Title

Electric Oceans: Impacts of EMFs on Marine Ecosystems

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Impacts of EMFs on marine ecosystems

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Introduction

Energy is the fundamental currency of the universe, driving the mechanisms of natural and artificial systems alike. From the molecular bonds in our bodies to the colossal fusion reactions within stars, every process hinges on the availability and ability of energy transmission.

The capacity to harness energy has allowed human civilization to develop in the way we know and understand it today. From harnessing fire to the construction of aqueducts to the monumental leap of the Industrial Revolution. These innovations are the essence of humanity's historical strides in developing our current societies.

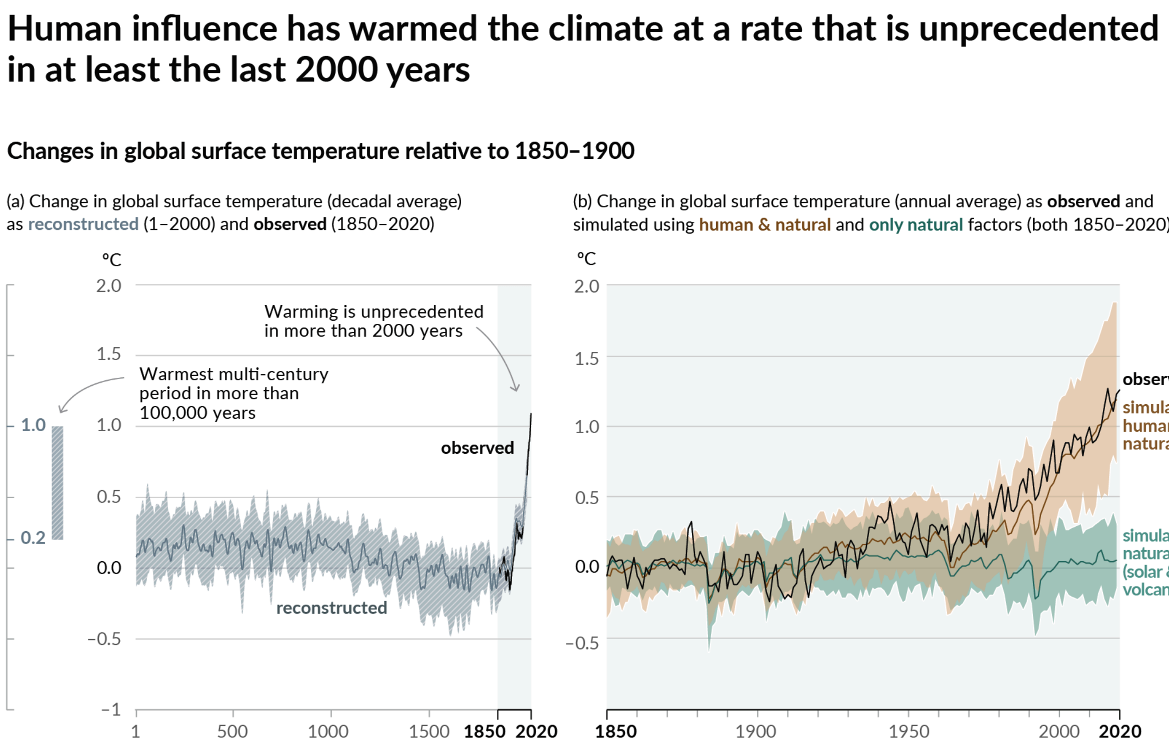
However, just as every currency transaction incurs fees, our quest for energy comes at a cost. Our fossil fuel-powered world, while spurring unprecedented growth has also introduced not a few environmental costs.

As we seek more efficient and sustainable ways to harness energy, we must recognize and address the challenges these solutions bring, balancing innovation with environmental stewardship.

Climate and Energy

The extensive use of fossil fuels has transformed the world in every conceivable way. Fossil fuels have been instrumental in driving industrial growth, powering economies, and improving the quality of life for billions of people. They have enabled unprecedented advancements in technology, transportation, and infrastructure, fostering global connectivity and economic development.

On the other side, the release of significant quantities of greenhouse gases, primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), into the atmosphere as a result, has had a profound impact on our climate. As these gases trap more heat, global temperatures continue to rise (IPCC, 2023).



(IPCC, 2023)[1]

Addressing climate change requires a nuanced approach that acknowledges the seriousness of the issue while promoting practical solutions. It is crucial to recognize that climate change is not merely an environmental concern but a complex challenge that intersects with economic stability, public health, and global equity. Effective climate action requires a nuanced understanding that balances immediate needs with long-term sustainability (IPCC, 2023), ensuring that strategies are inclusive, equitable, and conducive to fostering resilience in both natural and human systems (Krane, 2017).

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[1] **"History of global temperature change and causes of recent warming**
Panel (a) Changes in global surface temperature reconstructed from paleoclimate archives (solid grey line, years 1–2000) **and from direct observations**(solid black line, 1850–2020), both relative to 1850–1900 and decadally averaged. The vertical bar on the left shows the estimated temperature (*very likely* range) during the warmest multi-century period in at least the last 100,000 years, which occurred around 6500 years ago during the current interglacial period (Holocene). The Last Interglacial, around 125,000 years ago, is the next most recent candidate for a period of higher temperature. These past warm periods were caused by slow (multi-millennial) orbital variations. The grey shading with white diagonal lines shows the *very likely* ranges for the temperature reconstructions.
Panel (b) Changes in global surface temperature over the past 170 years (black line) relative to 1850–1900 and annually averaged, compared to Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model simulations [...] of the temperature response to both human and natural drivers (brown) and to only natural drivers (solar and volcanic activity, green). Solid coloured lines show the multi-model average, and coloured shades show the *very likely* range of simulations" https://www.ipcc.ch/report/ar6/wg1/figures/summary-for-policymakers/figure-spm-1/ (IPCC, 2023)

Alternative Energies

Relying heavily on fossil fuels as a single energy source not only exacerbates environmental degradation but also undermines energy security. A diversified energy portfolio would not only support environmental goals but also promote economic stability, as heavy dependence on a single energy source makes energy markets susceptible to geopolitical tensions and price volatility (Streimikiene et al., 2023).

Renewable energy technologies can reduce the economic risks associated with fossil fuel price fluctuations and supply uncertainties. Policies promoting energy diversification and renewable energy adoption could contribute to a stable and secure energy supply. Diversifying the energy grid with renewable sources like wind, and solar, would provide buffers against such volatility and reduce the risk of supply disruptions (Rabbi et al., 2022).

However, while the integration of these technologies into the energy grid would alleviate some of the burdens placed on and by fossil fuels, they come with their own set of challenges (IEA, 2019) (Holechek et al., 2022).

Eolic Energy

Eolic energy, from the Greek "Aeolus", keeper of the winds, is the generation of electricity through the use of wind turbines. By harnessing the kinetic energy of wind, turbines convert the wind's natural power into mechanical energy, which is then transformed into electrical energy.

Wind Farms

Wind turbines are placed either on land or out at sea. Wind farms located on land, have been instrumental in testing the viability of wind energy. They consist of multiple wind turbines strategically placed to capture the maximum amount of wind energy. However, they are not without challenges.

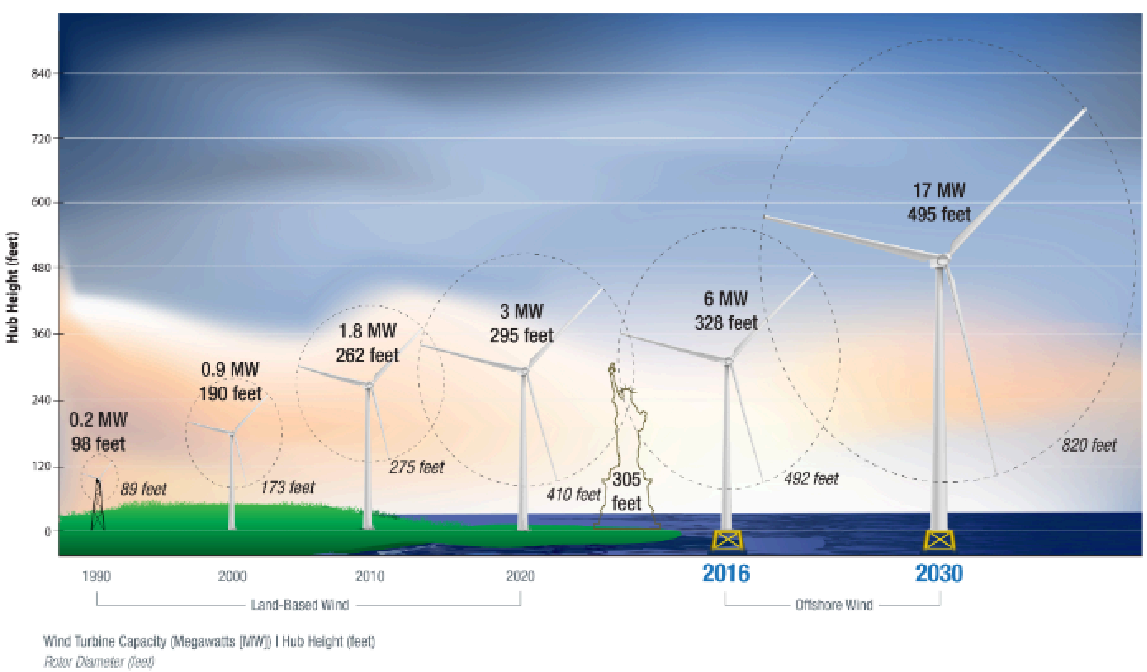
The size and placement of land-based wind farms are often constrained by geographical and environmental factors. Areas with sufficient wind speeds, where wind turbines need to be erected, are not distributed uniformly across all regions. Additionally, the presence of mountains, hills, and other obstacles can disrupt wind flow, reducing the efficiency of energy capture (Tercan, 2021).

The visual and noise impact of land-based wind farms has occasionally led to opposition from local communities (WINDExchange, 2021). The need for large tracts of land can also result in competition with other land uses, such as agriculture and residential development. While land-based wind farms have proven effective in many locations, these limitations highlight the need for exploring other avenues to harness wind energy more efficiently.

Offshore wind farms

Offshore wind farms extend the principles of eolic energy into marine environments, leveraging the stronger and more consistent winds found over open water. Offshore wind farms offer several advantages over their onshore counterparts, including reduced visual impact, less competition for land use, and the potential for larger turbine installations due to the absence of physical barriers (Chen & Su, 2022).

Offshore wind farms are typically situated on continental shelves, where water depths are relatively shallow, facilitating the installation of turbine foundations. Advances in floating turbine technology are expanding the feasibility of offshore wind projects into deeper waters, further increasing the available areas for development. The strategic placement of offshore wind farms can enhance grid stability and energy supply diversity, contributing to a more robust and flexible energy system (Ryndzionek & Sienkiewicz, 2020).



(Musial et al., 2023)

Offshore wind turbines are significantly larger than those on land, with some blades extending over 100 meters in length, allowing them to capture more wind energy. They are also taller reaching higher altitudes where there's not only less turbulence but the speed of the wind significantly increases, and the larger the blades are the more energy they're able to capture.

Offshore wind farms offer the possibility of having larger blades without the constriction transportation imposes on them.

The economic aspects of wind energy are also notable. Technological advancements have significantly reduced the cost of wind power. According to the U.S. Department of Energy, the cost of wind energy has decreased by over 90% since the 1980s, making it increasingly competitive with traditional energy sources (Musial et al., 2023). These advancements include improvements in turbine technology, economies of scale, and enhanced efficiency in wind energy production.

Moreover, the wind energy sector generates employment opportunities across various stages, from manufacturing and installation to maintenance and research (Aldieri et al., 2019). This economic stimulus is particularly beneficial for both rural and coastal communities, where wind farms are often situated.

