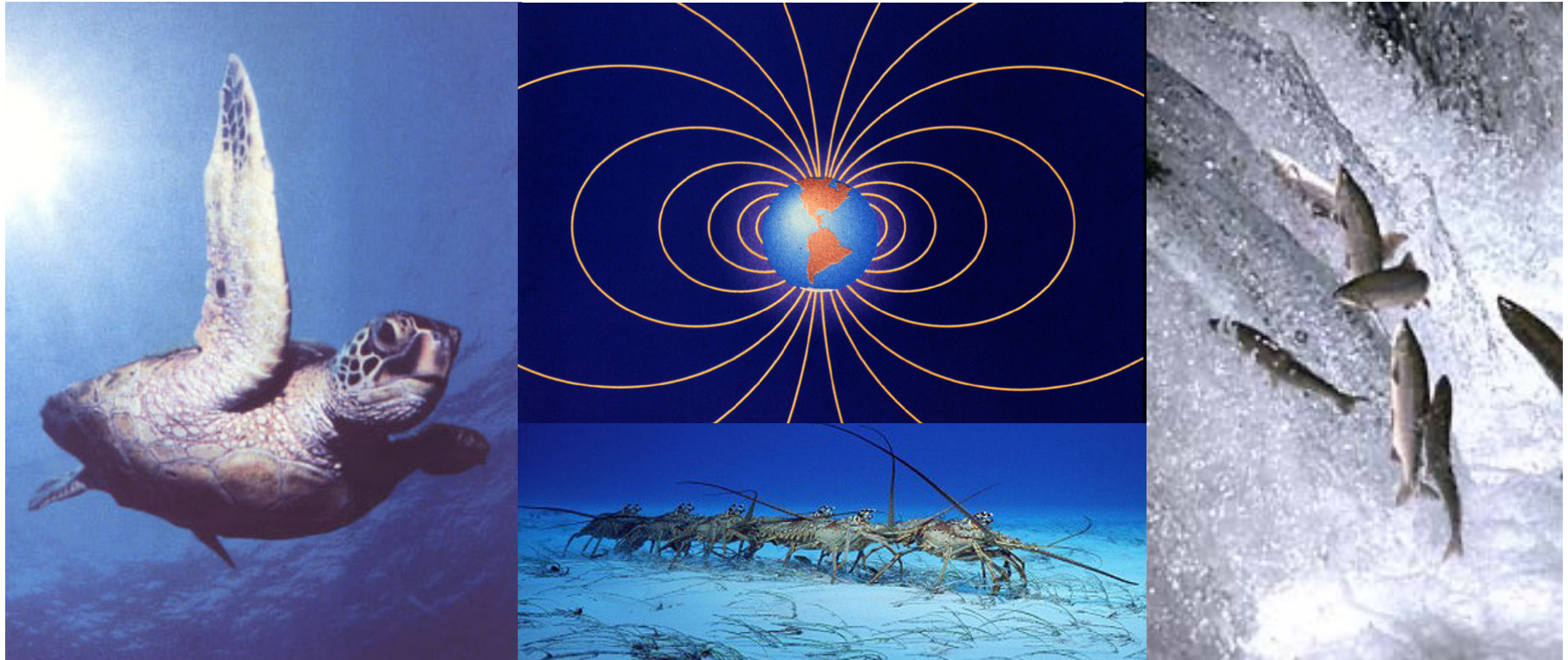


Magnetoreception in Marine Animals and Bio-Inspired Algorithms for Long-Range, GPS-free Navigation

Ken Lohmann, Department of Biology, University of North Carolina at Chapel Hill

Sonke Johnsen, Department of Biology, Duke University

Brian Taylor, Department of Mechanical & Aerospace Engineering, Case Western Reserve University



OVERVIEW: Three-pronged Interdisciplinary Research Plan

PART 1: Study the bio-sensory basis of long-range magnetic navigation in sea turtles and other aquatic animals using [behavioral and neurobiological approaches](#)

PART 2: Study strategies and algorithms of magnetic navigation using [engineering approaches](#) that include modeling, simulations, and robotics

PART 3: Use [“Big Data” analytics, machine learning, and computational approaches](#) to study the navigation of marine animals, with the goal of uncovering new strategies and concepts with engineering relevance

Investigating the bio-sensory basis for long-range geomagnetic navigation using behavioral and neurobiological approaches

Key finding: Sea turtles have TWO different magnetic senses, each based on a different underlying mechanism

Sea turtles are magnetic navigation specialists

- Sea turtles migrate across entire ocean basins to reach specific locations



- Navigation depends largely on an ability to detect Earth's magnetic field
- Turtles have a magnetic compass sense (can detect direction of the magnetic field)
- Turtles have a 'magnetic map' (the equivalent of a simple biological GPS) based on sensing geographic variation in Earth's magnetic field.
- To a turtle, different parts of the ocean feel different because different areas have different magnetic signatures.

