fins; base, mid and tip of tail) could be labeled and skeleton connections between body parts defined. The annotated frames were used to create a model by training the dataset for 100,000 iterations then confirming that model training (0.34%) and test (0.71%) errors were minimized. Videos were analyzed using the box tracking method and results saved as csv files for analysis in R. Plotted trajectories and videos with overlaid body parts were used to visually confirm tracking efficacy for each trial. Additional detail can be found in Newton et al. (2023) and online (https://github.com/DeepLabCut/DeepLabCut).

Data Analysis

For spatial use analyses, the arena was either divided along the west-east axis into two (north, south) equal hemispherical regions of interest (ROI), or along the perimeter of the tank to create three (north, central, south) equal ROIs of 120° total arc length. The former method was used to test for changes in spatial use under GMF-N or GMF-S displacement, and the latter method was used to delineate three equal ROI, account for the wall association of skates, and test if they were attracted (greater central ROI use) or repelled (greater north or south ROI use) by EMF stimuli.

DLC data files were concatenated into a master file, wrangled, analyzed and figures produced in R Studio using *base* R and the packages *tidyverse*, *dplyr*, *circular*, *zoo*, *spectral*, *lmer*, *bpnreg*, *goeveg*, *stats*, *MuMIn, ggplot2, and viridis*. The raw behavioral response data for each trial was collected as a 30 Hz time series and subject to autocorrelation. Thus, we used Schoener's ratio (Swihart and Slade 1985) to determine the minimum temporal resolution necessary to remove autocorrelation and achieve independent sampling. Thus, the time series of each trial was down sampled at 1-minute intervals resulting in 10 independent data points per trial and autocorrelation removal was confirmed using corAR1 in *nlme*. Response data were checked for normality with *car* and transformed with the appropriate exponents (lambda = 0.25 - 1.2) as determined by *rcompanion*.

To make our data comparable to previous studies (e.g., Lohmann et al. 1996, Putman et al. 2014), we assumed the skates used the first five minutes to discern their GMF displacement or exposure to EMF and the latter five minutes to elicit their angular response. Thus, we investigated the mean angular response of big and longnose skates for the final five minutes of the magnetic trials in R using *circular* and *circ_MLE*. However, traditional circular statistical methods (e.g., Rayleigh test, Watson Wheeler, Akaike Information Criterion) do not allow for

repeated measures designs. Therefore, we transformed the mean body angle data from a circular (i.e., angular) format to their linear sine (*sin* Θ) and cosine (*cos* Θ) components then compared each parameter using the nested generalized linear mixed model (GLMM) described below. We assumed that any magnetic condition with a significant difference in *sin* Θ or *cos* Θ from that of the appropriate reference condition meant that the corresponding body angles for those conditions were different as well. Because our frame of reference used 0° to indicate north, and using the definitions of trigonometric functions, the *sin* Θ values were interpreted to indicate significant changes in body angle along the east-west axis, whereas *cos* Θ values indicated changes along the north-south axis.

To examine how the behavioral response of skates might vary during exposure to EMF and GMF stimuli, the spatial use (ROI) data were converted to counts then analyzed using a GLMM in R (package *lmer*; e.g., Count ~ ROI * EMF * GMF + (1 | individual), see Tables 1-6). Likewise, the mean velocity and body angle data were analyzed using a GLMM (e.g., response variable ~ EMF * GMF + (1 | individual / session / trial), see Tables 7-20). The GLMM models included terms for the main effects of EMF, GMF, ROI (if necessary), and their interactions. A random effects term nested the multiple independent trial data points within each session and multiple sessions within individual skates to mitigate against pseudo replication from the repeated measures of the nested design. A pseudo R^2 value for GLMMs was generated by *MuMin* to explain the variance of the fixed and random effects. ANOVA type II (Wald) and III (Chi Square) tests were used to determine significance levels for fixed main and interaction effects. Tukey's pairwise comparisons between EMF and GMF were done posthoc using *emmeans* with the appropriate p-value adjustments. A significance level of *alpha* = 0.05 was used for all statistical comparisons. The final models and their output are in the supplemental section (Tables 7-20).

RESULTS

Spatial Use

We predicted that skates displaced to the north would prefer to occupy the southern half of the arena and skates displaced to the south would prefer the northern half. However, the mean spatial use of the arena by big and longnose skates was not significantly different between the northern and southern hemispherical ROI when individuals were exposed to ambient or GMF-N and GMF-S pseudo displacement conditions (Figures 3A-C & 4A-C) under EMF-0. Among the three edge regions of the tank, under GMF-control there was a significant fixed effect of greater mean use of the central third ROI than the northern or southern third ROI by big and longnose skates in all treatments (EMF-0; Figures 3A & 4A, Tables 1 & 2, EMF-AC; Figures 3D & 4D, Tables 3 & 4, and EMF-DC; Figures 3G & 4G, Tables 5 & 6). Longnose skates did not show a preference for the northern vs. southern third ROIs under any EMF condition (Figure 4); however, big skates used the northern more than the southern third ROI under GMF-C and GMF-N (Figure 3D-E, G-H), but not GMF-S (Figure 3F, I), displacement. Thus, within a given GMF condition, the general pattern of spatial use within big and longnose skates did not change with EMF exposure.

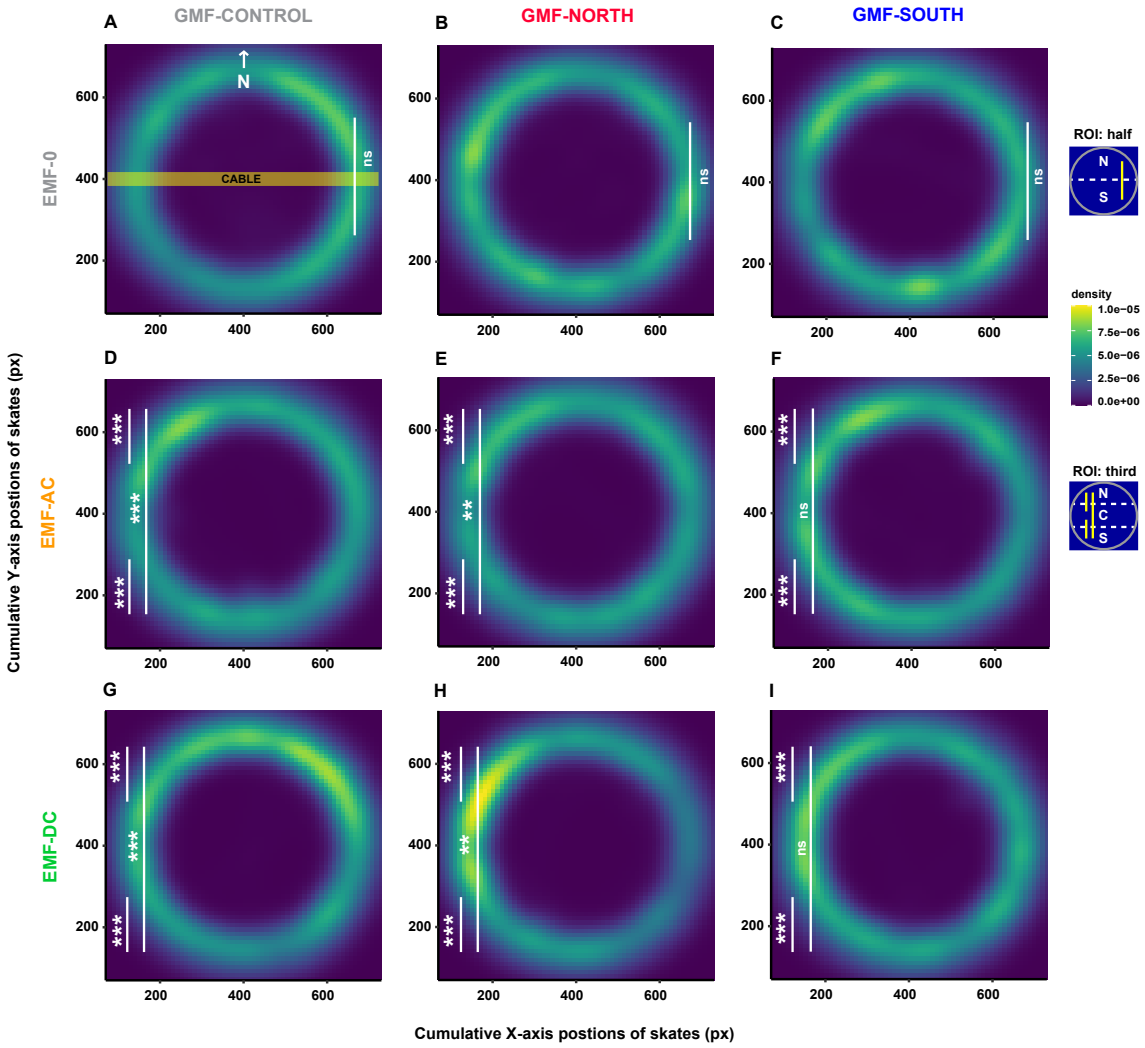


Figure 3. Cumulative spatial use of the arena by big skates during exposure to geomagnetic displacement and electromagnetic noise stimuli. Icons on the upper right of the figure depict regions of interest (ROI) within the arena for statistical comparisons between spatial use of each set. Bars on the left side of panels indicate statistical comparisons between the three northern, central, and southern third ROI to test if skates were attracted or repelled from the central ROI during exposure to EMF noise stimuli (a-c; bars removed for visual clarity). Bars on the right side of panels indicate statistical comparisons between the two northern and southern hemispherical ROI to test if skates preferred to use southern or northern ROI during exposure to GMF-N or GMF-S displacement stimuli. Big skates preferred to use the central third ROI more than the northern and southern third ROI, and the northern more than the southern third ROI during GMF-C (a, d, g), and GMF-N (b, e, h), but not GMF-S (c, f, i) displacement conditions. The spatial use of the arena by big skates did not differ between the northern and southern ROI during a) GMF-C, b) GMF-N, and c) GMF-S displacement conditions without EMF. Significance values: # = 0.1, * = 0.05, ** = 0.01, *** = 0.001.