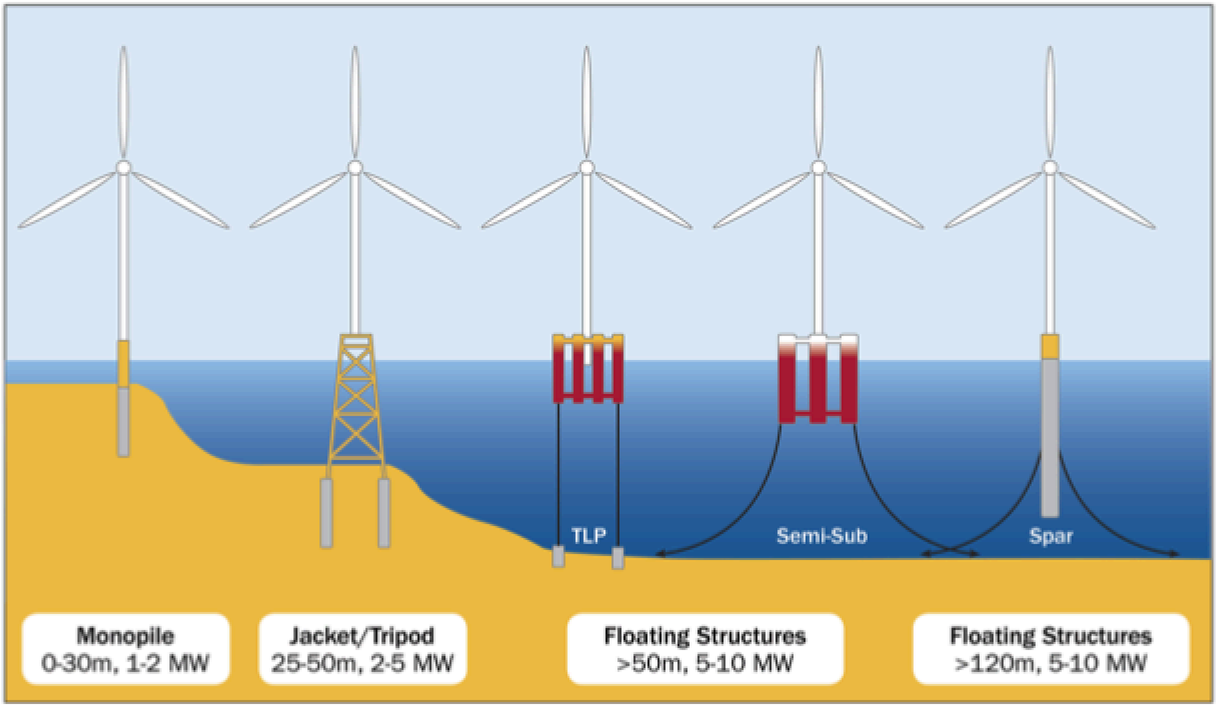
The integration of offshore wind farms into the broader energy landscape represents a forward-thinking approach to addressing both energy and climate challenges. By harnessing the abundant and renewable energy of offshore winds, we can significantly reduce greenhouse gas emissions, bolster energy security, and support the transition to a sustainable energy future.

Impacts on Marine Life

The installation and operation of offshore wind farms raise concerns about their potential impacts on marine ecosystems.

The construction process,[2] which includes seabed preparation and pile-driving, generates significant noise and vibrations underwater. These disturbances can have adverse effects on sound-sensitive marine species such as cetaceans (whales and dolphins) and certain fish, potentially altering their behavior and migration patterns or causing physical harm (Middel & Verones, 2017). Additionally, construction can increase water turbidity and potentially release pollutants, which can degrade habitats used for feeding and breeding by various marine organisms.

[2] The oceans comprise about 70% of Earth's surface, however, most offshore turbines are currently limited to shallow waters from about 30m to 60m. This depth can be increased but securing turbines to the seabed beyond this point becomes challenging. Floating platforms enable access to stronger winds in deeper waters compared to traditional fixed offshore turbines. However, this comes with not few engineering challenges. Turbines are large, rotating devices, and although floating platforms have been extensively used in the oil and gas sectors, this technology cannot always be directly applied to wind energy generation (UKRI, n.d.).



(Bailey et al., 2014)[3]

During their operational phase, offshore wind farms may continue to impact marine life.

The physical structures of the turbines may pose a risk of entanglement for marine animals, particularly for larger species such as whales, which can become caught in associated cabling and mooring lines (NRDC, 2022).

The interaction between turbine EMF's (Electromagnetic fields) produced by the transmission cables and natural GMFs (Geomagnetic fields) may pose a set of invisible yet significant challenges to marine life as well.

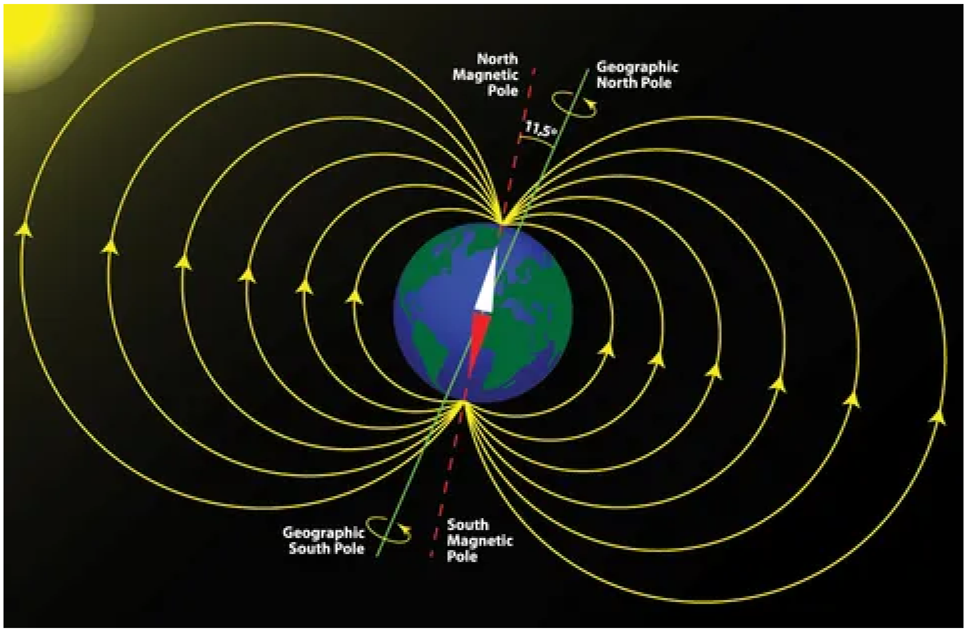
GMF & EMF

Life arose in Earth's magnetic field.

Earth's magnetic field, or geomagnetic field (GMF), is a protective shield generated by the movement of molten iron within the Earth's outer core. This field extends from the highest points in the atmosphere to the deepest ocean trenches. Its structure, mirrors that of a bar magnet's dipole field, with lines originating from the southern hemisphere and looping around the planet

[3] Offshore wind turbines anchoring systems.

to re-enter the northern hemisphere (K. J. Lohmann et al., 2022). As such, it displays predictable variations around the world, for instance, the total intensity or strength of the field is typically strongest near the poles and weakest near the equator. (K. J. Lohmann et al., 2022).



(Oskin, 2012)

At its highest altitude, the GMF meets the solar wind, a stream of charged particles emanating from the Sun. This interaction forms the magnetosphere, which deflects most of the solar wind's harmful and potentially deadly charged particles that would otherwise strip away the atmosphere and expose the planet to intense radiation.

Life originated within the Earth's magnetic field and wouldn’t be possible otherwise.

Navigation

Besides protecting the Earth from cosmic sun rays, the GMF field provides useful information for orientation and navigation. Humans have utilized the geomagnetic field for directional navigation for centuries (Wiltschko & Wiltschko, 2022). Explorers and navigators have been able to determine their direction and orient themselves by interpreting these magnetic fields. Their vector property forms the foundation of the compass, allowing it to align itself with the magnetic field lines pointing toward the magnetic poles. This simple yet effective tool has been fundamental in aiding maritime and overland travel, allowing for the exploration of unknown territories and facilitating trade and communication across distant lands throughout history.

Given the geomagnetic field's constant presence on Earth – and in a remarkable demonstration of biological adaptation–, it's no surprise that many animal species have also developed the ability to utilize the Earth's GMF for navigation (Albert et al., 2020).

Creatures such as migratory birds, sea turtles, and even some types of fish can detect subtle variations in the magnetic field to orient themselves and navigate across vast distances during their migratory journeys. This magnetic sense enables them to follow consistent routes year after year, often across continents and oceans, to reach breeding sites, feeding grounds, and wintering areas. This innate ability to interact with the geomagnetic field is a key factor in the survival and reproductive success of these migratory species.

Animal Navigation

The concept that animals could use Earth's magnetic field as a geographic map was first suggested over a century ago by Viguier in 1882 (Viguier, 1882), but it did not gain acceptance initially due to a lack of evidence that animals could detect magnetic fields. It wasn't until nearly a century later that the idea resurfaced with more detail, particularly in studies involving homing pigeons, and even then, it faced significant skepticism.

A breakthrough in understanding came with experiments on sea turtle hatchlings by Lohmann and Lohmann in the mid-1990s (K. Lohmann & Lohmann, 1994). They were able to prove that loggerhead turtles from Florida could use the Earth's magnetic field to maintain their position within the North Atlantic Subtropical Gyre, a crucial ability for their survival during the early years of their life.

By manipulating the magnetic inclination and intensity in controlled experiments, they found that turtles could detect and respond to these variations using the magnetic field as a navigational map. This research was pivotal, showing for the first time that animals could use magnetic inclination and intensity as coordinates in a magnetic map. Further studies with salamanders reinforced these findings, proving that other species could also use magnetic parameters to determine their geographical position, thereby establishing the feasibility and broader application of magnetic maps in animal navigation (K. J. Lohmann et al., 2022).

Since then it is generally accepted that animals can access two different types of information from Earth's magnetic field. Some species possess an inner *magnetic compass*, that enables them to establish and follow specific routes, such as heading north or south. Others can use the Earth's magnetic field for positional information, helping them determine their geographic location, an inner *magnetic map* (K. J. Lohmann et al., 2022).

The navigational use of magnetic information and its behavioral and ecological implications are relatively well-documented. However, our understanding of magnetoreception's physiological and neurobiological aspects remains limited (Wiltschko & Wiltschko, 2006). There are, however, many studies suggesting the use of specialized organs, especially among certain species of fish known as elasmobranchs.

Elasmobranchs

Elasmobranchs are a subclass of cartilaginous fish which includes sharks, rays, and skates. These fascinating creatures are characterized by their cartilaginous skeletons, multiple gill slits, and unique sensory systems, such as electroreception and a highly developed sense of smell. Elasmobranchs play crucial roles in marine ecosystems as apex predators and have adapted to diverse environments, from shallow coastal waters to the deep sea. Their unique biology and behaviors make them a key focus of marine research and conservation efforts.

This subclass of animals has the remarkable ability to detect electromagnetic fields through specialized sensory organs known as the *ampullae of Lorenzini*. These organs, located primarily around the head, consist of jelly-filled canals that connect to electroreceptive cells. This system allows elasmobranchs to sense the weak electric fields generated by the muscle contractions of prey, and navigate by detecting the Earth's magnetic field. The ampullae of Lorenzini provide these marine predators with a significant advantage in locating prey, navigating (Anderson et al., 2017) complex environments, and interacting within their species (Bedore & Kajiura, 2013).