One long-term objective: Determine the mechanism(s) that underlie magnetic field detection in sea turtles and other aquatic animals.

Mechanism is not known for certain in ANY animal (no receptor has been identified).

Several hypotheses, including:

- 1.) chemical magnetoreception (a.k.a. radical pairs or cryptochrome mechanism)
 - series of chemical reactions that starts with photoexcitation; light required
- 2.) magnetite

In birds and insects, evidence suggests that the magnetic compass (not the map) might depend on chemical magnetoreception.

- Consistent with this: magnetic compass in birds is disrupted by broadband oscillating magnetic fields in 0.1 – 10 MHz range, as predicted by theory (Ritz et al., 2004, *Nature*).

Resonance effects indicate a radical-pair mechanism for avian magnetic compass

Thorsten Ritz¹, Peter Thalau², John B. Phillips³, Roswitha Wiltschko² & Wolfgang Wiltschko²

¹Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA

²Zoologisches Institut, Fachbereich Biologie und Informatik, J.W. Goethe-Universität, Siesmayerstrasse 70, D-60054 Frankfurt am Main, Germany

³Department of Biology, 2119 Derring Hall, Virginia Tech, Blacksburg, Virginia 24061, USA

Migratory birds are known to use the geomagnetic field as a source of compass information^{1,2}. There are two competing hypotheses for the primary process underlying the avian magnetic compass, one involving magnetite³⁻⁵, the other a magnetically sensitive chemical reaction⁶⁻⁸. Here we show that oscillating magnetic fields disrupt the magnetic orientation behaviour of migratory birds. Robins were disoriented when exposed to a vertically aligned broadband (0.1–10 MHz) or a single-frequency (7-MHz) field in addition to the geomagnetic field. Moreover, in the 7-MHz oscillating field, this effect depended on the angle between the oscillating and the geomagnetic fields. The birds

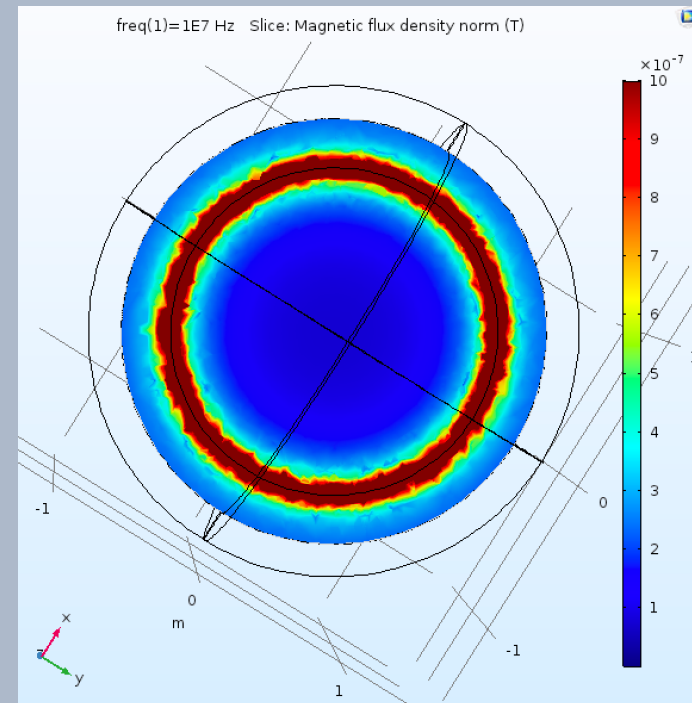
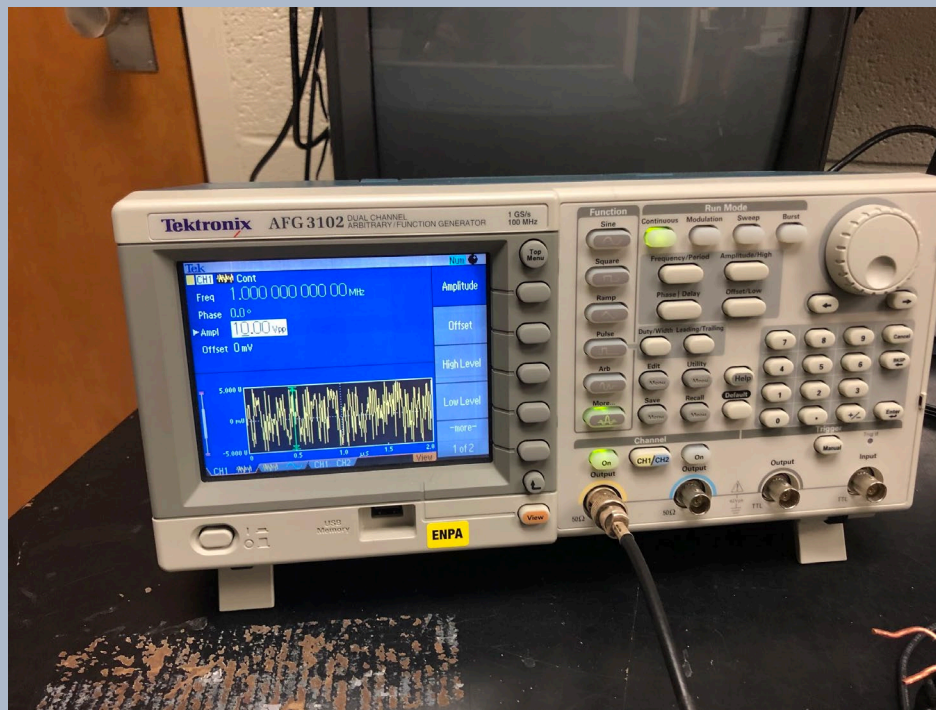
For turtles, is the magnetic map sense and/or the magnetic compass sense disrupted by the same oscillating magnetic fields that disrupt the bird magnetic compass?