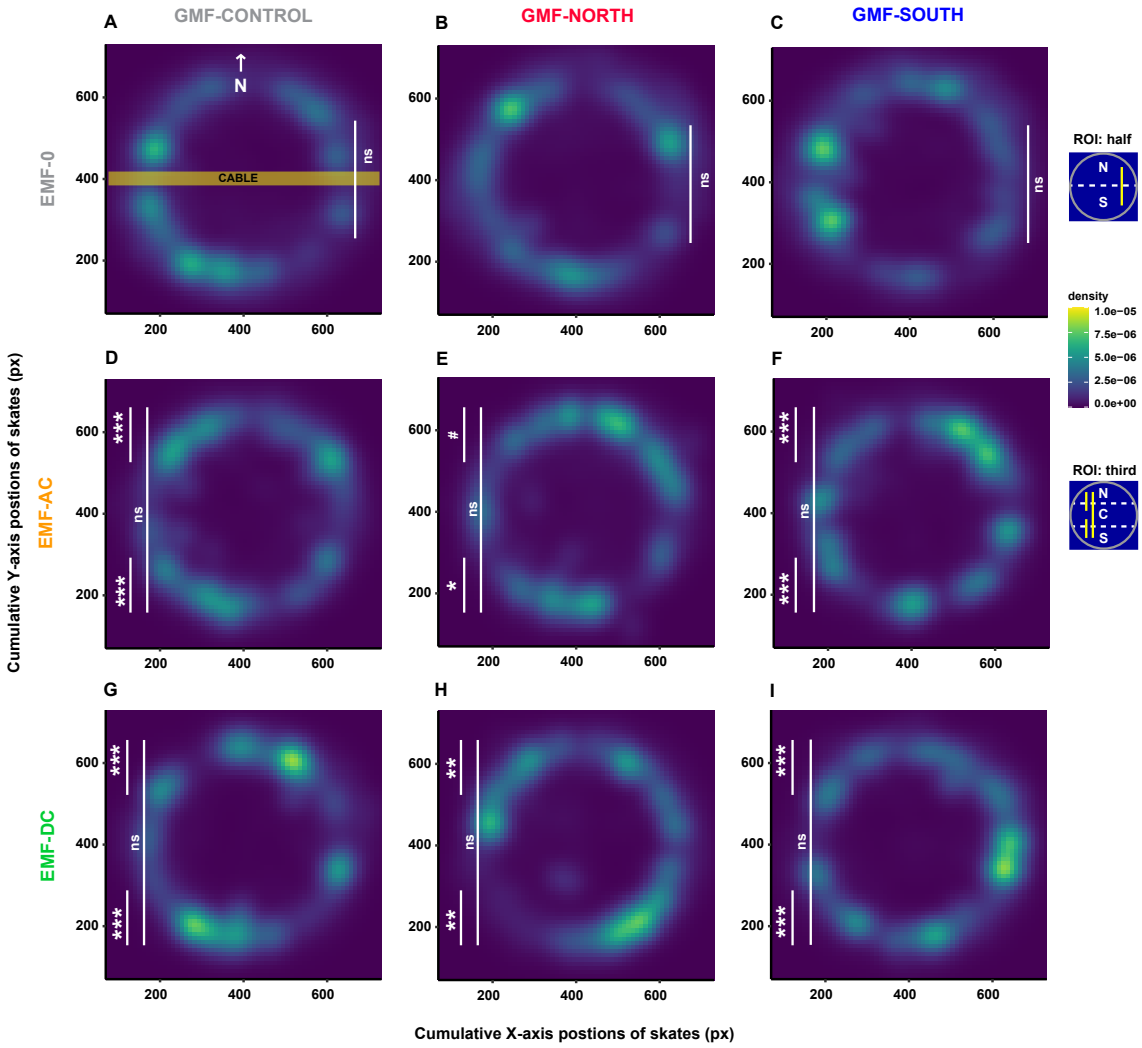


Figure 4. Cumulative spatial use of the arena by longnose skates during exposure to geomagnetic displacement and electromagnetic noise stimuli. Icons on the upper right of the figure depict regions of interest (ROI) within the arena for statistical comparisons between spatial use of each set. Bars on the left side of panels indicate statistical comparisons between the three northern, central, and southern third ROI to test if skates were attracted or repelled from the central ROI during exposure to EMF noise stimuli (a-c; bars removed for visual clarity). Bars on the right side of panels indicate statistical comparisons between the two northern and southern hemispherical ROI to test if skates preferred to use southern or northern ROI during exposure to GMF-N or GMF-S displacement stimuli. Longnose skates preferred to use the central third ROI more than the northern and southern third ROI, which were used equally during all GMF and EMF conditions. The spatial use of the arena by big skates did not differ between the northern and southern ROI during a) GMF-C, b) GMF-N, and c) GMF-S displacement conditions without EMF. Significance values: # = 0.1, * = 0.05, ** = 0.01, *** = 0.001.

Mean Velocity

The mean velocity of big skates showed significant fixed main effects of EMF, GMF exposure and their interaction (Figure 5, Table 7). In big skates, the main effect of GMF displacement relative to GMF-C conditions (mean ± SE = 8.31 ± 2.53 cm/s) was a significant reduction of their mean velocity during GMF-N (-12.1%) and GMF-S (-10.7%) displacement (Figure 5A, Table 8). Pairwise post hoc comparisons indicated that the effects of GMF-N and GMF-S were primarily realized under EMF-0 conditions, not during EMF-AC or EMF-DC exposure (Table 9).

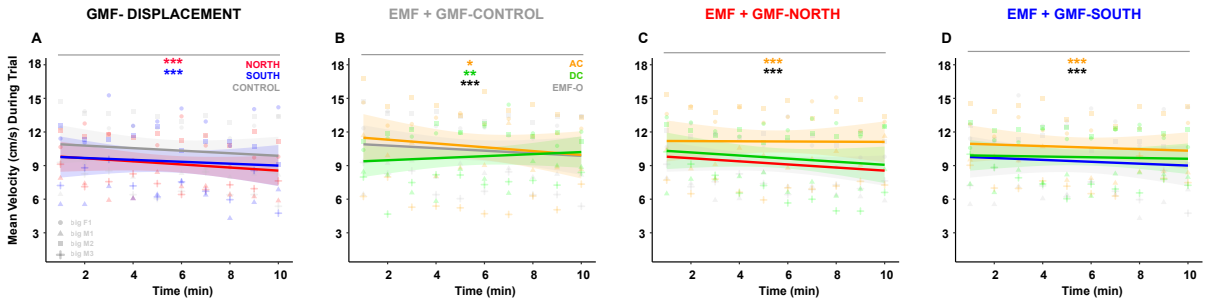


Figure 5. The mean velocity of big skates during exposure to GMF displacement, EMF alone, and EMF during GMF displacement. Big skates had: A) a significantly greater mean velocity during control trials (gray) compared to during GMF-N (red) or GMF-S (blue) displacement trials; B) a significantly greater mean velocity during EMF-AC trials (orange) and controls (gray) compared to EMF-DC (green) trials under ambient GMF (control); C) a significantly greater mean velocity during EMF-AC trials (orange) compared to controls (red) and EMF-DC (green) trials under GMF-N displacement; and D) a significantly greater mean velocity during EMF-AC trials (orange) compared to controls (blue) and EMF-DC (green) trials under GMF-S displacement. Control trials (red and blue lines) during (C) GMF-N and (D) GMF-S displacement are the same as those of (A) GMF displacement without EMF. Significance values: # = 0.1, * = 0.05, ** = 0.01, *** = 0.001. Red symbols compare GMF-N to GMF controls, blue symbols compare GMF-S to GMF controls, orange symbols compare EMF-0 to EMF-AC, green symbols compare EMF-0 to EMF-DC, black symbols compare EMF-AC to EMF-DC.

The main effect of EMF stimulus on big skates relative to that of EMF-0 controls was a significant increase in mean velocity during EMF-AC (+5.5%) exposure and decrease during EMF-DC (-7.4%) exposure (Table 8). Pairwise post hoc comparisons showed this pattern held under GMF-C conditions (Figure 5B, Table 10). Exposing big skates to EMF stimuli during GMF displacement resulted in significant fixed interaction effects on their mean velocity (Table 6). During GMF-N displacement, the velocity was significantly greater due to interactions with both EMF-AC and EMF-DC (~12.5%) exposure relative to the GMF-C, EMF-0 control condition

(Figures 5A & C, Table 8). However, pairwise post hoc comparisons within GMF-N displacement indicated big skate velocity was significantly greater during EMF-AC exposure compared to EMF-DC and EMF-0, while EMF-DC and EMF-0 were not different from each other (Figure 5C, Table 10). During GMF-S displacement, exposure to EMF-AC had no effect on the mean velocity big skates but exposure to EMF-DC had a significant interaction that resulted in greater (+11.2%) mean velocity relative to the GMF-C, EMF-0 control condition (Figures 5A & D, Table 8). As with GMF-N displacement, pairwise post hoc comparisons showed that the velocity of GMF-S displaced big skates was significantly greater during EMF-AC exposure compared to EMF-DC and EMF-0 while EMF-DC and EMF-0 did not differ (Figure 5D, Table 10).

Longnose skates showed a significant main effect of EMF but no significant main effect of GMF; thus, there was no interaction between EMF and GMF (Figure 6, Table 11). The lack of a main effect on the velocity of longnose skates by GMF displacement was supported by no significant difference in their mean velocity under GMF-N (-5.5%) and GMF-S (-6.5%) displacement relative to GMF-C conditions (mean ± SE = 1.86 ± 0.29 cm/s; Figure 6A, Table 12).

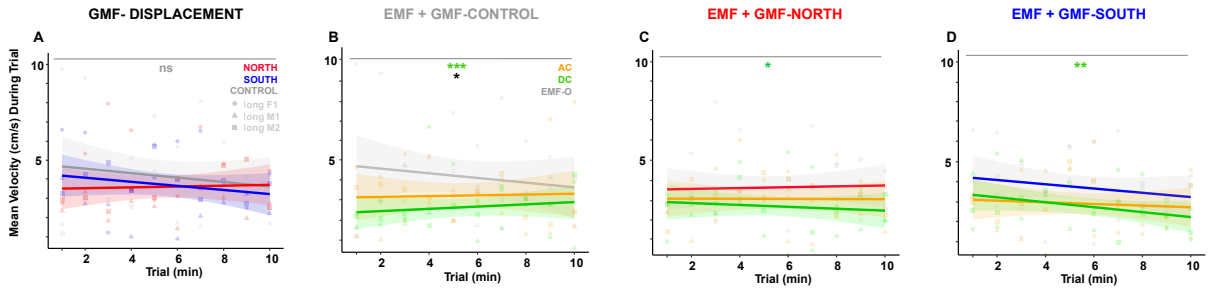


Figure 6. The mean velocity of longnose skates during exposure to GMF displacement, EMF alone, and EMF during GMF displacement. Longnose skates had: A) no significant difference in mean velocity during control (gray), GMF-N (red), or GMF-S (blue) displacement trials; B) a significantly greater mean velocity during control (gray) compared to EMF-AC (orange) trials, and during EMF-AC compared to EMF-DC (green) trials under ambient GMF (control); C) a significantly greater mean velocity during controls (red) compared to EMF-DC (green) trials under GMF-N displacement; and D) a significantly greater mean velocity during controls (blue) compared to EMF-DC (green) trials under GMF-S displacement. Control trials (red and blue lines) during (C) GMF-N and (D) GMF-S displacement are the same as those of (A) GMF displacement without EMF. Significance values: # = 0.1, * = 0.05, ** = 0.01, *** = 0.001. Red symbols compare GMF-N to GMF controls, blue symbols compare GMF-S to GMF controls, orange symbols compare EMF-0 to EMF-AC, green symbols compare EMF-0 to EMF-DC, black symbols compare EMF-AC to EMF-DC.

Likewise, there were no significant differences in the pairwise post hoc comparisons among all GMF conditions without EMF exposure. The main effect of EMF on longnose skates was a significant reduction in mean velocity during exposure to EMF-DC (-22.9%) and a large but statistically non-significant reduction in velocity during EMF-AC (-9.6%) exposure (Figure 6B, Table 12). Pairwise post hoc comparisons showed significant reductions in the mean velocity of longnose skates during EMF-DC exposure compared to EMF-AC and EMF-0 controls under each of the GMF conditions (Figure 6B-D, Table 13).

Mean Body Angle

The distribution of mean body angles for big skates under the GMF-C, EMF-0 control condition was unimodal and oriented at 17.2° (0° = north) during the final five minutes of trials (Figure 7A). During GMF-N and GMF-S displacement, the distributions became more uniform (Figures 7B, C). When exposed to EMF-AC, the distribution of mean body angles became bimodal and oriented at 338° and 155° (Figure 7D), while during EMF-DC exposure, the distribution of angles was uniform (Figure 7G). Under GMF-N displacement, the distribution was bimodal during EMF-AC (132°, 315°; Figure 7E) and unimodal during EMF-DC (298°; Figure 7H) exposure. Under GMF-S displacement, the distribution was uniform during EMF-AC (Figure 7F) and became unimodal during EMF-DC (235°; Figure 7H) exposure.