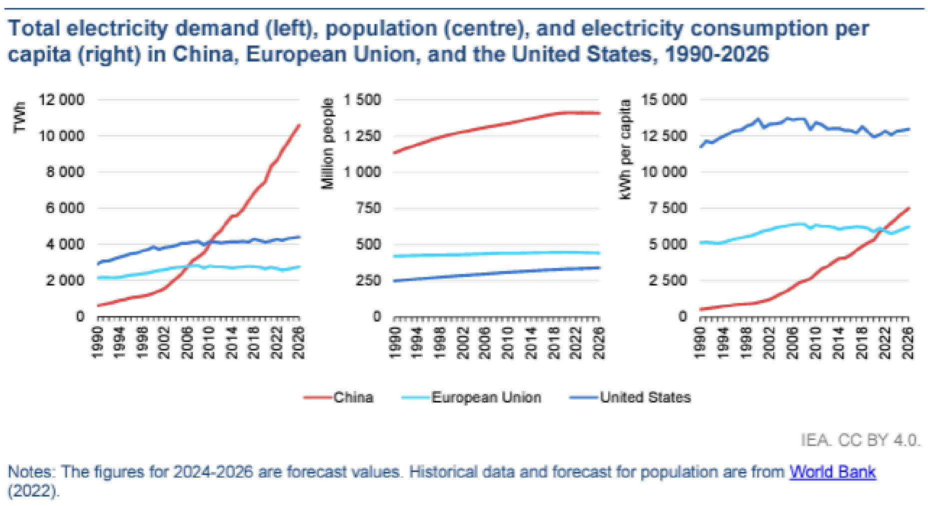
This form of magnetoreception is a unique feature in marine animals due to the need for seawater, which has high conductivity, as the surrounding medium. The ampullary organs of skates and rays are sufficiently sensitive to detect voltage differences caused by the fish moving in various directions.

It is important to note that there is still no concrete evidence that this information is actually used by elasmobranchs for compass orientation (Wiltschko & Wiltschko, 2006). However, physiological studies have shown that their electrosensory system can detect the on- and offset of weak magnetic stimuli (Newton et al., 2024), thus it has been hypothesized that they could in fact use Earth's geomagnetic field (GMF) to navigate (Kalmijn, 2000; Molteno & Kennedy, 2009; Newton et al., 2024; Paulin, 1995).[4]

[4] "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 Uroliphidstingrays can detect the polarity (Urobatis halleri; Kalmijn 1978, U. jamaicenis; Newton

Offshore Wind Farms and GMF

In our effort to address the effects of climate change and diversify our energy grid, the global demand for marine renewable energy infrastructure is rising (IEA, 2021; Samsó et al., 2023) as demand continues to increase (IEA, 2024).



[5]

In order to make use of this energy source the power generated by offshore wind farms needs to be transported to shore to be distributed to towns, cities; factories, households, etc. The subsea cables that are employed for this task have a secondary side effect, they emit radial magnetic fields into the surrounding seawater environment thus inducing secondary electric fields.

Submarine Power Cables

Subsea power cables, or SPCs, serve multiple purposes, including supplying power to shore[6], transferring electricity from marine renewable energy devices (MREDs), and providing electrical interconnections between countries (autonomous grid connections). The latter two applications involve carrying the strongest electric currents (Albert et al., 2020; Taormina et al., 2020; Worzyk, 2009).

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and Kajiura 2020a), intensity and inclination angle (U. jamaicenis; Newton and Kajiura 2020b) cues of the GMF" (Newton et al., 2024).

[5] (IEA, 2024)

[6] SPCs are also use to supply power from the mainland to islands or offshore installations such as oil rigs.

SPCs generate both electric and magnetic fields. The electric fields are confined within the cable. However, insulation technology is only partially effective in blocking magnetic emissions and is not currently considered in cable design (Albert et al., 2020).

Offshore wind farms require the greatest number of SPCs (Sun et al., 2012) The power transmission system is made up of cables normally around 20-30 cm in diameter, that are usually rated between 138-230 kV and connect the offshore collection point to the shore. For distances less than 50 km, high-voltage alternating current (HVAC)[7] cables are the most economical and convenient option (Albert et al., 2020; Wei et al., 2017).

These anthropogenic-generated electromagnetic fields (EMFs) can impact the local geomagnetic landscape and thus could alter the behavior of EMF-sensitive elasmobranchs that rely on the geomagnetic field (GMF) to navigate (Newton et al., 2024).

Understanding these interactions is crucial for developing strategies to mitigate any negative impacts on these marine species, which play essential roles in their ecosystems.

Experiment

To test and understand whether EMFs generated by offshore wind farms could interfere with the behavior of elasmobranchs, a series of controlled experiments were designed and conducted by Capstone Advisory Co-Chair Dr. Kyle Newton.[8]

Experimental Design

The experiment involved two species of skates: the longnose skate (*Beringraja rhina*) and the big skate (*Beringraja binoculata*). These species were selected due to their known sensitivity to EMFs and their relative ease of management, making them ideal candidates for assessing behavioral changes in response to electromagnetic interference.

The following description of the experiment's methods comes directly from Dr. Newton's "The Effects of Anthropogenic Electromagnetic Fields on the Behavior of Geomagnetically Displaced

[7] HVAC cables, or high-voltage alternating current cables, are used to transmit electrical power over long distances. They operate by alternating the direction of the current, which helps in efficiently transmitting power while minimizing losses over shorter distances, making them a cost-effective choice for connections under 50 km.

[8] A more detailed and thorough explanation of the experiment, methods and results of Dr. Newton is available in "The Effects of Anthropogenic Electromagnetic Fields on the Behavior of Geomagnetically Displaced Skates" (Newton et al., 2024)

Skates (2024)", and considers only a summarized description of the methods relevant to this project. The complete method description can be found in the article.

Method

Skates

Big skates (n = 4; disc width (DW) = 30-40 cm)[9].

Longnose skates (n = 3; DW = 50-60 cm)[10].

After 30 days of being captured, the skates were considered sufficiently acclimated to captivity and deemed healthy for testing.[11]

Experimental Setup

The experimental setup consists of a large water tank equipped with a Merrit coil system. This system is able to alter the electromagnetic environment within the tank, effectively creating a scenario of magnetic displacement[12]. This setup allows to observe how skates react when their electrosensory input is altered.

The container in which the skates were placed consisted of a 1.8m in diameter round polyethylene tank filled to a depth of 60 cm placed on a wooden pallet platform.

Beneath the tank, a model high-voltage cable (HVC) that can switch between alternating current (AC) and direct current (DC) simulates the type of electromagnetic emissions of submarine power cables. This feature is critical as it helps distinguish the effects of different types of current on skate behavior.

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[9] Obtained by capture (n = 2) using a 2-meter-wide benthic beam trawl at coordinates 44.701° N, -124.143° W at a depth of 35 meters, and donated (n = 2) from local aquaria (Newton et al., 2024).

[10] Caught using a bottom set longline at coordinates 43.317° N, -129.745° W at a depth of 310 meters (Newton et al., 2024).

[11] Skates were housed in flow-through seawater tanks (2 meters in diameter) on a 12:12 hour light:dark cycle. They were fed a mixture of shrimp, clams, herring, and nutritional supplements every other day, amounting to 7-10% of their body weight per week. After a minimum feeding period of 30 days, the skates were considered sufficiently acclimated to captivity and deemed healthy for behavioral testing. All procedures followed the ethical guidelines set by the Institutional Animal Care and Use Committee of Oregon State University under protocol #2022-0257 (Newton et al., 2024).

[12] Refers to the simulation of GMF of a different location, thus "displacing" through magnetic stimuli the skates to a different geographic location. What proceeds is to analyze its movements, swimming patterns. A possible out come could be to see it aligning it self towards its original location: of its displaced north, it would try to swim back south.

Geomagnetic and Electromagnetic Field Stimuli

The GMF control (GMF-C) stimulus exposure involved trials conducted at the ambient GMF[13]. GMF procedural control (GMF-PC) involved the same parameters with no alteration other than the activation of the setup.

Control EMF stimulus conditions consisted of exposure to the non-energized model HVC that did not emit EMF noise (EMF-0).

Behavioral Trial Procedure

The trials started by transferring an individual skate from its husbandry tank into the experimental tank and allowing it to acclimate for 10 minutes[14].

Under one GMF condition (GMF-C, GMF-PC, GMF-N, or GMF-S)[15], three separate 10-minute EMF stimulus trials (EMF-0, EMF-AC, or EMF-DC)[16] were conducted in random order, considering an intertrial interval of 60-180 seconds. After completing the three EMF trials for a particular GMF condition, the skate was returned to its husbandry tank, effectively concluding the session.

Once all individuals were tested under that same GMF condition, sessions ended for the day, and the skates rested for 2-4 days before the next session of trials.[17]

Monitoring and Data Collection

A high-definition camera mounted above the tank captured the skates' movements at 30 frames per second. This setup ensures that each frame serves as a distinct data point (30 data points per second), providing a detailed record of skate position throughout the experiment.

All trials were recorded using the *standard* camera setting on a GoPro Hero 11 Black, capturing 4K resolution video at 30fps.

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[13] Newport, OR, with parameters [F = 51.1 μT (horizontal = 20.6 μT, vertical = 46.9 μT), I = 66°] (Newton et al., 2024)

[14] "This acclimation period was determined based on a minimum of three baseline activity trials (> 60 minutes) that enabled the skates to return to their baseline activity levels. This approach aligns with previous studies on loggerhead sea turtles (*Caretta caretta*) by Lohmann et al. (1991), Chinook salmon (*Oncorhynchus tshawytscha*) by Putman et al. (2014), European eels (*Anguilla anguilla*) by Naisbett-Jones et al. (2017), and bonnethead sharks by Keller et al. (2021)." (Newton et al., 2024)

[15] For this project we only considered GMF-C and GMF-PC.

[16] For this project we only considered EMF-0

[17] This process was repeated until each skate was exposed to every permutation of EMF and GMF treatments (n = 9). Each permutation was conducted five times per animal (total number of trials per skate = 45) to simulate the scenario of a skate using GMF cues to navigate and encountering an MRE array, thus being exposed to EMF multiple times over a relatively short time frame.

The movements are tracked using DeepLabCut[18], a sophisticated machine-learning software that identifies and tracks each skate.[19] This technology registers the position (X, Y coordinates, and angle of the skate) of the skates within the tank which allows for acceleration and velocity calculations, allowing to understand how skates respond to altered electromagnetic fields in terms of their orientation, trajectory, and speed.

Expected Outcomes

When exposed to EMFs similar to those emitted by wind farm cables we would expect to see an alteration in the natural behavior of skates, particularly their navigation abilities. However, the data we analyzed for this project only considers "Control" and "Procedural Control", so we would expect to observe no changes in movement patterns, such as altered swimming paths or disorientation. If we did we would need to take this "noise" into consideration when proceeding to analyze the results of the behavior of the animals under different conditions.

Data Analysis

After plotting and testing the data from the experimental setup we saw no significant differences between settings "control" and "proc_control". We did observe a difference in behavior amongst species. Where the big skate appeared to be more active during sessions, the longnose skates took longer resting breaks. This suggests that the potential impact of EMFs on skates will most likely vary among species.

Spatial Use

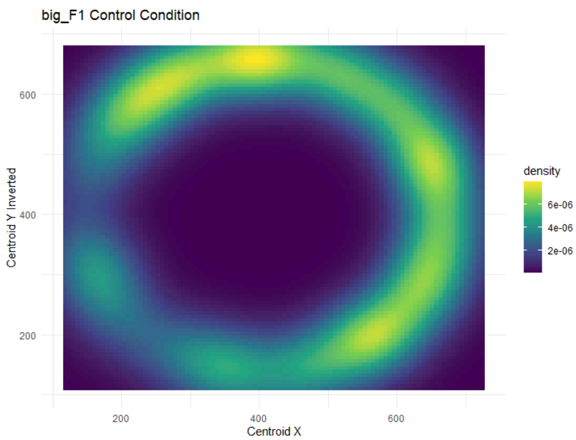
Control v. Procedural Control

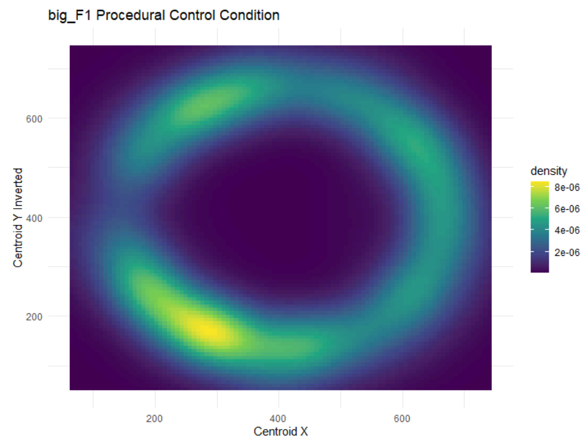
These heat maps were created using a coordinates system (X, Y) that shows the position of the skate at a given moment in time (every 100 ms). The denser areas show where the animal's activity is spatially distributed over time. For this, two conditions were considered: GMF=GMF-C and EMF=EMF-0; and GMF=GMF-PC and EMF=EMF-0.Individuals

[18] DeepLabCut (DLC) v2.3.0.
[19] 12 body parts (nose; anterior, tip, and posterior of left and right pectoral fins; left and right pelvic fins; base, mid, and tip of the tail).