Under GMF-C and EMF-0 control conditions, the distribution of mean body angles for longnose skates was bimodal and oriented at 350° and 23° during the final five minutes of trials (Figure 8A). The distributions became unimodal during GMF-N displacement (0.4 rad; Figure 8B) and

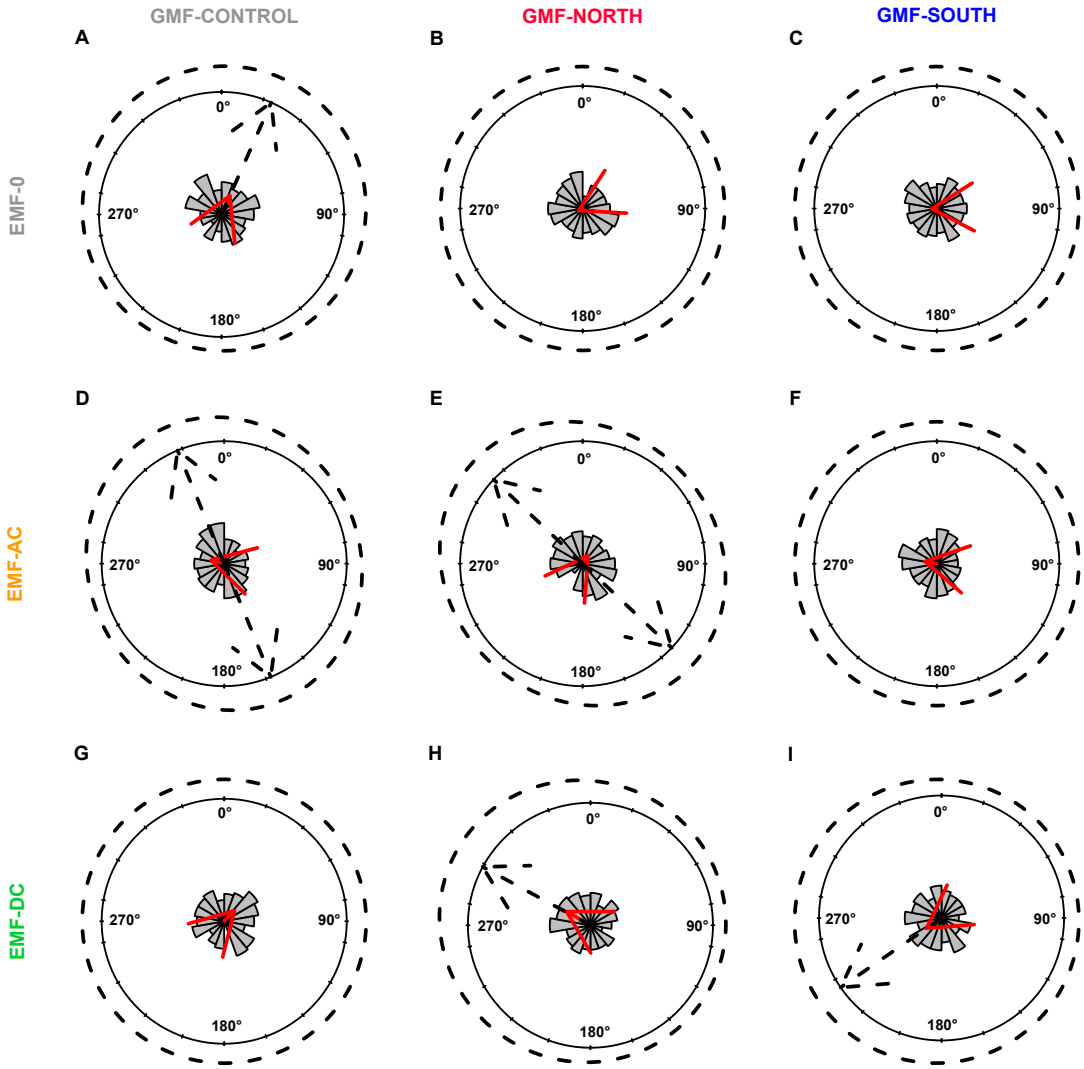


Figure 7. The mean body angle of big skates during the latter half of trials that exposed them to GMF displacement, EMF alone, and EMF during GMF displacement. Polar histograms indicate the relative number of body angle observations within 20° bins, red arrows indicate the mean angle of all the observations, black dotted lines and arrows indicate the density and mean direction, respectively, of the best model of the distribution calculated by the *cric_MLE* package in R. The distribution of the mean body angle of big skates was unimodal under A) GMF-C and EMF-0, uniform under B) GMF-N and C) GMF-S displacement, bimodal under D) EMF-AC exposure and E) GMF-N displacement and EMF-AC exposure, uniform under F) GMF-S displacement and EMF-AC exposure, uniform under G) EMF-DC exposure, and unimodal under H) GMF-N and EMF-DC exposure, and unimodal under I) GMF-S displacement and EMF-DC exposure.

bimodal during GMF-S displacement (338°, 189°; Figure 8C). When exposed to EMF-AC, the distribution of mean body angles became unimodal and oriented at 109° (Figure 8D), and during EMF-DC exposure, the distribution became uniform (Figure 8G). Under GMF-N displacement

the distribution was bimodal during EMF-AC (120°, 309°; Figure 8E) and bimodal during EMF-DC (120°, 390°; Figure 8H) exposure. Under GMF-S displacement, the distribution was uniform during EMF-AC (Figure 8F) and unimodal during EMF-DC (286°; Figure 8H) exposure.

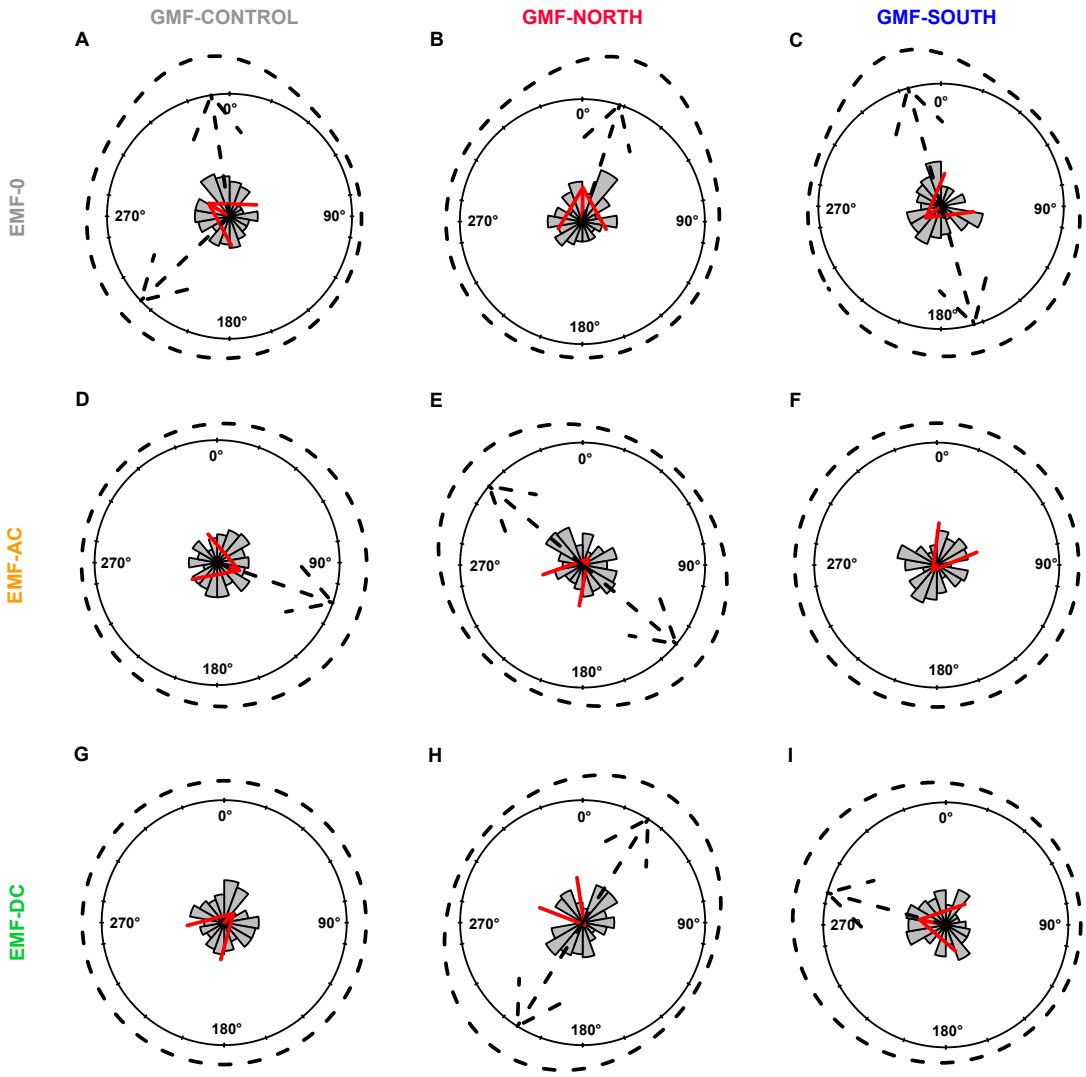


Figure 8. The mean body angle of longnose skates during the latter half of trials that exposed them to GMF displacement, EMF alone, and EMF during GMF displacement. Polar histograms indicate the relative number of body angle observations within 20° bins, red arrows indicate the mean angle of all the observations, black dotted lines and arrows indicate the density and mean direction, respectively, of the best model of the distribution calculated by the *cric_MLE* package in R. The distribution of the mean body angle of longnose skates was bimodal under A) GMF-C and EMF-0, unimodal under B) GMF-N displacement, and bimodal under C) GMF-S displacement, unimodal under D) EMF-AC exposure, bimodal under E) GMF-N displacement and EMF-AC exposure, uniform under F) GMF-S displacement and EMF-AC exposure, uniform under G) EMF-DC exposure, and bimodal under H) GMF-N and EMF-DC exposure, and unimodal under I) GMF-S displacement and EMF-DC exposure.

The *sin* Θ (variation on east-west axis) of big skates showed significant fixed main effects of GMF displacement, EMF stimuli, their interaction (Table 14) and several pairwise comparisons (Tables 15-17). However, the *cos* Θ data (variation on north-south axis) for big skates showed no fixed effects for GMF, EMF, or their interaction and will not be discussed further. The main effect of GMF displacement on the mean body angle of big skates relative to GMF-C conditions (mean ± SE = 0.05 ± 0.02 rad; Figure SI-3A), was a significant reduction in *sin* Θ during GMF-N (-4.6°) and GMF-S (-4.1°) displacement (Table 15). Pairwise post hoc comparisons showed that under EMF-0 conditions, the main effect of GMF-N on the mean body angle of big skates was due to a significant difference in *sin* Θ (Table 16). The main effect of EMF stimuli on the mean body angle of big skates compared to EMF-0 controls (mean ± SE = 2.9° ± 1.1°; Figure SI-3B) was a significant reduction in *sin* Θ during EMF-AC (-5.2°) but not EMF-DC (-1.7°) exposure (Table 15). Pairwise post hoc comparisons indicated that the main effect of EMF-AC relative to EMF-0 on the mean body angle of big skates under ambient GMF-C conditions was due to a significant difference in *sin* Θ (Table 17). Big skates exposed to EMF stimuli during GMF displacement had a significant fixed interaction effect on mean body angle (Table 14) due to an increase in *sin* Θ of GMF-N displaced skates exposed to EMF-AC (+6.3°, Table 15). Pairwise comparisons elucidated that this increase was because the *sin* Θ for GMF-N displaced big skates exposed to EMF-AC was significantly greater than during EMF-DC exposure but less than during EMF-0 conditions (Table 17). Under GMF-S displacement, there was no significant effect of EMF stimuli (Table 17). During EMF-AC exposure, there was no significant effect of GMF displacement, but during EMF-DC exposure *sin* Θ was significantly reduced under GMF-N displacement compared to GMF-S and GMF-C conditions (Table 16). Therefore, the main effect of GMF-S was due to a significant reduction in *sin* Θ between GMF-N and GMF-S displaced big skates exposed to EMF-DC (Table 16).

The *sin* Θ of the mean body angle of longnose skates showed no significant fixed main effects of GMF displacement, EMF stimuli, their interaction and will not be discussed further. The *cos* Θ data for longnose skates showed a significant fixed main effect of EMF; however there was no effect ofGMF or their interaction (Table 18). There was a main effect of EMF on the mean body angle of longnose skates due to a significant change in *cos* Θ during EMF-AC exposure (-8.2°) relative to EMF-0 controls (mean ± SE = 5.7 ± 2.9°; Table 19). Pairwise comparisons showed that this effect was primarily due to a significant difference between EMF-AC and EMF-0 controls during ambient GMF-C conditions, and a large, but not statistically significant, difference between EMF-AC and EMF-DC during GMF-S displacement (Table 20). There was no effect of EMF during GMF-N displacement.