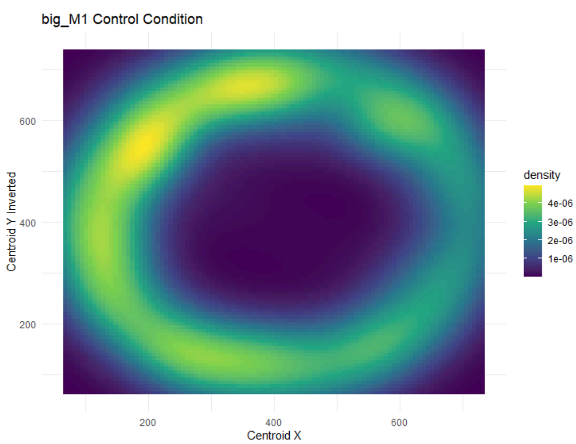
Big Skates

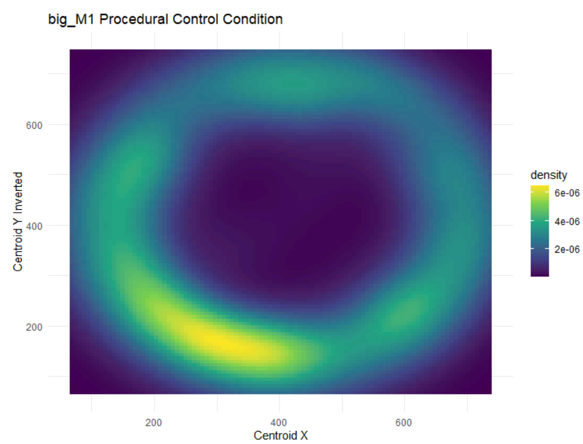
Big Skate Female 1



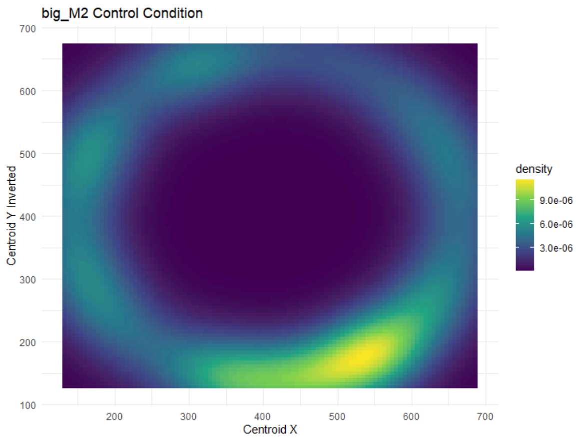


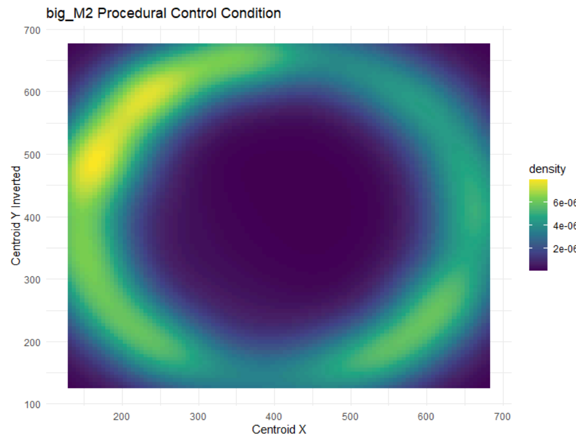
Big Skate Male 1





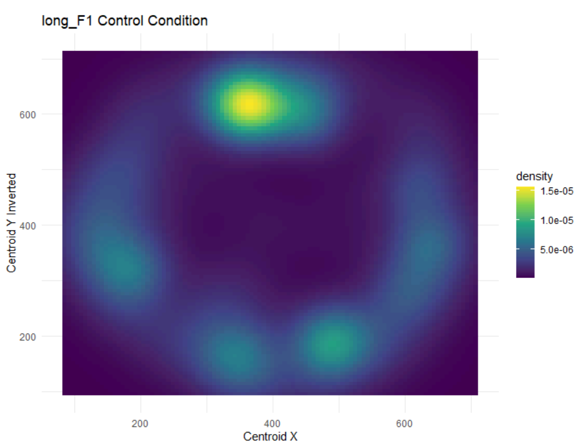
Big Skate Male 2

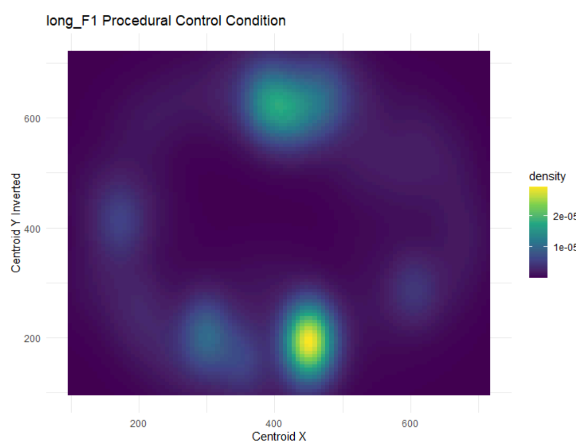




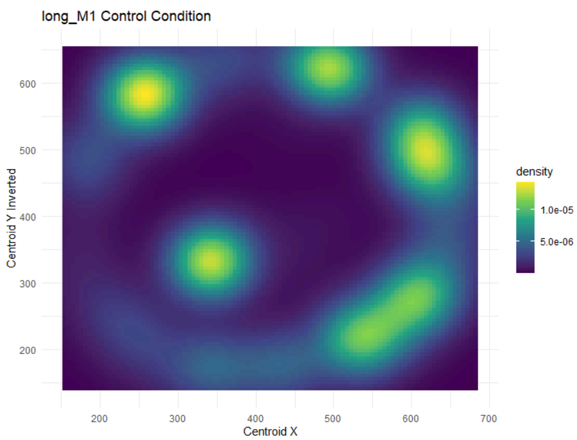
Longnose Skates

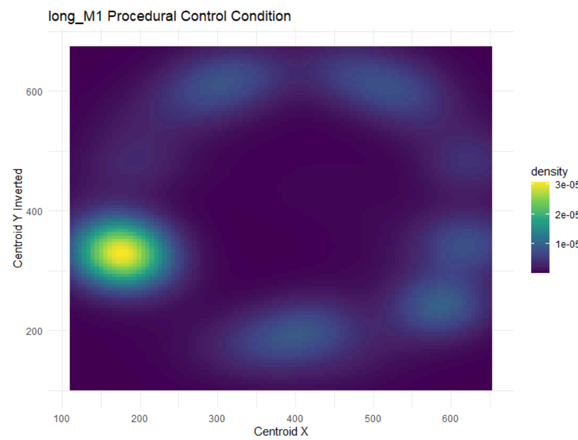
Longnose Skate Female 1



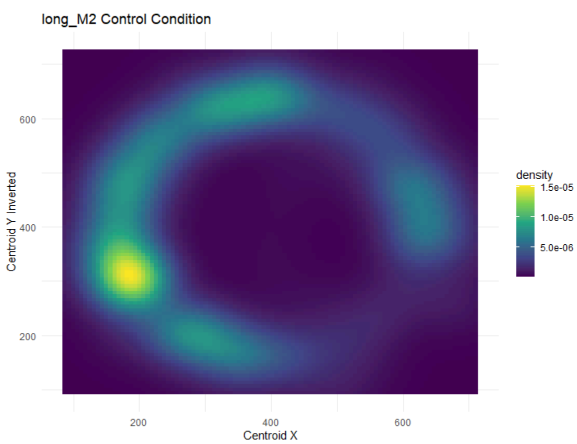


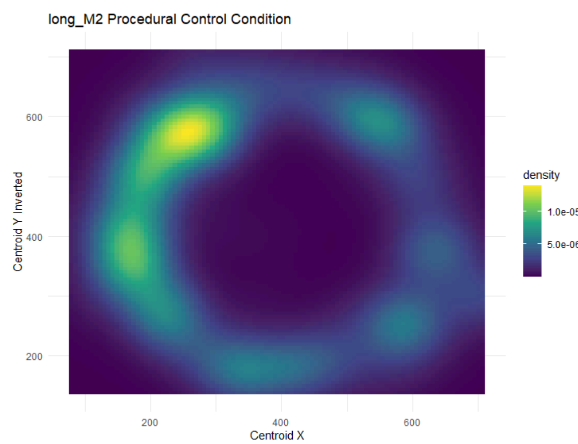
Longnose Skate Male 1





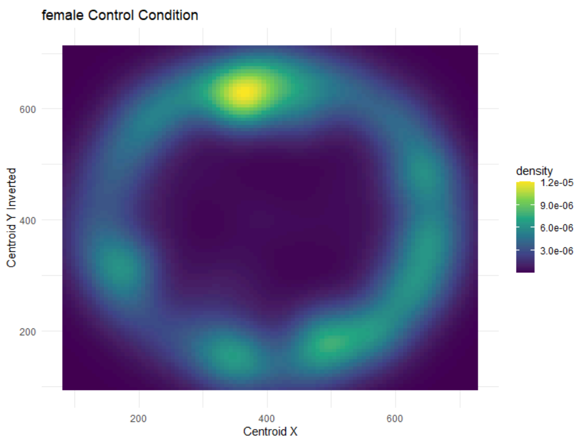
Longnose Skate Male 2

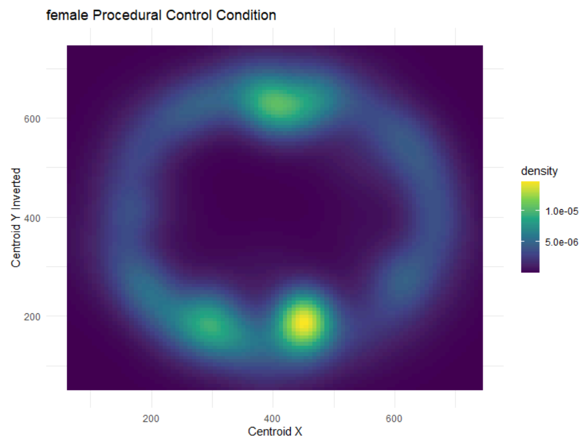




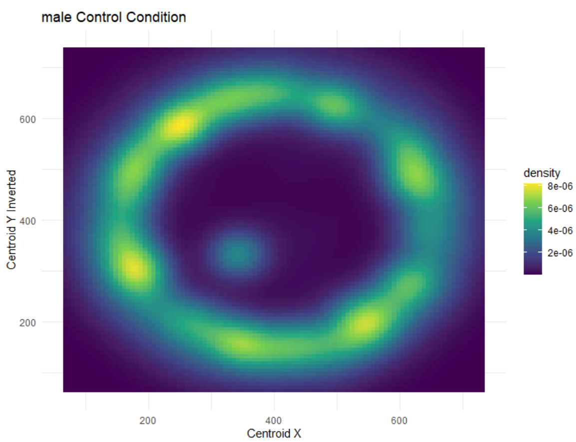
Big & Longnose skates by Sex

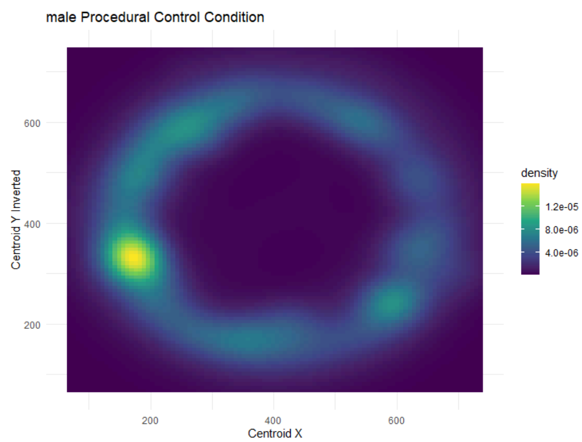
Female





Male





Big Skate (Beringraja binoculata):

Control (GMF = control, EMF = EMF-0)

	Variable	Mean	Standard_Deviation
1	centroid_vel	0.0960	18.6451
2	centroid_acc	0.0088	197.8777
3	body_angle_deg	2.0179	99.7491

Procedural Control (GMF = proc_control, EMF = EMF-0)

	Variable	Mean	Standard_Deviation
1	centroid_vel	0.0155	19.2026
2	centroid_acc	0.3451	210.7249
3	body_angle_deg	-3.7069	102.3808

- Under the procedural control condition, the mean velocity is slightly lower compared to the control condition.
- The mean acceleration seems to increase.
- There is a notable shift in the body angle mean from positive to negative, although the standard deviations remain high, indicating diverse orientation patterns.