DISCUSSION

We tracked the spatial use, mean velocity, and mean body angle of skates within the experimental tank to quantify their behavioral response to the electro- and geomagnetic stimuli. Although there was no consistent response across species for each metric, we found that big and longnose skates could detect and respond to GMF displacement stimuli (H1, H2), the EMFs emitted by energized AC and DC cables (H3, H4), and exposure to EMF during GMF displacement altered their GMF-evoked behavioral responses (H5). The significant changes in spatial use, mean velocity, and mean body angle are summarized into general trends for each species in Figure 9.

In response to GMF-N and GMF-S displacement without EMF, neither species of skate significantly altered their preference for the northern or southern hemispherical ROI relative to GMF-C conditions (Figure 9), which does not support our prediction that displaced skates would occupy different portions of the tank.

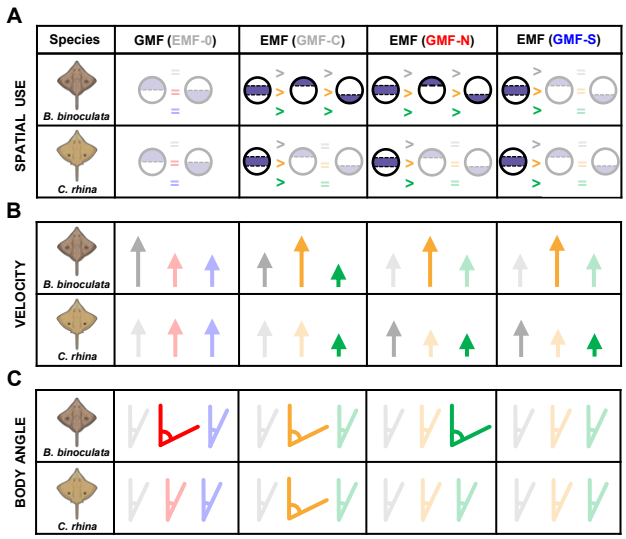


Figure 9. Summary of the main results for the effect of EMF exposure on GMF displaced skates. Icon color indicates EMF exposure (gray = no EMF, orange = EMF-AC, green = EMF-DC), or GMF displacement (gray = GMF-C, red = GMF-N, blue = GMF-S) conditions. A) Circular icons indicate the use of the experimental arena divided into halves (GMF + (EMF-0)) or thirds (EMF + (GMF-C, GMF-N, GMF-S)) and mathematical symbols indicate equal use (=) or greater use (>) of a given region relative to another. The relative size of arrow and angle icons indicates the relative magnitude of the B) mean velocity or C) change in mean body angle. Solid icons indicate treatments that differed statistically ($p \leq 0.05$) and translucent icons indicate those that did not differ within a given condition.

As the GMF displacement stimuli within the arena were uniform; GMF sensitive animals would be required to physically move to reorient their sensory array, sample the altered GMF cues from a variety of perspectives, and better get their bearings (Wiltschko and Wiltschko 2007). As such, our findings of no alteration of spatial use of hemispherical ROI during GMF-N and GMF-S displacement relative to GMF-C conditions might indicate that the constraints imposed by our available facilities and acquiring skates of sufficiently small size impacted the spatial and directional responses of skates. Relatively large skates confined to swimming in a mesocosm might not be reliable indicators of GMF-based orientation and navigation behavior as reported by previous authors using vertebrates of smaller size (Lohmann et al. 1996, Naisbett-Jones et al. 2017, Putman. et al. 2014), including juvenile bonnethead sharks (Keller et al. 2021) with a total length commensurate to that of our skates.

Under all GMF and EMF conditions, both species of skates preferred the central ROI over the northern and southern thirds. The lack of change in spatial use across all EMF conditions indicates that relatively strong EMF (~10x GMF intensity) from AC and DC cables did not repel skates away from the EMF source in our mesocosms. However, since the skates preferred the central ROI even under control conditions, we cannot discern if the skates were attracted to the cable as has been demonstrated with little skates that spent more time near an energized DC cable (Hutchinson et al. 2020), the juvenile Lake sturgeon (*A. fulvescens*, Bevelhiemer et al. 2013) and spotted catsharks (*Scyliorhinus canicula*, Gill et al. 2009) that spent more time near AC cables, and was hypothesized as a possibility in green sturgeon (*Acipenser medirostris*, Wyman et al. 2023) and juvenile Chinook salmon (Wyman et al. 2018) that took more time to transit an area with an energized DC cable. Interestingly, under GMF-C and GMF-N big skates preferred the northern third ROI over the southern third ROI under all EMF conditions, while under GMF-S displacement, there was no preference for the northern third over the southern third. Therefore, big skates did slightly shift their spatial distribution with the direction of GMF-S displacement, likely demonstrating the detection of, and response to, GMF displacement stimuli.

In our constrained mesocosm, the orientation of an organism may be a better metric for scoring directional preference rather than the spatial use of the arena (e.g. Minkoff et al. 2020, Naisbett-Jones et al. 2020). However, while under each of the GMF treatments the distribution of mean body angles for longnose skates varied with EMF treatment, the pattern of relative change in mean body angle of our skates exposed to GMF and EMF showed no clear signal. While the body angle responses did not support our hypothesis of north displacement motivating skates to orient southward (and vice versa), together these results might indicate a generalized change in body angle of skates to EMF stimuli that becomes reduced during GMF displacement conditions.

The velocity responses to altered geo- and electro-magnetic fields had a clearer signal than spatial use and/or angle responses (Figure 9). Under GMF-N and GMF-S displacement big skates reduced their mean velocity relative to GMF-C. This pattern was also observed in longnose skates, but neither change was statistically significant perhaps because, under control conditions, longnose skates were less active overall (V_{mean} = 3.2 cm/s ± 0.1 SE) compared to big skates (V_{mean} = 10.1 cm/s ± 0.1 SE). Across all GMF conditions, big skates had the greatest velocity when exposed to EMF-AC. During GMF-C, big skate velocity was lowest under EMF-DC, but there was no difference between EMF-0 and EMF-DC conditions during GMF-N and GMF-S displacement. Across all GMF conditions, longnose skates had the lowest velocity when exposed to EMF-DC. During GMF-C, longnose skate velocity was lower than both EMF-0 and EMF-AC; however, under GMF-N and GMF-S displacement, there was no difference between AC and DC. Thus, for both big and longnose skates, the patterns of change in mean velocity observed under GMF-C were altered in the same fashion under GMF-N and GMF-S displacement. Similar reduction of activity in the presence of an energized DC cable has been observed in the field in little skates (Hutchison et al. 2020), juvenile Chinook salmon (Wyman et al. 2018) and green sturgeon (Wyman et al. 2023).

If the ampullae of Lorenzini are the primary detectors of magnetic stimuli (Adrianov et al. 1974, 1984, Akoev et al. 1976, Brown and Ilyinsky 1978), then their attunement to the onset and offset of stimuli might make them better suited to detecting and mediating responses to fluctuating AC compared to DC magnetic fields, especially for less active species such as longnose skates. We originally hypothesized that the low frequency components of our EMF-AC stimuli might make the induced electric fields attractive to skates because they might be perceived somewhat similar to the fluctuating weak bioelectric fields emitted by the ion exchange and sinusoidal ventilation mechanism of respiring prey (Bedore et al. 2013). However, the relatively high intensity of the fluctuating EMF-AC used in this study (± 500 μT) might have made the induced

electric stimuli less biologically relevant and more overwhelming to big skates, which could explain why they maintaining an elevated swimming velocity and had greater changes in the east-west component of their mean body angle distribution under EMF-AC across all GMF conditions. This possibility aligns with the more aversive responses among the greater repertoire of Lake sturgeon responses (e.g., pectoral fin flare, reduced velocity, sudden stops, rapid turns, escapes, body spasms) to strong (> ± 1000 μT) EMF-AC stimulus exposure (Bevelhimer et al. 2013).

Conversely, the temporal stability of constant EMF-DC could have allowed big and longnose skates, once they reduced their velocity, to detect minute GMF displacement stimuli and elicit directed changes in body angle to the west, as seen in the shifts toward unimodal and bimodal angular distributions. For species located along the western coastline of the United States, this might indicate an offshore movement into deeper water. If so, this could imply that big skates under the “navigational pressure” induced by GMF-N displacement could respond more predictably, or intentionally, when they encounter EMF-DC cables compared to EMF-AC which might elicit more of an escape response (higher velocity, greater deviation in angle distribution from control) that could be inshore or offshore.

The reduced velocity and more uniform angular distribution responses of big skates to constant stimuli (i.e., GMF-N, GMF-S, and EMF-DC) and longnose skates to EMF-DC align with the reduced velocity and increased turning behavior seen in little skates exposed to the constant EMF from energized DC cables in the field and could indicate searching behavior (Hutchison et al. 2020). Prior studies have shown that gray bamboo sharks can categorize visual stimuli into groups (Fuss et al. 2014, 2017; Schluessel et al. 2014). Because elasmobranchs have similar neural substrates, it is likely that batoid skates and rays can also categorize environmental stimuli, such as magnetic fields, into groups. If so, then it is possible that big skates recognized

the constant GMF and EMF-DC stimuli as similar, perceived them as “magnetic displacement,” and responded to both magnetic stimuli by slowing down and increasing their turning behavior to sample ambient magnetic fields and get their bearings (e.g., Lohmann et al. 1996, Putman. et al. 2014).

Conclusions

Our data show that big and longnose skates respond to electro- and geomagnetic stimuli in species-specific ways. Our data suggest that if free swimming big skates encountered anthropogenic EMF-DC in the field, they might exhibit a greater change in behavior compared to EMF-AC, similar to the investigation behavior (reduced velocity, increased turning) seen in little skates (Hutchison et al. 2020). Conversely, if longnose skates encountered EMF in the field, they might elicit distinct behavioral responses depending on if they encountered EMF-AC in their home range (GMF-C; increased turning), or EMF-DC (reduced velocity) during a migration (GMF-N or GMF-S). Such a distinction might arise if a migrating, or GMF displaced, longnose skate was using the relatively minute spatial changes in the temporally constant GMF as a navigational cue. Thus, attunement to GMF stimuli could prime the skate to perceive and respond more readily to constant EMF-DC stimuli such that they further reduce their velocity to avoid disorientation and maintain their desired bearing. In this case, the constant EMF-DC stimulus might not swamp the electro- or magneto- sensory system of skates nor prevent them from detecting the relatively small signal of GMF displacement. Conversely, the large fluctuating EMF-AC stimuli could overstimulate the sensory systems of skates and prompt them to vacate the general area with an elevated velocity. Exposing free ranging elasmobranchs in large tanks to various levels of EMF-AC and EMF-DC could determine the minimum thresholds and detection distances of stimuli, and generate EMF dose-response curves that describe how behavioral responses vary with dosage. Future studies that aim to answer these questions could build on our results and further our understanding of how magnetic stimuli are detected by

various species, and which species would be the most suitable sentinels to elucidate the impacts of anthropogenic EMF on marine fauna.

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COMPETING INTERESTS

The authors declare no competing interests.