Longnose Skate (Beringraja rhina)

Control (GMF = control, EMF = EMF-0)

	Variable	Mean	Standard_Deviation
1	centroid_vel	-0.0672	8.5090
2	centroid_acc	1.0824	106.9430
3	body_angle_deg	-10.5124	95.1995

Procedural Control (GMF = proc_control, EMF = EMF-0)

	Variable	Mean	Standard_Deviation
1	centroid_vel	-0.1346	8.1775
2	centroid_acc	0.6334	106.4112
3	body_angle_deg	-5.9456	99.3292

- Both conditions show relatively low mean velocities, with procedural control being slightly lower.
- The mean acceleration is higher in the control condition compared to the procedural control condition.
- The body angle mean is negative in both conditions, with procedural control showing a smaller negative mean.

Statistical Testing

Statistical tests to assess the significance of differences in velocity, acceleration, and body angles between the two conditions for each species.

Statistical Testing Results

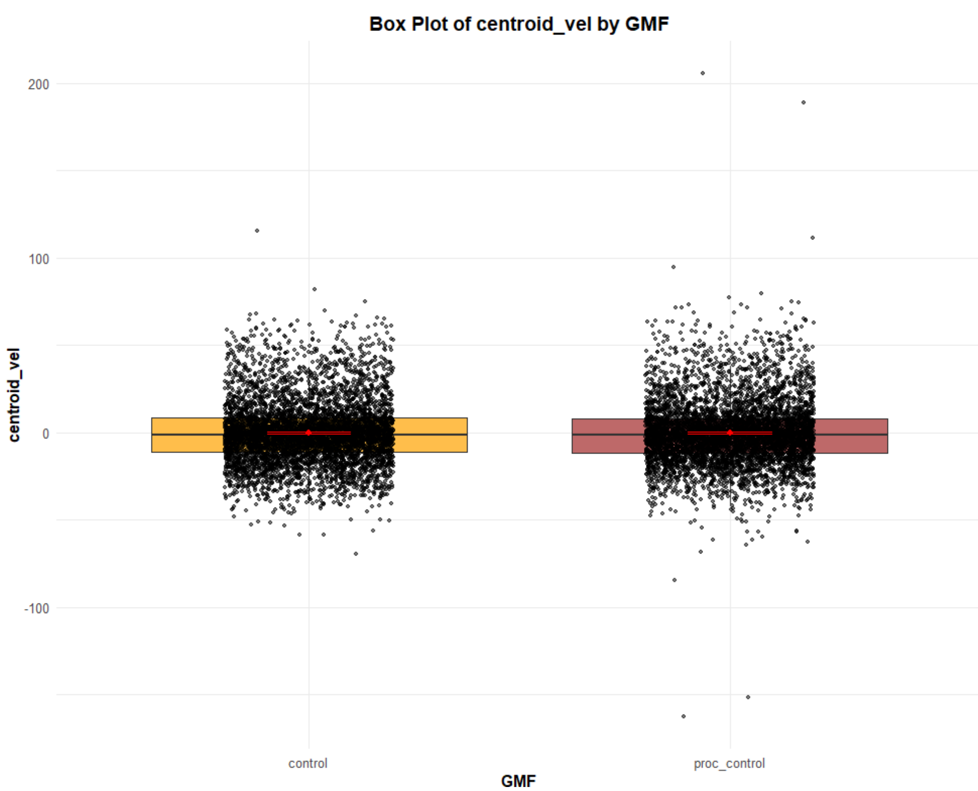
Big Skate (Beringraja binoculata)

Velocity:

```
  Subject_ID mean_control mean_proc_control deviation deviation_from_mean squared_deviation_from_mean
  <chr>             <dbl>             <dbl>     <dbl>               <dbl>                       <dbl>
1 big_F1            0.073            -0.018     0.091               0.01                      0.0001
2 big_M1            0.128             0.006     0.122               0.041                     0.00168
3 big_M2            0.087             0.058     0.029              -0.052                     0.00270
# A tibble: 1 × 7
      N D_prime   SSD    SD   SEd t_value critical_t_value
  <int>   <dbl> <dbl> <dbl> <dbl>   <dbl>            <dbl>
1     3   0.081 0.004 0.047 0.027    2.95             4.30
# A tibble: 1 × 2
  lower_bound upper_bound
        <dbl>       <dbl>
1      -0.037       0.198
# A tibble: 1 × 4
  t_value p_value conf_interval_lower conf_interval_upper
    <dbl>   <dbl>               <dbl>               <dbl>
1    2.95   0.098              -0.037               0.198
# A tibble: 1 × 2
  hypothesis                   interpretation
  <chr>                        <chr>
1 Failed to Reject the Null (H0) Failed to Reject the Null: There is no significant difference in mean velocity between GMF=control and GMF=proc_control.
```

T: 2.95 < CV 4.3 - P 0.098 > 0.05: Fail to reject the null.

- Conclusion: No significant difference in velocity between control and procedural control conditions.

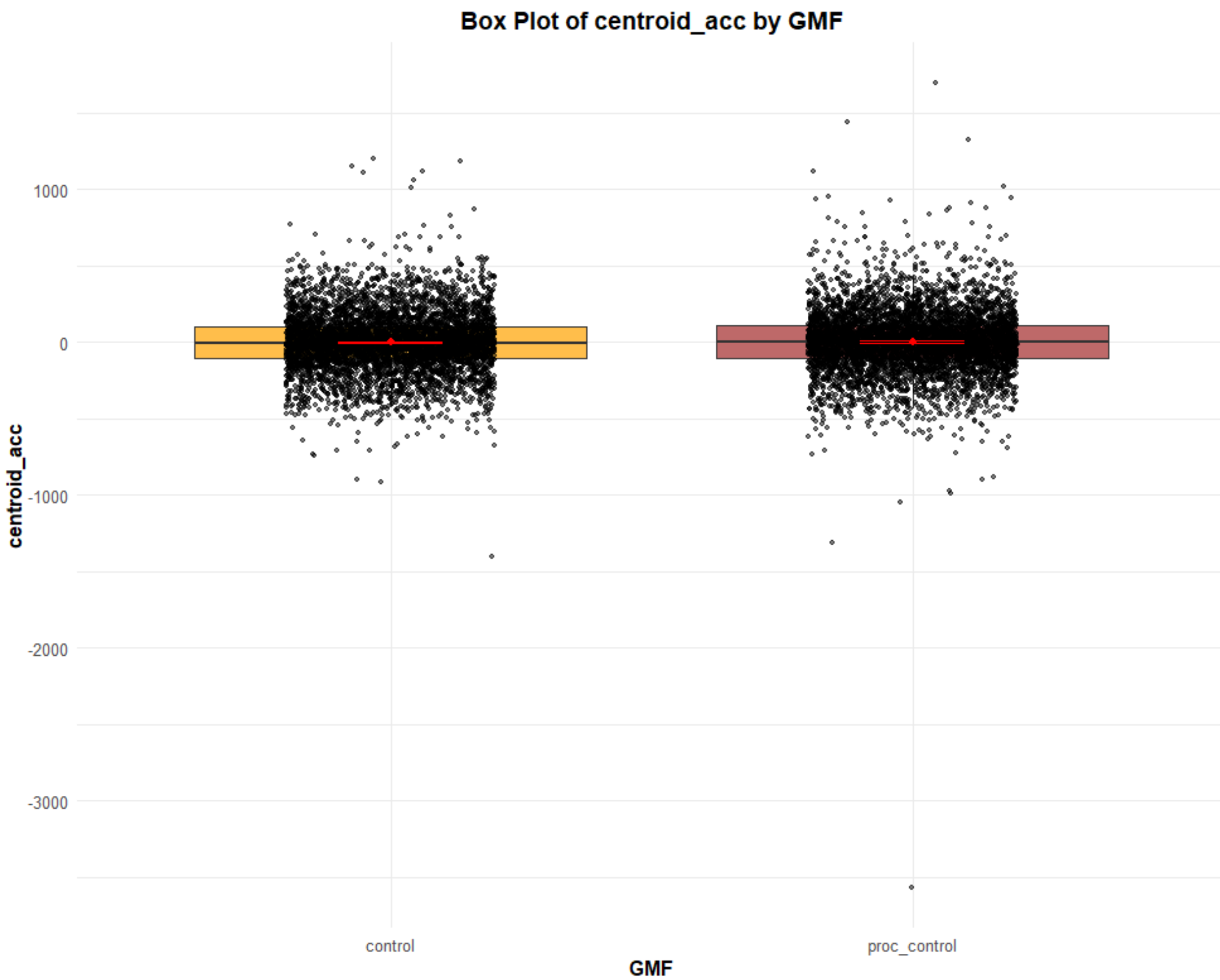


Acceleration

```
  Subject_ID mean_control mean_proc_control deviation deviation_from_mean squared_deviation_from_mean
  <chr>             <dbl>             <dbl>     <dbl>               <dbl>                       <dbl>
1 big_F1            0.176             1.15     -0.978              -0.639                      0.408
2 big_M1            0.021             0.029    -0.008               0.331                      0.110
3 big_M2           -0.17             -0.138    -0.032               0.307                      0.0942
# A tibble: 1 × 7
      N D_prime   SSD    SD   SEd t_value critical_t_value
  <int>   <dbl> <dbl> <dbl> <dbl>   <dbl>            <dbl>
1     3  -0.339 0.612 0.553 0.319   -1.06             4.30
# A tibble: 1 × 2
  lower_bound upper_bound
        <dbl>       <dbl>
1       -1.71        1.03
# A tibble: 1 × 4
  t_value p_value conf_interval_lower conf_interval_upper
    <dbl>   <dbl>               <dbl>               <dbl>
1   -1.06   0.399               -1.71                1.03
# A tibble: 1 × 2
  hypothesis                   interpretation
  <chr>                        <chr>
1 Failed to Reject the Null (H0) Failed to Reject the Null: There is no significant difference in mean velocity between GMF=control and GMF=proc_control.
```

T: -1.06 < CV: 4.3 - P 0.399 > 0.05 Fail to reject the null.

- Conclusion: No significant difference in acceleration between control and procedural control conditions.