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DATA AVAILABILITY

All datasets, R scripts with detailed analyses, and code are available on the Open Science Framework repository, https://osf.io/azydm/

SUPPLEMENTAL INFORMATION

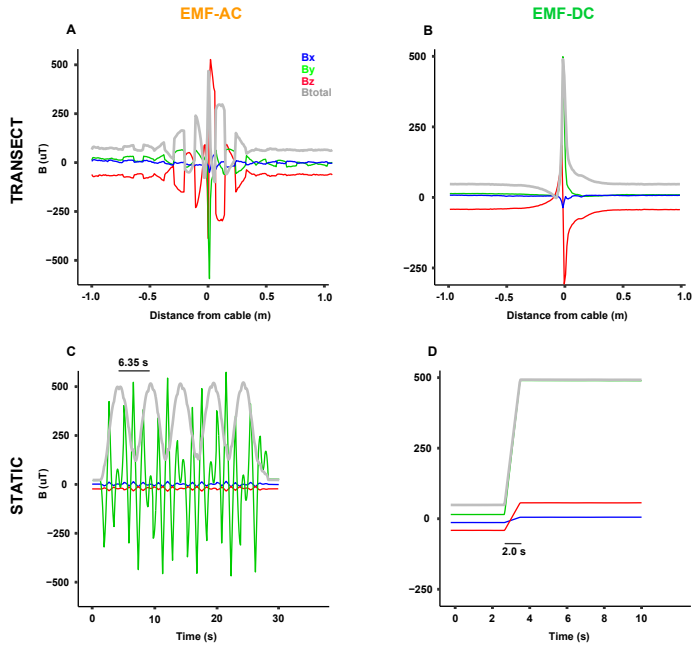

Figure SI-1. The EMF emitted by AC cables varied with space and time, whereas the EMF from DC cables varied with space. Transects of a tri-axial magnetometer from south (left) to north (right) along the bottom of the experimental tank (2 m diameter) depict how EMF noise stimuli from (a) fluctuating AC and (b) constant DC electric cables vary with distance from the mock subsea cable located directly beneath the tank along the central west-east axis (0 m). Continuous magnetometer readings from directly over the mock cable shows the total strength of EMF stimuli from c) 60Hz AC electrical current fluctuates at an overall frequency of 0.157 Hz, whereas the EMF from d) DC electrical current has a 2.0 s onset to reach a constant value. The total EMF stimulus strength (gray lines; B_{total}) was the vector sum of the X (blue line; B_x), Y (green line: B_y), and Z (red line: B_z) components. The total strength of EMF stimuli were 10X (AC = ± 510 μT; DC = + 510 μT) that of the ambient geomagnetic field (51 μT). All magnetometer readings were recorded at 10 Hz with the +X-axis oriented to the east, the +Y-axis to the north, and +Z-axis was upward.

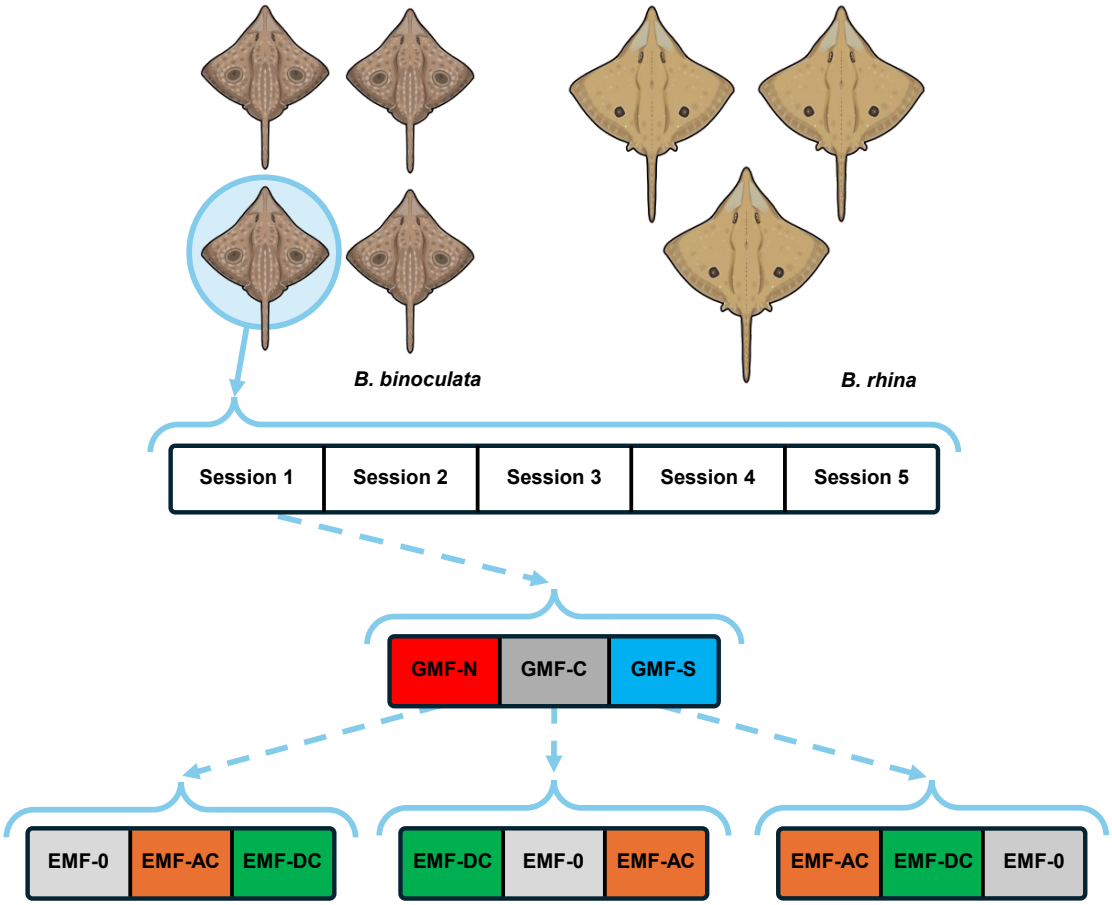

Figure SI-2. Nested block (repeated measures) experimental design of skates exposed to GMF and EMF stimuli. During one session, each skate underwent nine different magnetic treatments that consisted of three electromagnetic exposure treatments (e.g., EMF-0 (control, no EMF), EMF-AC (from an AC cable), and EMF-DC (from a DC cable)), under three different geomagnetic conditions (e.g., GMF-C (control, ambient GMF), GMF-N (GMF displacement to a northern geographic location), and GMF-S (GMF displacement to a southern geographic location)). Sessions were repeated five times for a total of 45 magnetic exposures per skate.

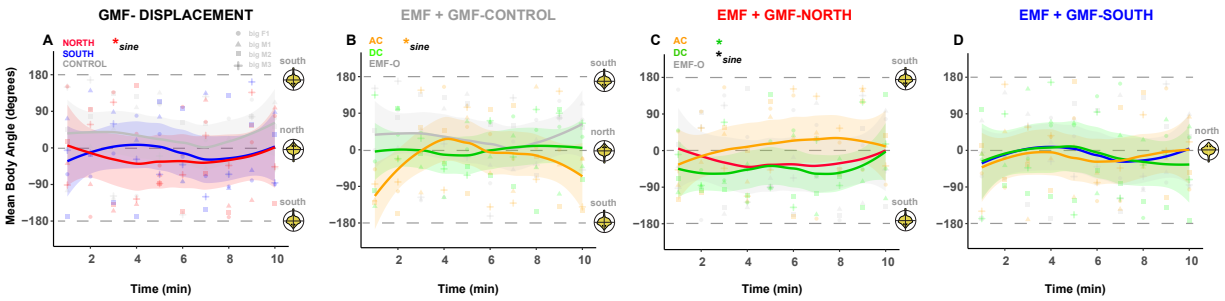

Figure SI-3 The mean body angle of big skates during exposure to GMF displacement, EMF alone, and EMF during GMF displacement. Big skates had: A) a significantly different *sine* of their mean body angle (i.e., opposite / hypotenuse) during control trials (gray) compared to GMF-N (red) but not GMF-S (blue) displacement trials; B) a significantly different *sine* of their mean body angle during control trials (gray) compared to EMF-AC (orange) but not EMF-DC (green) trials under ambient GMF (control); C) a significantly different *sine* of their mean body angle during EMF-DC (green) trials compared to control trials (gray) and EMF-AC (orange) trials under GMF-N displacement; and D) no significant difference in mean body angle among EMF-AC trials (orange), EMF-DC (green), and control (red) trials under GMF-S displacement. There were no significant differences in the *cosine* of their mean body angle under any conditions. Control trials (red and blue lines) during (C) GMF-N and (D) GMF-S displacement are the same as those of (A) GMF displacement without EMF. Note that circular data are depicted in a linear fashion, thus the top and bottom dotted lines (i.e., "south") of each panel indicate where the data wraps from top to bottom. Significance values: # = 0.1, * = 0.05, ** = 0.01, *** = 0.001. Red symbols compare GMF-N to GMF controls, blue symbols compare GMF-S to GMF controls, orange symbols compare EMF-0 to EMF-AC, green symbols compare EMF-0 to EMF-DC, black symbols compare EMF-AC to EMF-DC.

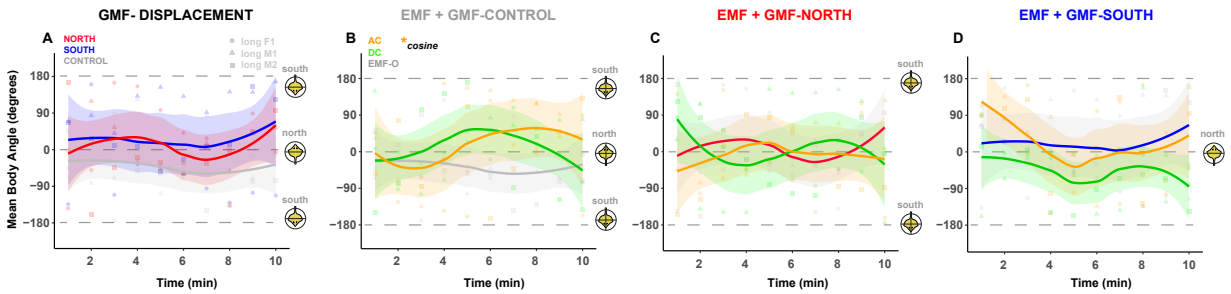

Figure SI-4. The mean body angle of longnose skates during exposure to GMF displacement, EMF alone, and EMF during GMF displacement. Longnose skates had: A) no significant difference in mean body angle during control trials (gray) compared to GMF-N (red) or GMF-S (blue) displacement trials; B) a significantly different co*sine* of their mean body angle (i.e., adjacent / hypotenuse) during control trials (gray) compared to EMF-AC (orange) but not EMF-DC (green) trials under ambient GMF (control); C) no significant difference in mean body angle among EMF-AC trials (orange), EMF-DC (green), and control (red) trials under GMF-N displacement; and D) no significant difference in mean body angle among EMF-AC trials (orange), EMF-DC (green), and control (red) trials under GMF-S displacement. There were no significant differences in the *sine* of their mean body angle under any conditions. Control trials (red and blue lines) during (C) GMF-N and (D) GMF-S displacement are the same as those of (A) GMF displacement without EMF. Note that circular data are depicted in a linear fashion, thus the top and bottom dotted lines (i.e., "south") of each panel indicate where the data wraps from top to bottom. Significance values: # = 0.1, * = 0.05, ** = 0.01, *** = 0.001. Red symbols compare GMF-N to GMF controls, blue symbols compare GMF-S to GMF controls, orange symbols compare EMF-0 to EMF-AC, green symbols compare EMF-0 to EMF-DC, black symbols compare EMF-AC to EMF-DC.