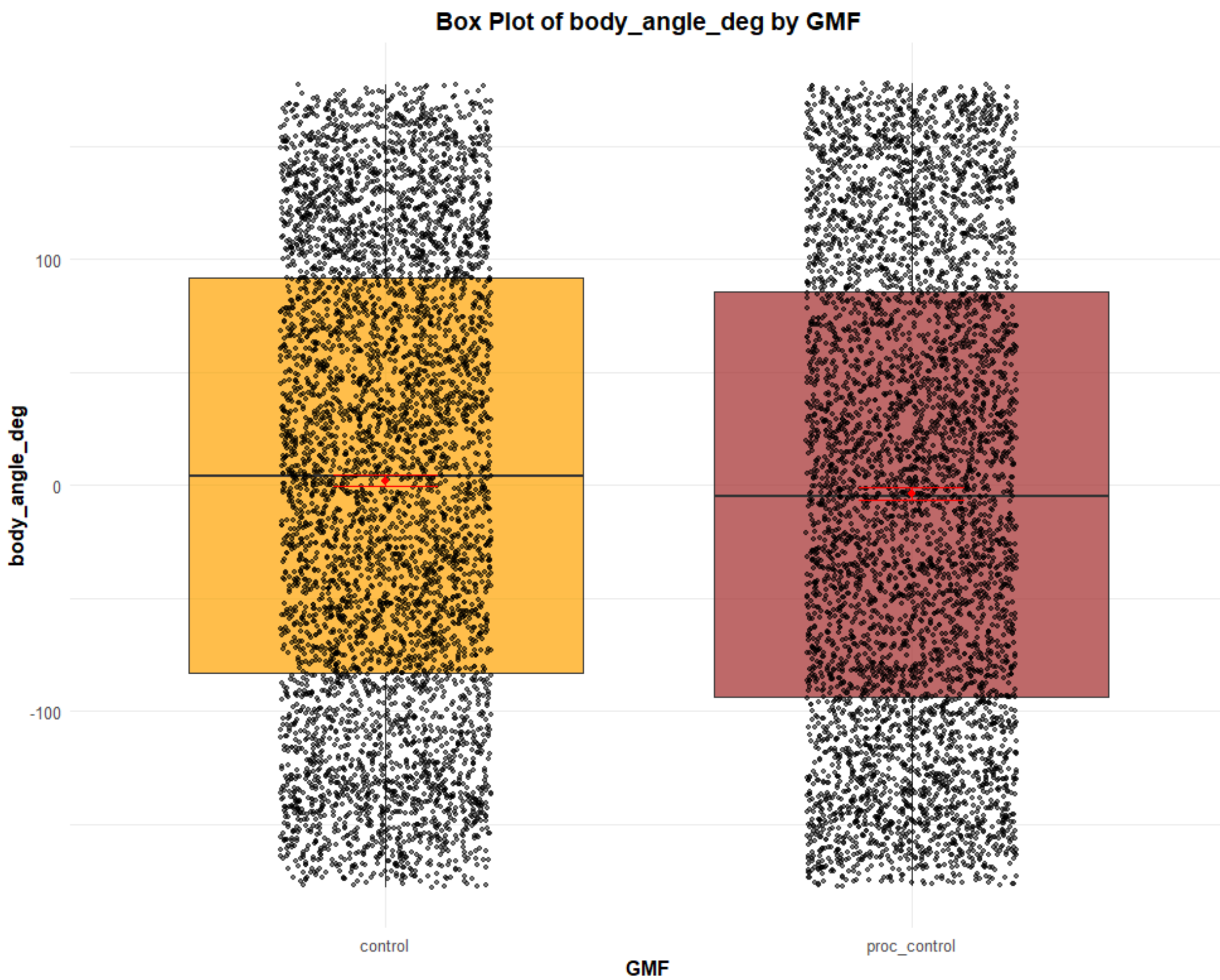


Body Angle

```
  Subject_ID mean_control mean_proc_control deviation deviation_from_mean squared_deviation_from_mean
  <chr>             <dbl>             <dbl>     <dbl>               <dbl>                       <dbl>
1 big_F1             15.4             -2.92     18.4                12.6                        160.
2 big_M1            -11.7             -6.66     -5.01              -10.7                        115.
3 big_M2              2.29            -1.55      3.84               -1.89                         3.58
# A tibble: 1 × 7
      N D_prime   SSD    SD   SEd t_value critical_t_value
  <int>   <dbl> <dbl> <dbl> <dbl>   <dbl>            <dbl>
1     3    5.73  278.  11.8  6.81   0.841             4.30
# A tibble: 1 × 2
  lower_bound upper_bound
        <dbl>       <dbl>
1       -23.6        35.0
# A tibble: 1 × 4
  t_value p_value conf_interval_lower conf_interval_upper
    <dbl>   <dbl>               <dbl>               <dbl>
1   0.841   0.489               -23.6                35.0
# A tibble: 1 × 2
  hypothesis                 interpretation
  <chr>                      <chr>
1 Failed to Reject the Null (H0) Failed to Reject the Null: There is no significant difference in mean velocity between GMF=control and GMF=proc_control.
```

T: .0.841 < CV 4.3 - P 0.489 > 0.05 Fail to reject the null.

  - Conclusion: No significant difference in body angle between control and procedural control conditions.

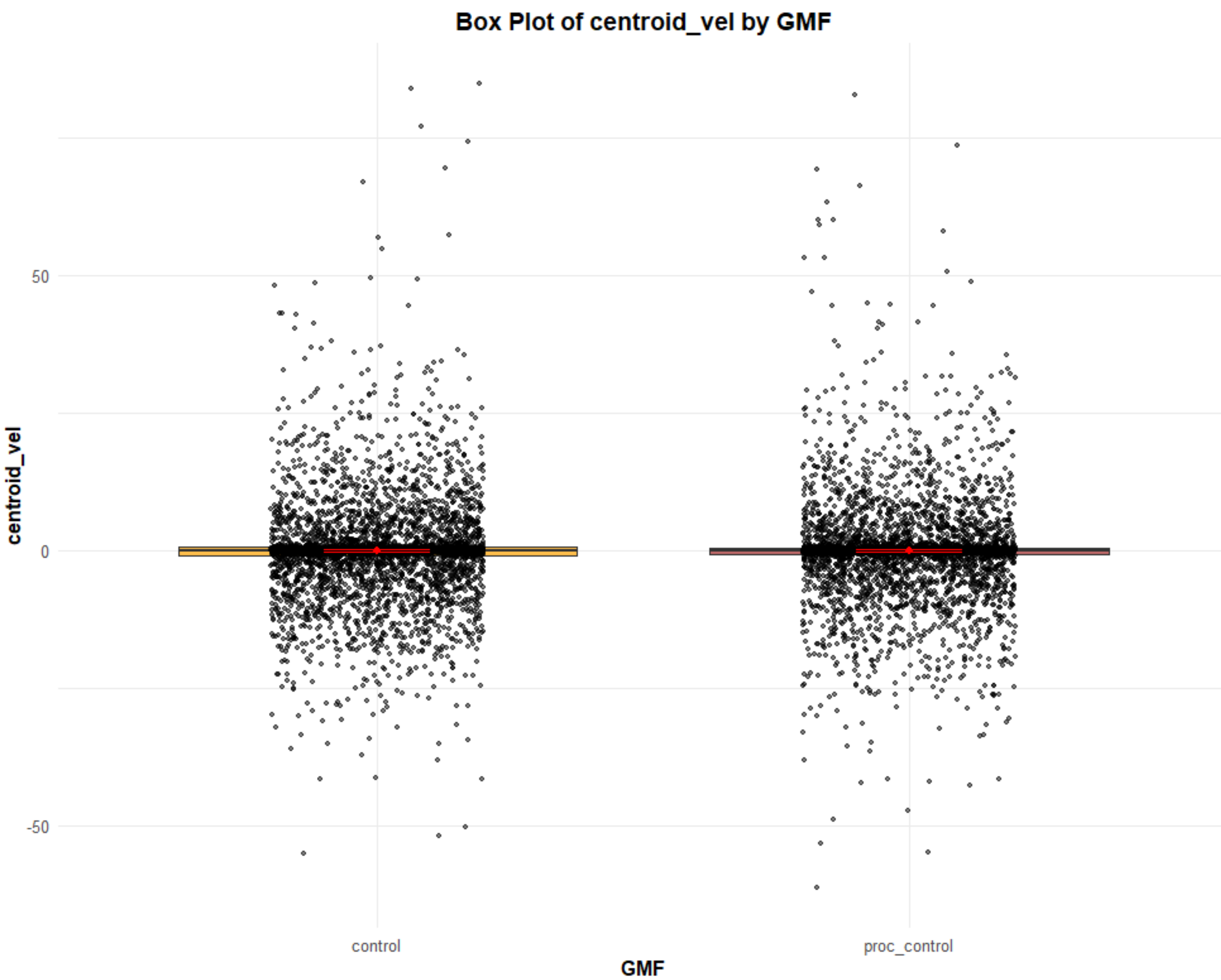


Longnose Skate (Beringraja rhina)

Velocity:

```
  Subject_ID mean_control mean_proc_control deviation deviation_from_mean squared_deviation_from_mean
  <chr>             <dbl>             <dbl>     <dbl>               <dbl>                       <dbl>
1 long_F1          -0.099            -0.237     0.138               0.073                    0.00533
2 long_M1          -0.122            -0.161     0.039              -0.026                    0.000676
3 long_M2           0.012            -0.007     0.019              -0.046                    0.00212
# A tibble: 1 × 7
      N D_prime   SSD    SD   SEd t_value critical_t_value
  <int>   <dbl> <dbl> <dbl> <dbl>   <dbl>            <dbl>
1     3   0.065 0.008 0.064 0.037    1.78             4.30
# A tibble: 1 × 2
  lower_bound upper_bound
        <dbl>       <dbl>
1      -0.093       0.224
# A tibble: 1 × 4
  t_value p_value conf_interval_lower conf_interval_upper
    <dbl>   <dbl>               <dbl>               <dbl>
1    1.78   0.218              -0.093               0.224
# A tibble: 1 × 2
  hypothesis                     interpretation
  <chr>                          <chr>
1 Failed to Reject the Null (H0) Failed to Reject the Null: There is no significant difference in mean velocity between GMF=control and GMF=proc_control.
```

T: 1.78 < CV 4.3 - P 0.218 > 0.05 Fail to reject the null.
 - Conclusion: No significant difference in velocity between control and procedural control conditions.