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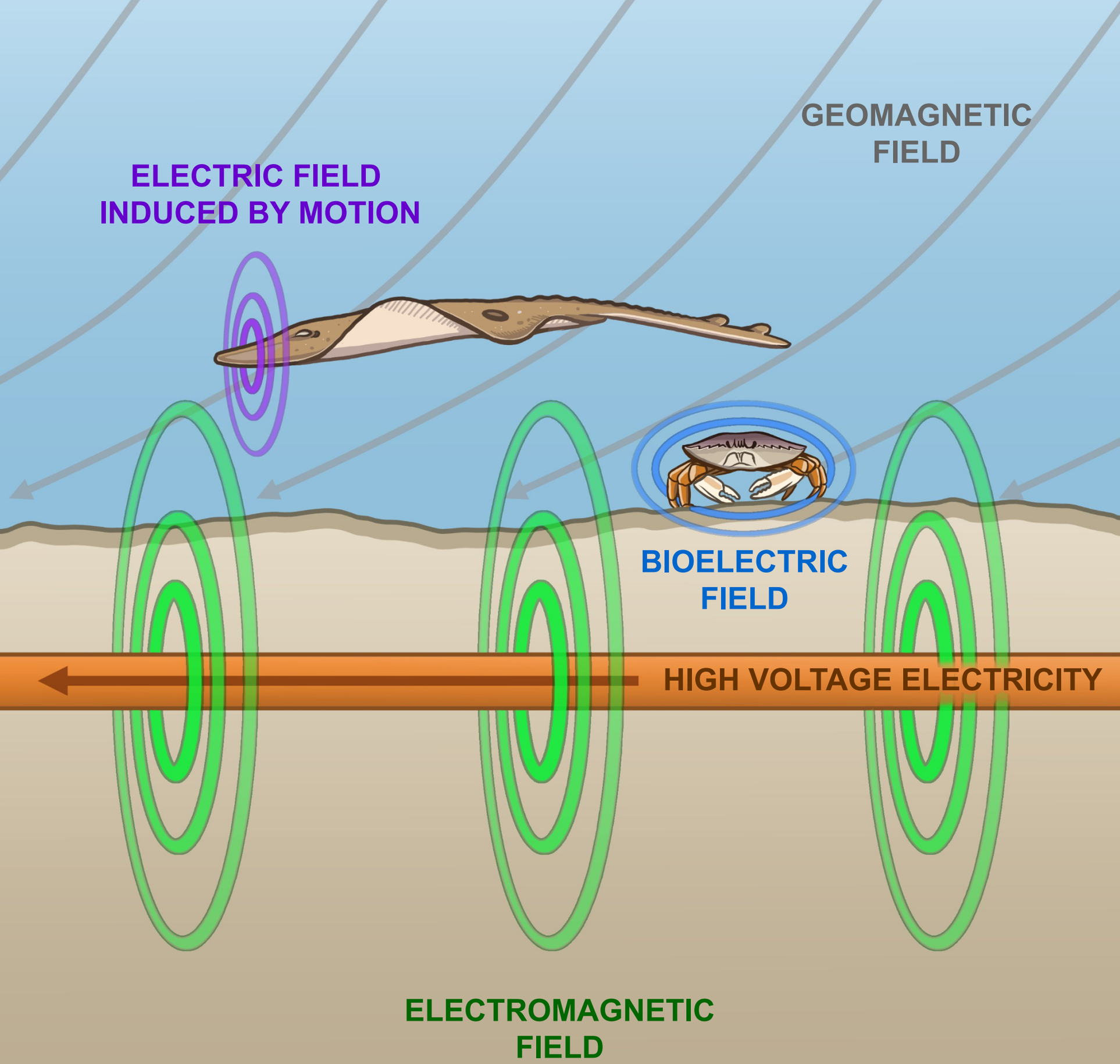

GEOMAGNETIC FIELD
ELECTRIC FIELD INDUCED BY MOTION
BIOELECTRIC FIELD
HIGH VOLTAGE ELECTRICITY
ELECTROMAGNETIC FIELD

FIGURE 1.

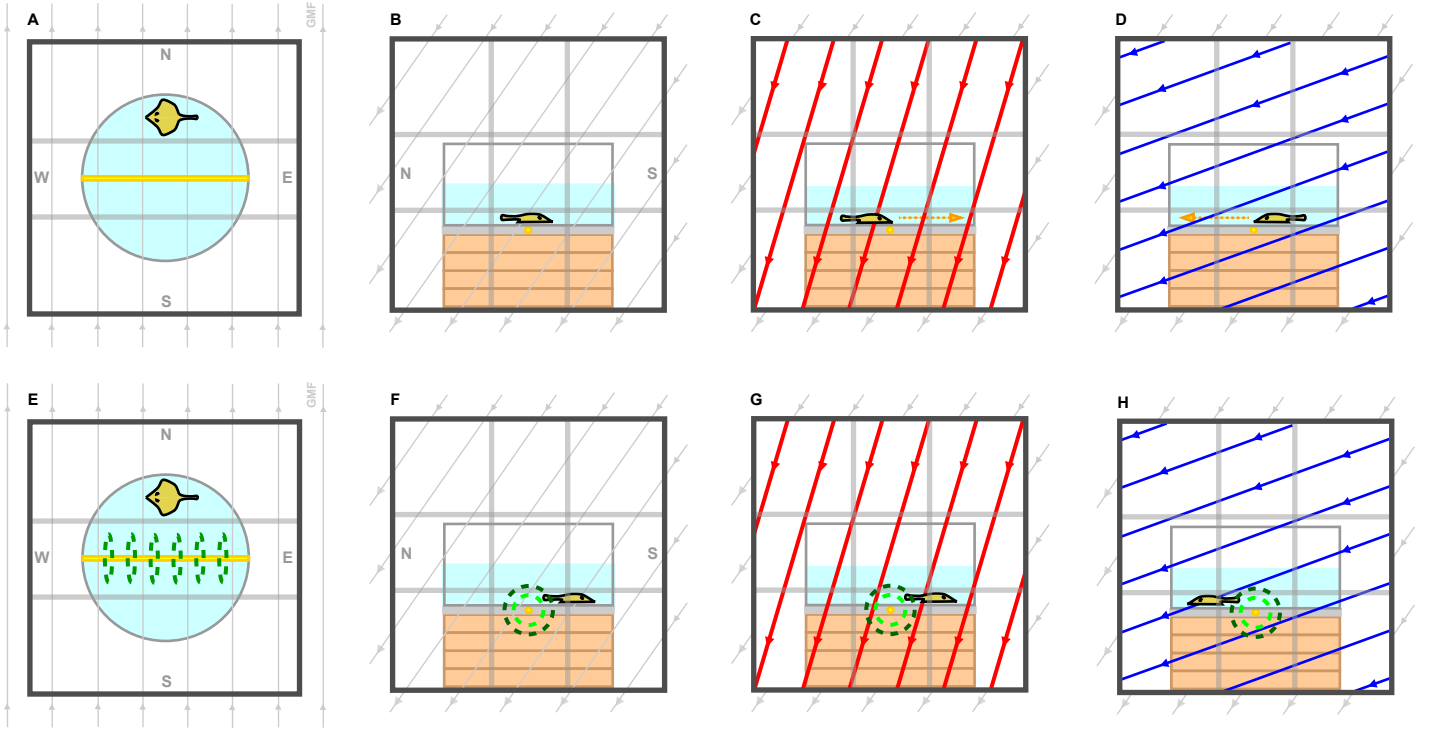


FIGURE 2.

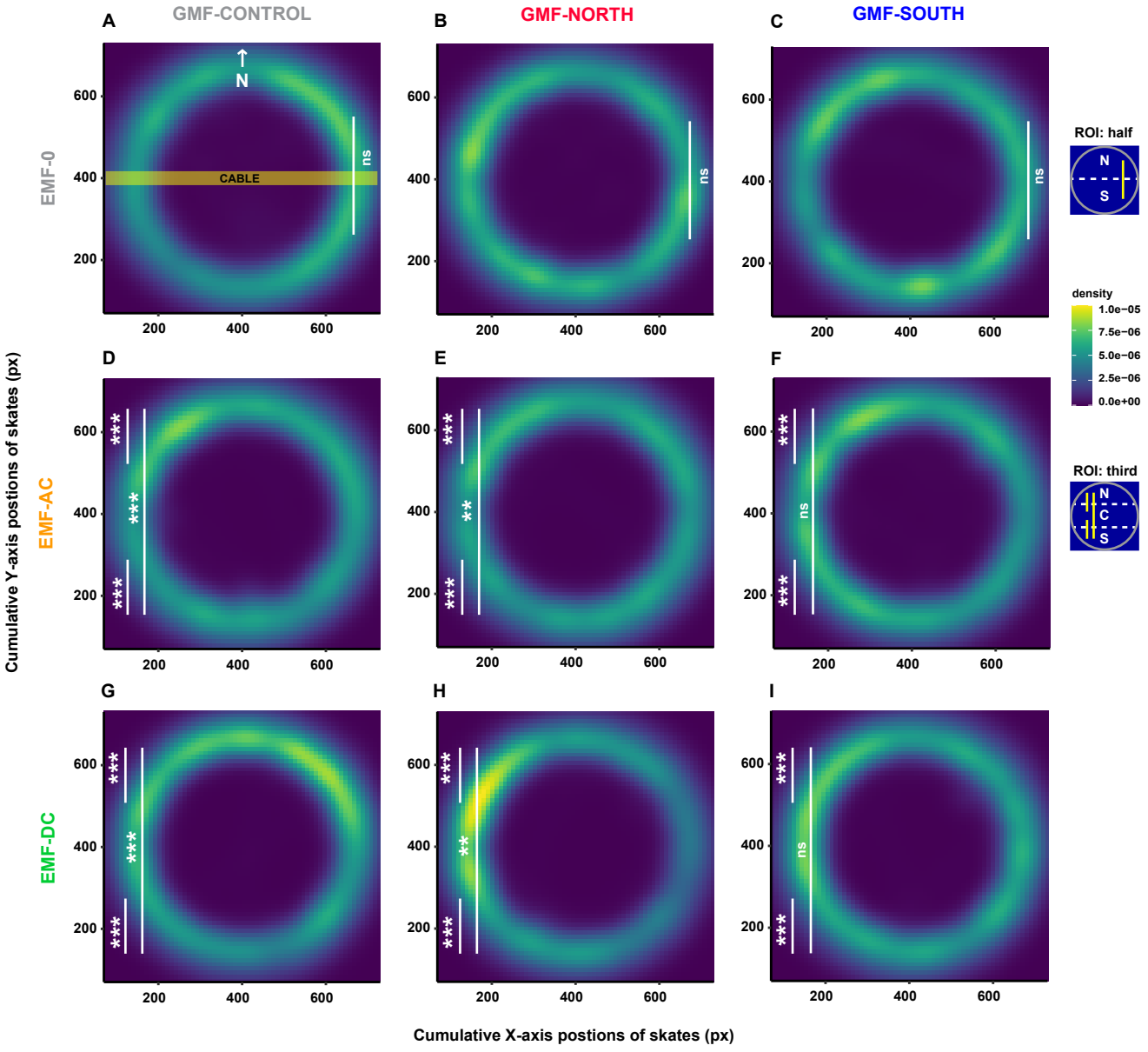
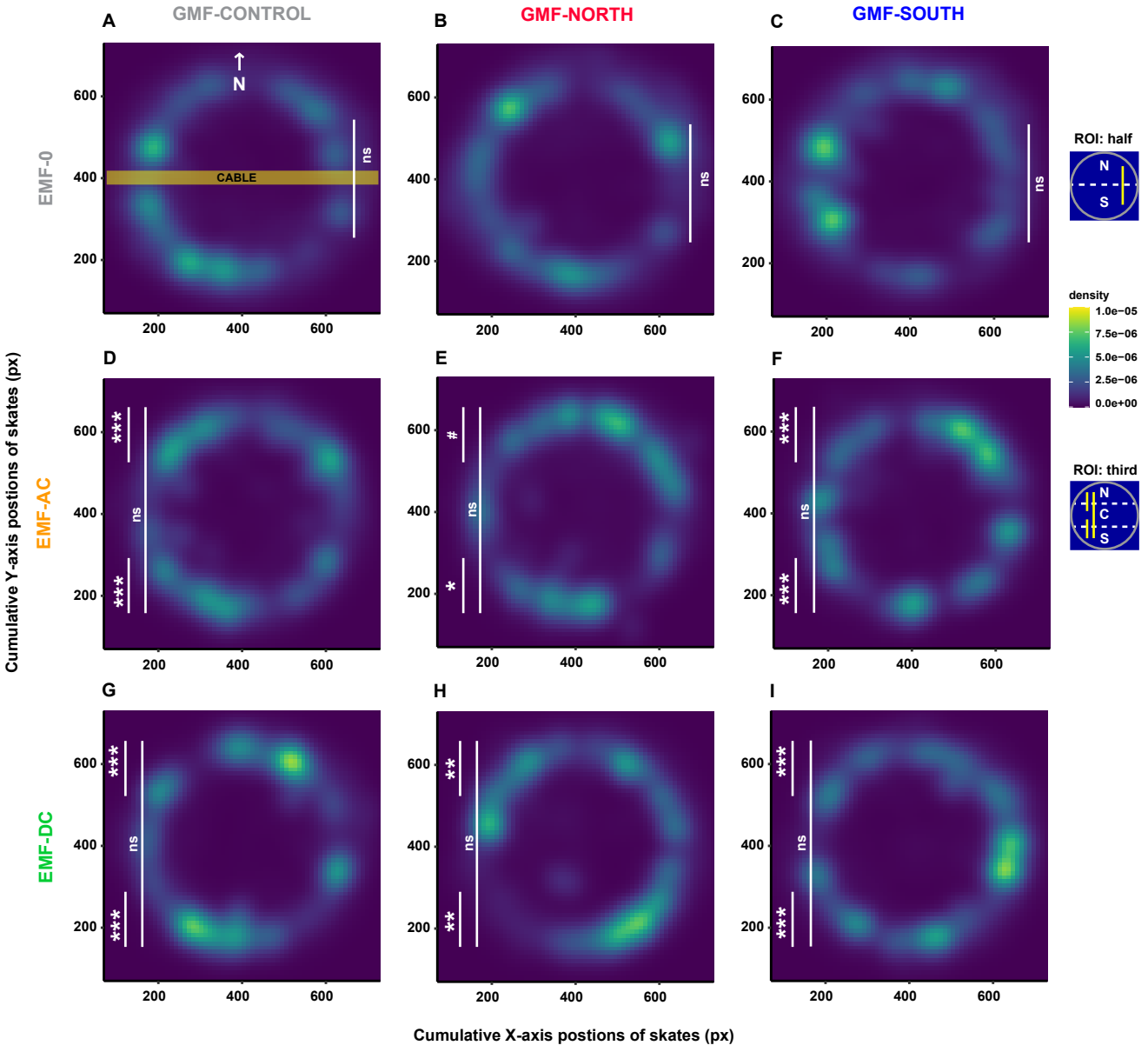

A
GMF-CONTROL
B
GMF-NORTH
C
GMF-SOUTH
EMF-0
EMF-AC
EMF-DC
N
CABLE
ns
***
**
ROI: half
N
S
ROI: third
N
C
S
density
1.0e−05
7.5e−06
5.0e−06
2.5e−06
0.0e+00
Cumulative Y-axis postions of skates (px)
Cumulative X-axis postions of skates (px)
200
400
600

FIGURE 3.


A
GMF-CONTROL
B
GMF-NORTH
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GMF-SOUTH
EMF-0
EMF-AC
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CABLE
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ROI: half
N
S
ROI: third
N
C
S
density
1.0e−05
7.5e−06
5.0e−06
2.5e−06
0.0e+00
Cumulative Y-axis postions of skates (px)
Cumulative X-axis postions of skates (px)
200
400
600

FIGURE 4.

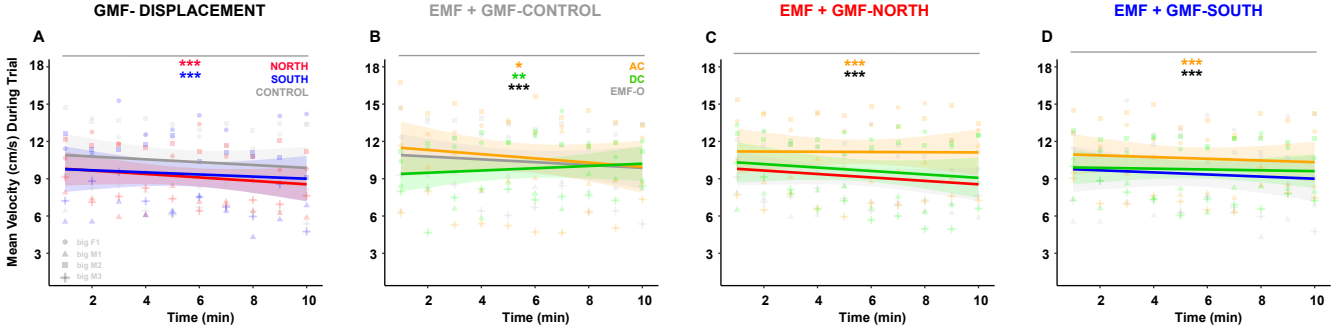

GMF- DISPLACEMENT
EMF + GMF-CONTROL
EMF + GMF-NORTH
EMF + GMF-SOUTH
A
B
C
D
Mean Velocity (cm/s) During Trial
Time (min)
NORTH
SOUTH
CONTROL
AC
DC
EMF-O
big F1
big M1
big M2
big M3

FIGURE 5.

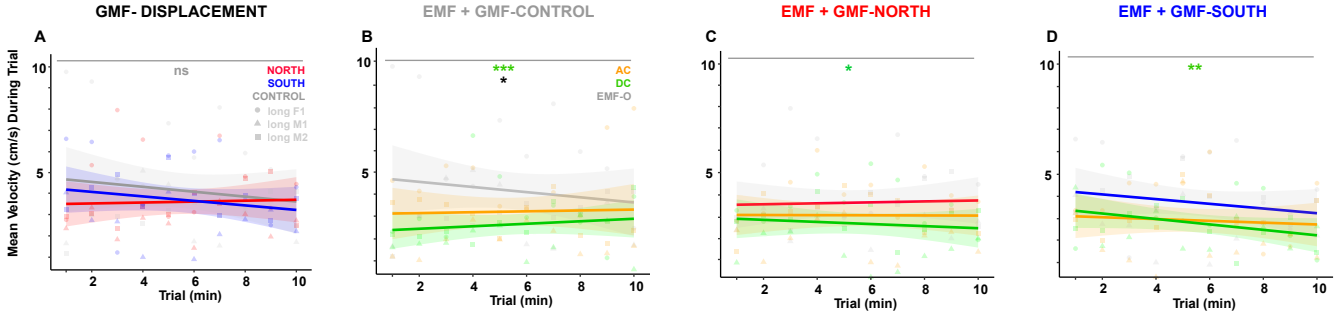
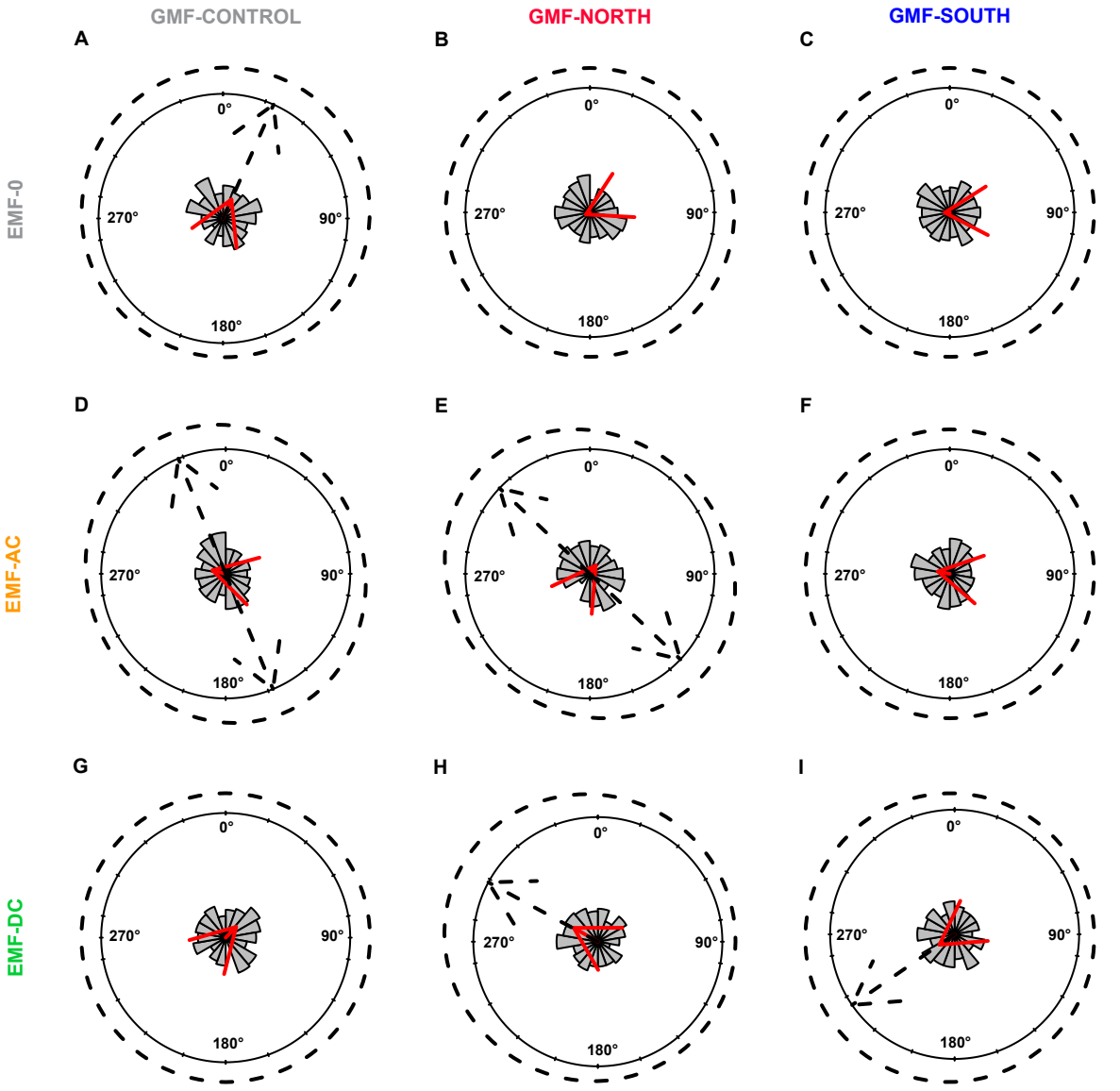

GMF- DISPLACEMENT
EMF + GMF-CONTROL
EMF + GMF-NORTH
EMF + GMF-SOUTH
A
B
C
D
Mean Velocity (cm/s) During Trial
Trial (min)
ns
NORTH
SOUTH
CONTROL
long F1
long M1
long M2
***
*
AC
DC
EMF-O
*
**

FIGURE 6.