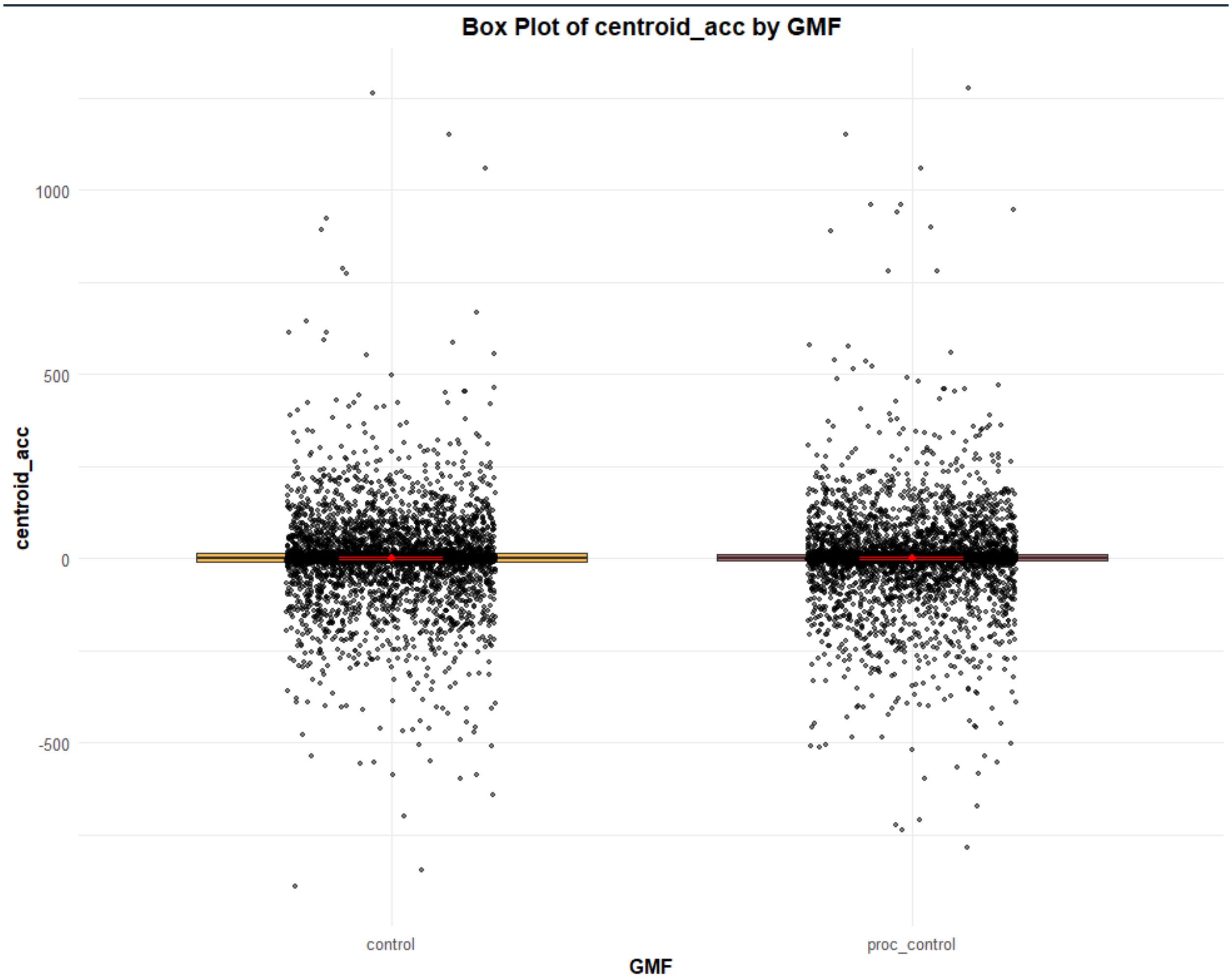


Acceleration

```
  Subject_ID mean_control mean_proc_control deviation deviation_from_mean squared_deviation_from_mean
  <chr>             <dbl>             <dbl>     <dbl>               <dbl>                       <dbl>
1 long_F1           1.39              0.837     0.556               0.089                       0.00792
2 long_M1           1.51              0.828     0.685               0.218                       0.0475
3 long_M2           0.402             0.241     0.161              -0.306                       0.0936
# A tibble: 1 × 7
      N D_prime   SSD    SD   SEd t_value critical_t_value
  <int>   <dbl> <dbl> <dbl> <dbl>   <dbl>            <dbl>
1     3   0.467 0.149 0.273 0.158    2.96             4.30
# A tibble: 1 × 2
  lower_bound upper_bound
        <dbl>       <dbl>
1      -0.211        1.15
# A tibble: 1 × 4
  t_value p_value conf_interval_lower conf_interval_upper
    <dbl>   <dbl>               <dbl>               <dbl>
1    2.96   0.097              -0.211                1.15
# A tibble: 1 × 2
  hypothesis                     interpretation
  <chr>                          <chr>
1 Failed to Reject the Null (H0) Failed to Reject the Null: There is no significant difference in mean velocity between GMF=control and GMF=proc_control.
```

T: 2.96 < CV 4.3 - P 0.097 > 0.05 Fail to reject the null.

- Conclusion: No significant difference in acceleration between control and procedural control conditions.

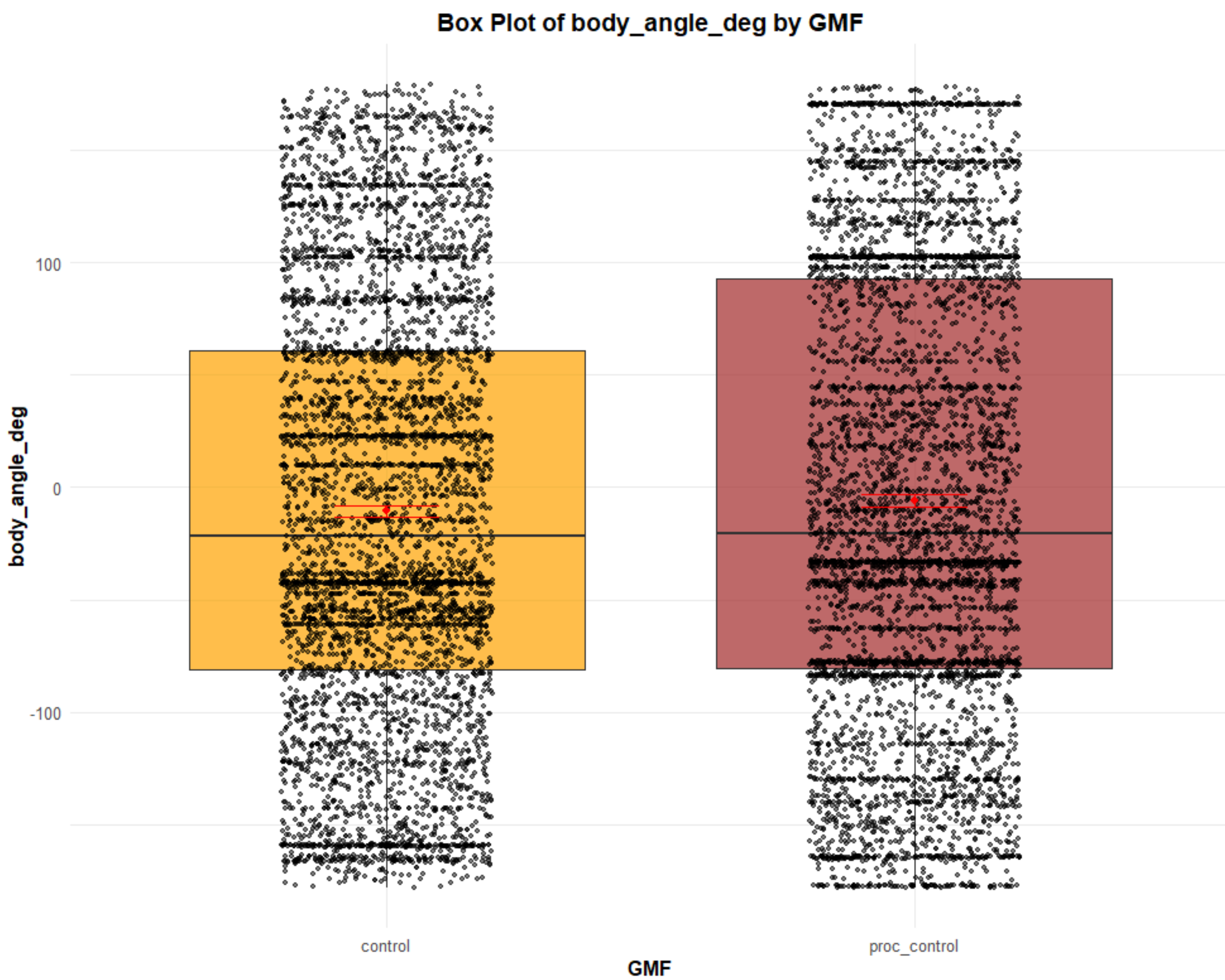


Body Angle

```
  Subject_ID mean_control mean_proc_control deviation deviation_from_mean squared_deviation_from_mean
  <chr>             <dbl>             <dbl>     <dbl>               <dbl>                       <dbl>
1 long_F1          -19.4               7.06     -26.5               -22.0                        484.
2 long_M1           -4.56             -1.58      -2.98                1.52                         2.30
3 long_M2           -7.28            -23.3       16.0                20.5                        420.
# A tibble: 1 × 7
      N D_prime   SSD    SD   SEd t_value critical_t_value
  <int>   <dbl> <dbl> <dbl> <dbl>   <dbl>            <dbl>
1     3   -4.50  906.  21.3  12.3  -0.366             4.30
# A tibble: 1 × 2
  lower_bound upper_bound
        <dbl>       <dbl>
1       -57.4        48.4
# A tibble: 1 × 4
  t_value p_value conf_interval_lower conf_interval_upper
    <dbl>   <dbl>               <dbl>               <dbl>
1  -0.366   0.749               -57.4                48.4
# A tibble: 1 × 2
  hypothesis                    interpretation
  <chr>                         <chr>
1 Failed to Reject the Null (H0) Failed to Reject the Null: There is no significant difference in mean velocity between GMF=control and GMF=proc_control.
```

T: -0.366 < CV 4.3 - P 0.749 > 0.05 Fail to reject the null.

- Conclusion: No significant difference in body angle between control and procedural control conditions.



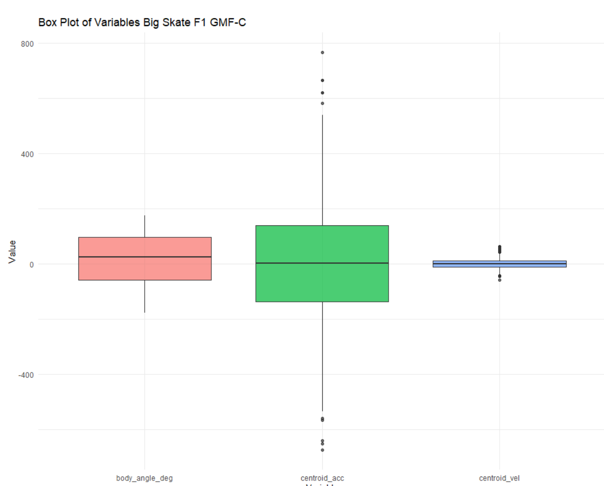
Big Skate Female 1

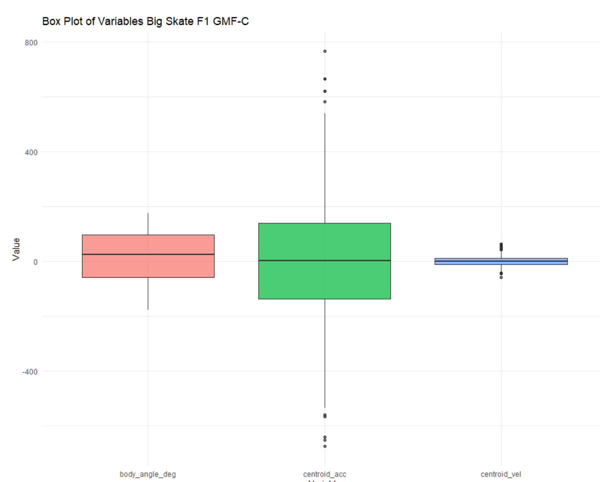
Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	0.073	347.707	18.646	0.435
Acceleration	0.175	44874.391	211.835	4.951
Angle	15.438	9044.351	95.101	2.223

Procedural Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	-0.018	382.228	19.551	0.459
Acceleration	1.154	55455.37	235.49	5.538
Angle	-2.919	10846.495	104.147	2.435