GMF-CONTROL
GMF-NORTH
GMF-SOUTH
EMF-0
EMF-AC
EMF-DC
A
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E
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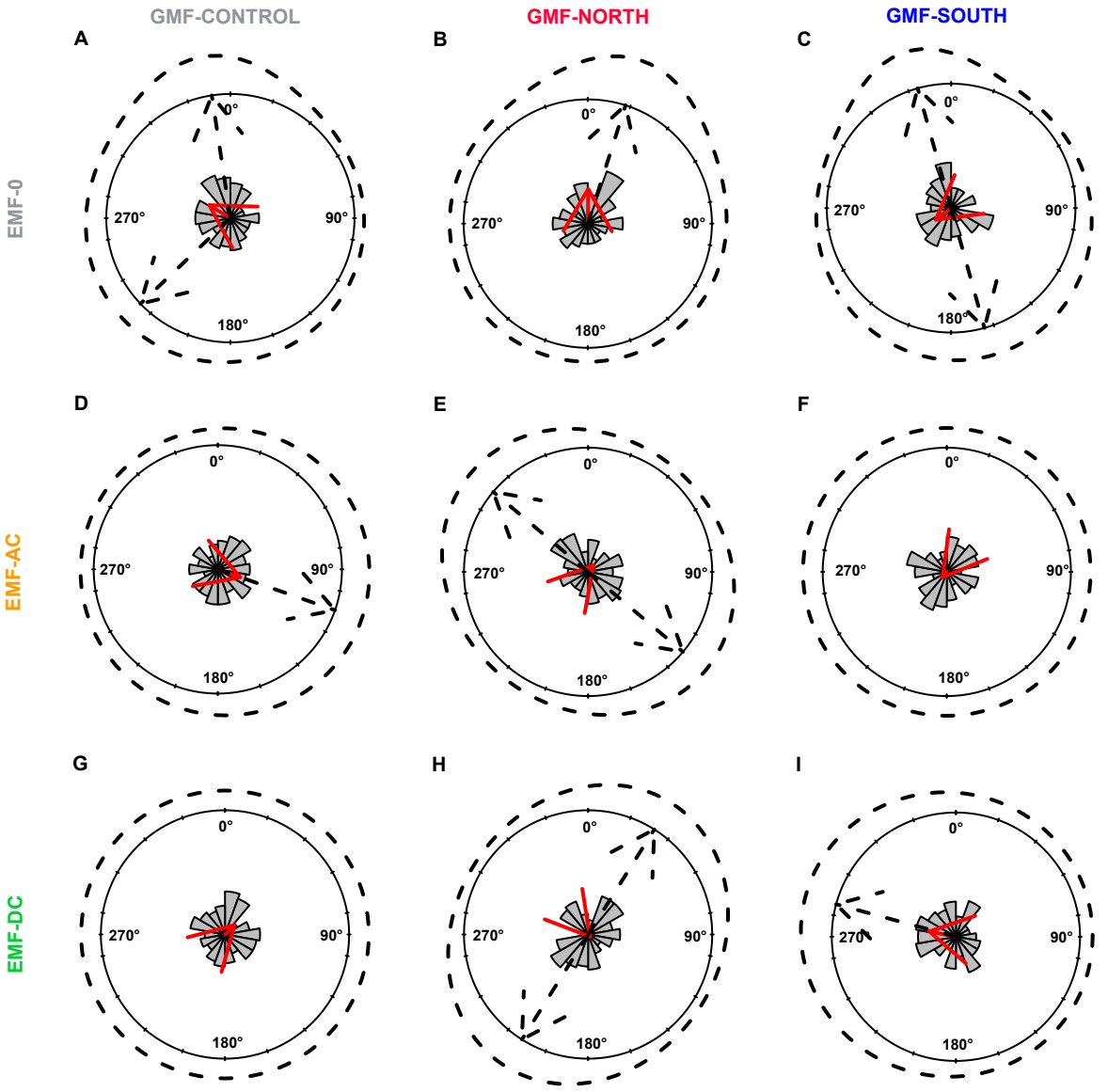
I
0°
90°
180°
270°

FIGURE 7.


GMF-CONTROL
GMF-NORTH
GMF-SOUTH
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E
F
G
H
I
0°
90°
180°
270°

FIGURE 8.

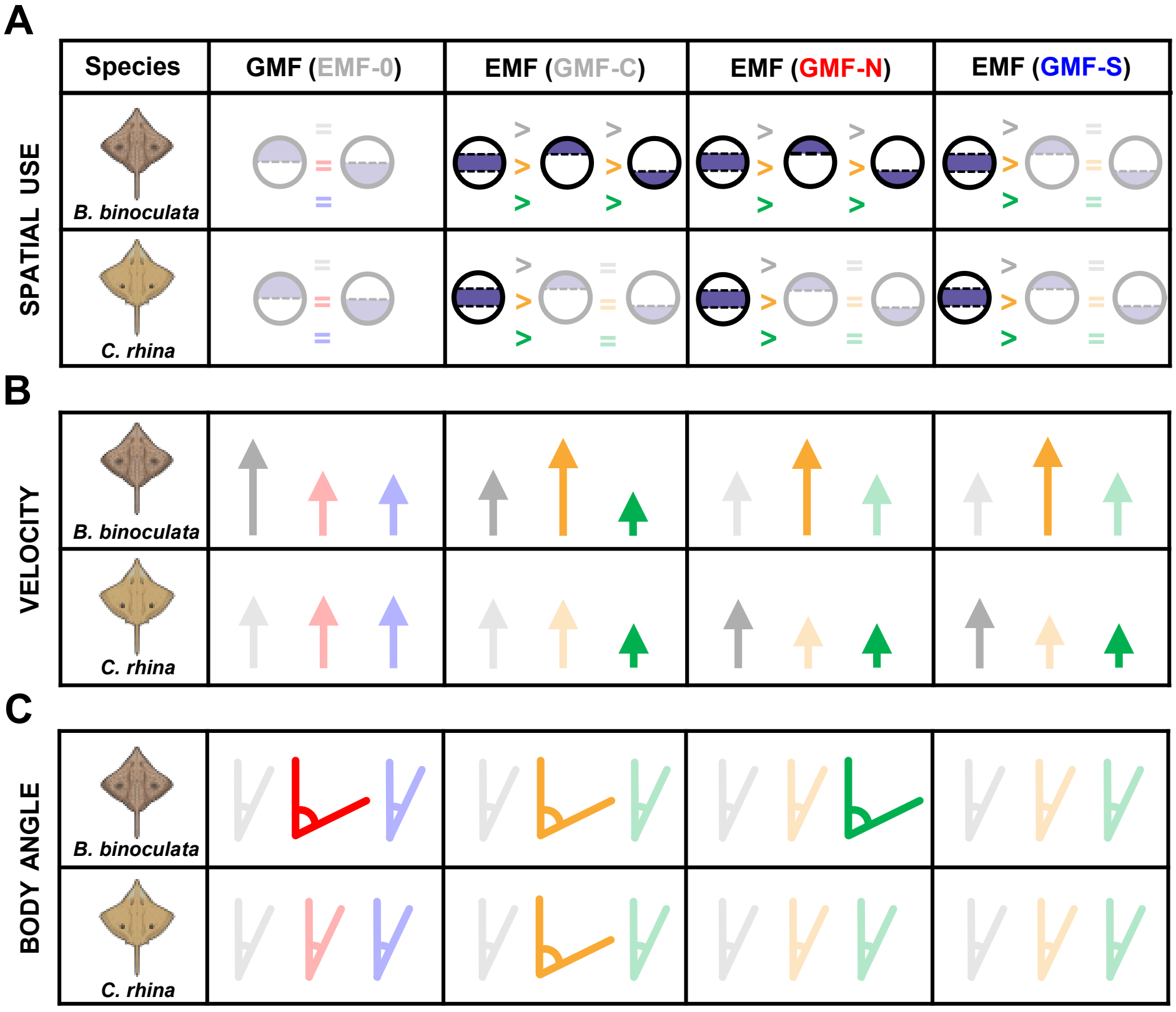
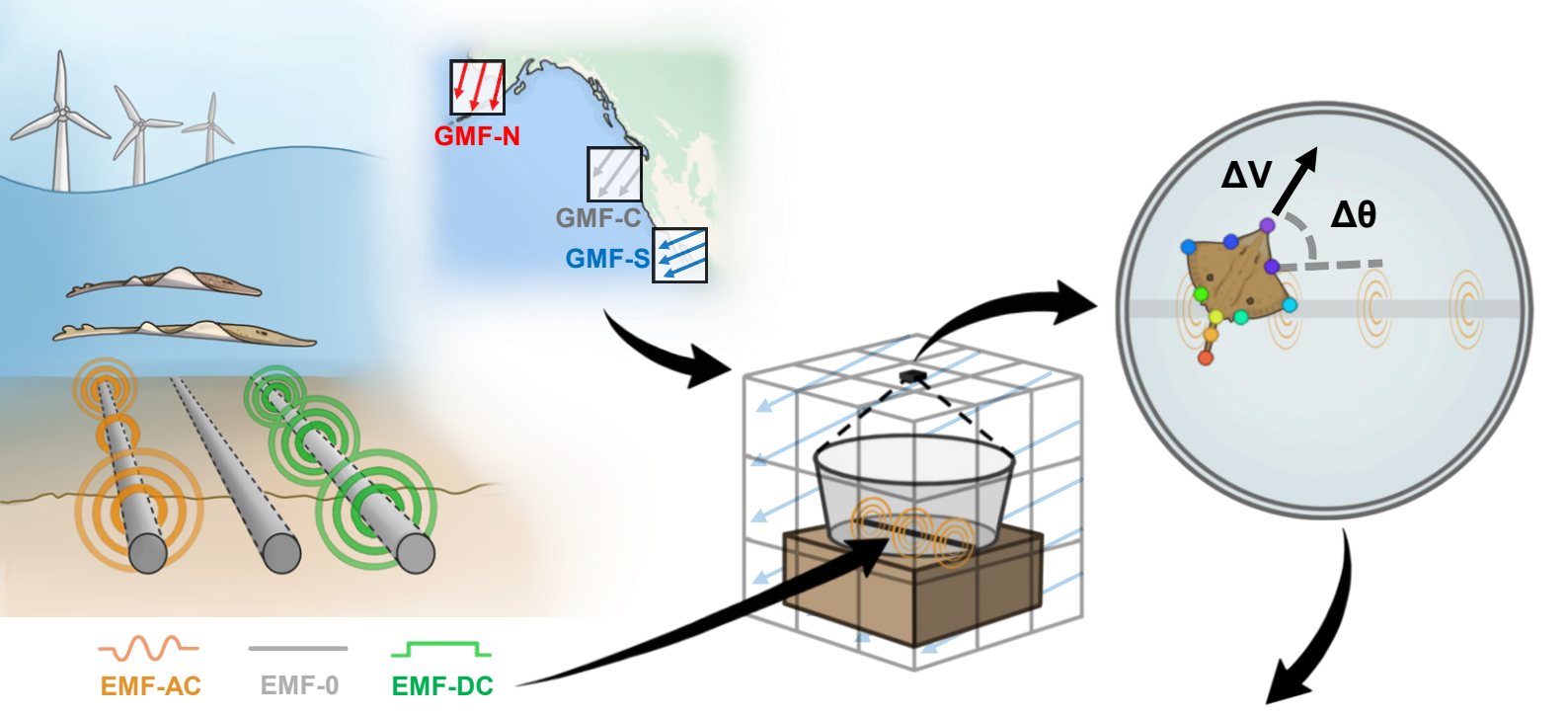
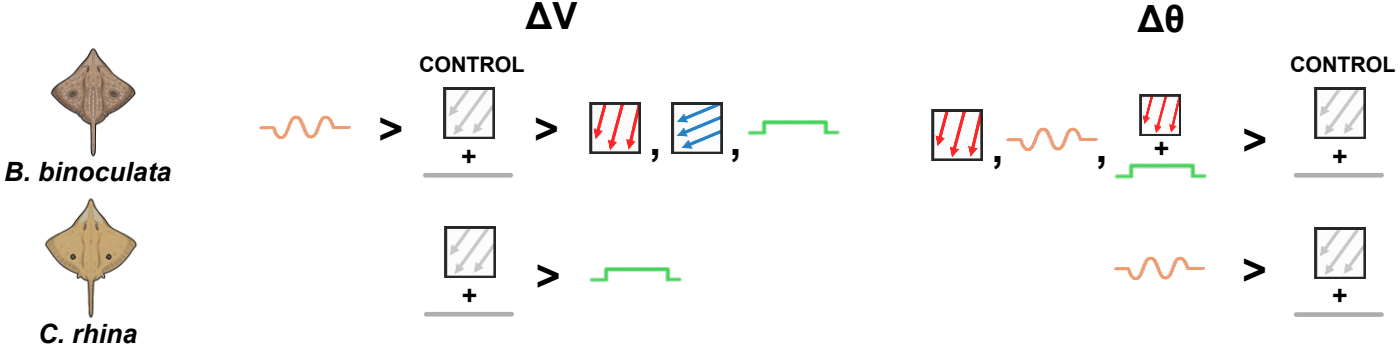

A
Species
GMF (EMF-0)
EMF (GMF-C)
EMF (GMF-N)
EMF (GMF-S)
SPATIAL USE
B. binoculata
C. rhina
B
VELOCITY
B. binoculata
C. rhina
C
BODY ANGLE
B. binoculata
C. rhina

FIGURE 9.


GMF-N
GMF-C
GMF-S
ΔV
Δθ
EMF-AC
EMF-0
EMF-DC

RESULTS


ΔV
Δθ
CONTROL
CONTROL
B. binoculata
C. rhina