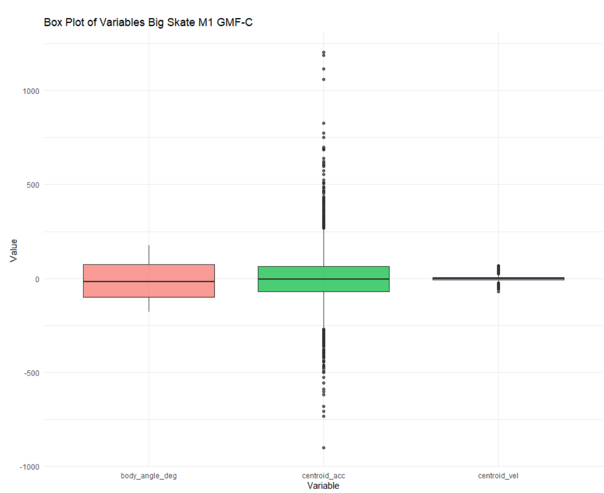
Big Skate Male 1

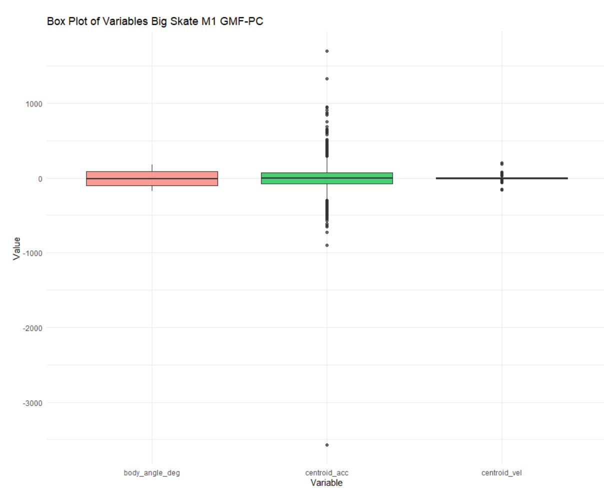
Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	0.128	207.387	14.401	0.337
Acceleration	0.021	27321.282	165.292	3.872
Angle	-11.671	9498.491	97.46	2.278

Procedural Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	0.006	285.64	16.901	0.396
Acceleration	0.029	36779.424	191.78	4.492
Angle	-6.657	10615.533	103.032	2.408





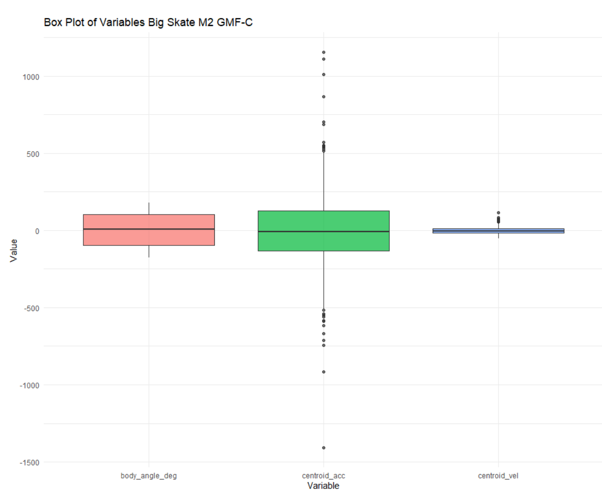
Big Skate Male 2

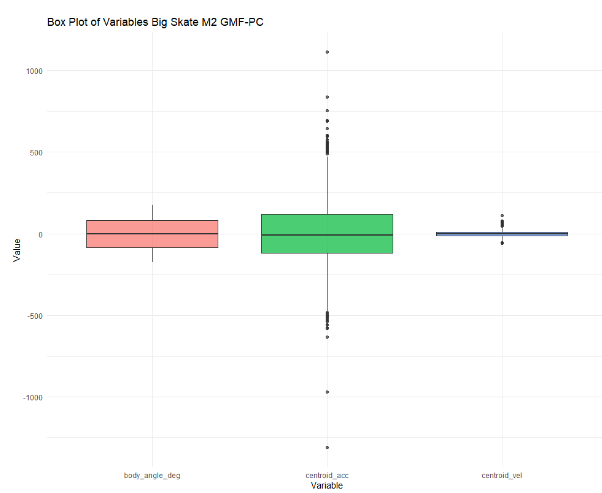
Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	0.087	487.74	22.085	0.516
Acceleration	-0.17	45262.017	212.749	4.973
Angle	2.286	10949.92	104.642	2.446

Procedural Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	0.058	438.458	20.939	0.489
Acceleration	-0.138	41140.353	202.831	4.735
Angle	-1.549	9982.236	99.911	2.332





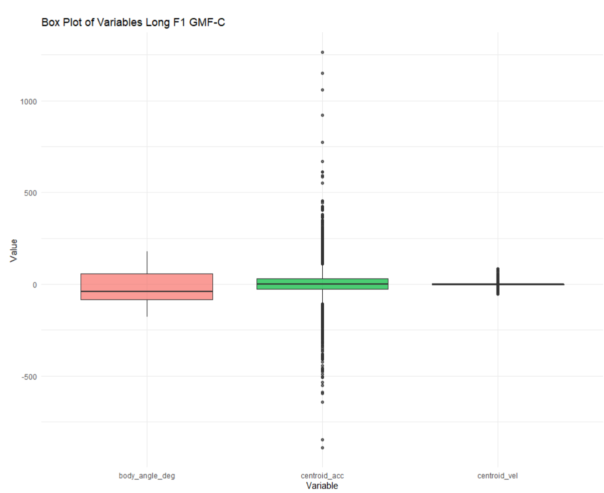
Longnose Skate Female 1

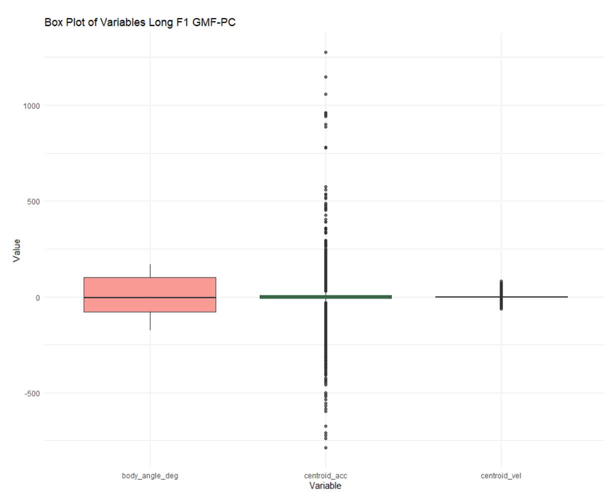
Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	-0.099	122.875	11.085	0.267
Acceleration	1.393	19844.671	140.871	3.408
Angle	-19.436	8975.043	94.737	2.241

Procedural Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	-0.237	112.333	10.599	0.252
Acceleration	0.837	20094.17	141.754	3.39
Angle	7.063	8883.28	94.251	2.22





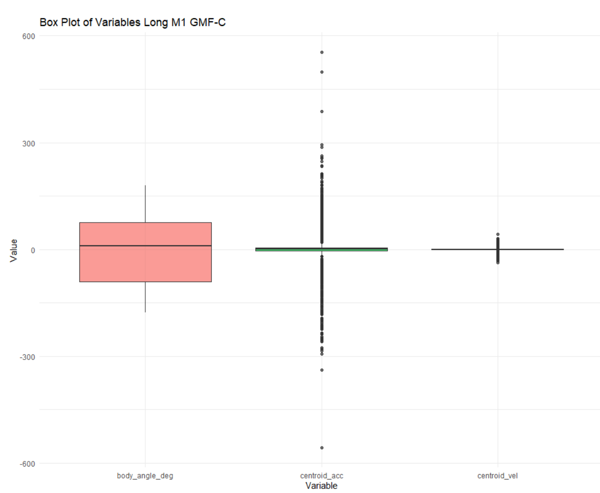
Longnose Skate Male 1

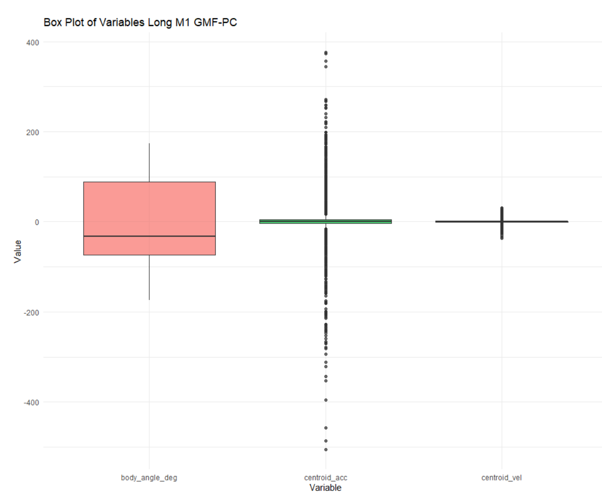
Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	-0.122	30.148	5.491	0.137
Acceleration	1.513	4207.579	64.866	1.631
Angle	-4.562	10300.172	101.49	2.466

Procedural Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	-0.161	26.065	5.105	0.122
Acceleration	0.828	4323.859	65.756	1.582
Angle	-1.579	10280.869	101.395	2.393





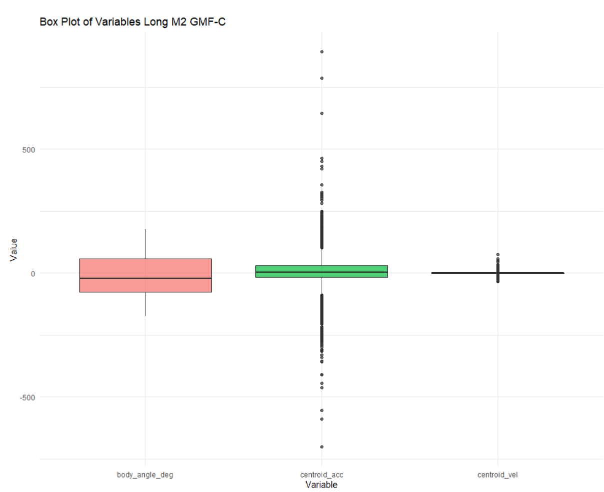
Longnose Skate Male 2

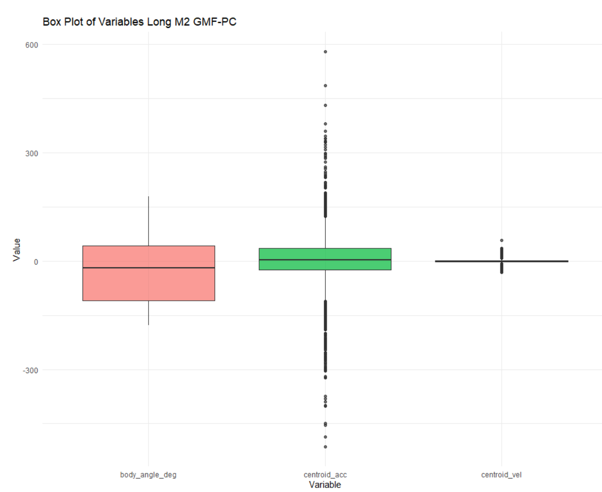
Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	0.012	61.457	7.839	0.185
Acceleration	0.402	9799.98	98.995	2.344
Angle	-7.276	7881.473	88.778	2.085

Procedural Control

	Mean	Variance	Standard Deviation	Standard Error
Velocity	-0.007	61.773	7.86	0.186
Acceleration	0.241	9494.397	97.439	2.319
Angle	-23.263	9958.265	99.791	2.348





Conclusion

This project builds on existing research highlighted in earlier sections of this essay, which have documented the general impacts of offshore wind farms on marine life. By focusing specifically on the longnose skate (*Beringraja rhina*) and the big skate (*Beringraja binoculata*) and their unique sensory capabilities, this study hopes to contribute to understanding how these animals react to stimuli.

The interaction between turbine EMFs and natural GMFs is an area of active research, highlighting the need for environmentally responsible energy development strategies. By continuing to study and address these ecological concerns, the integration of offshore wind technologies can proceed in harmony with marine conservation efforts, ensuring that these structures not only generate clean energy but also coexist sustainably with their natural surroundings.

This understanding equips us to appreciate the complexities of introducing large-scale energy infrastructure into sensitive marine environments, prompting ongoing innovation and adaptation to minimize ecological impacts while maximizing renewable energy gains.

However, offshore wind is a promising source of renewable energy, especially in the context of rising temperatures and increasing global energy demand. Thus, offshore wind farms' potential impacts on marine ecosystems should not halt the development and pursuit of this energy source. Any action we take, or refrain from taking, will inevitably impact our environment: there isn’t one easy fix to everything. This is why research like this is fundamental, so that the policies we draft are the most informed, and the technologies we develop are done with the best available science.

Understanding marine ecosystems will allow us to minimize the impacts of our actions.

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