To investigate, two behavioral assays were developed:

- 1.) Assay for the magnetic map sense
- 2.) Assay for the magnetic compass sense

RF Oscillating Magnetic Field Production

Collaborators: Reyco Henning, Andrew Gavin (UNC Physics Department)



Used function generator and loop antenna to generate oscillating magnetic fields replicating those used in the bird studies (should disrupt chemical magnetoreception)

Tested effect of RF fields on *magnetic map sense* of turtles using map assay

- Turtles were conditioned (trained) to associate a particular magnetic signature with food
- We can tell when turtles recognize the magnetic signature, because they show a particular pattern of excited behavior (they expect to be fed)

Magnetic Map Assay

- Turtles were conditioned (trained) to associate a particular magnetic signature with food
- We can tell when turtles recognize the magnetic signature, because the turtles show a particular pattern of excited behavior (they expect to be fed)
- Using this assay, we found NO effect of oscillating magnetic fields
- Results suggest that the magnetic map sense does NOT rely on chemical magnetoreception

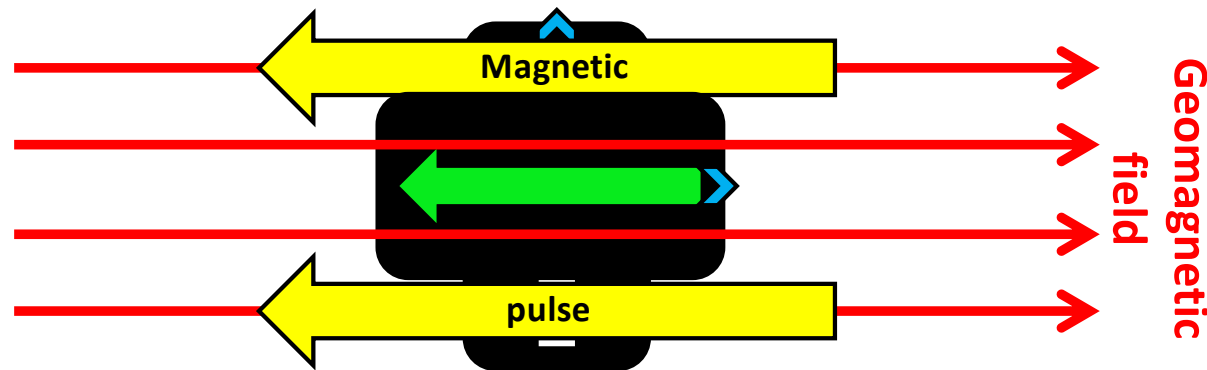
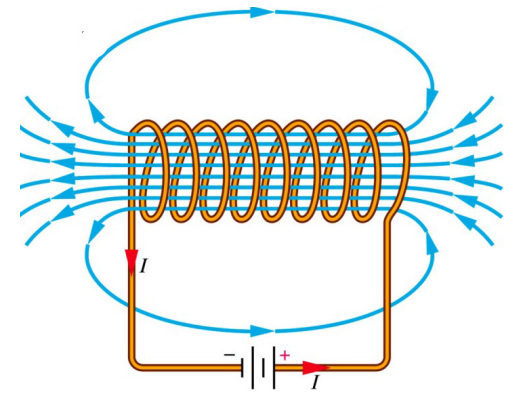


If the turtle magnetic map sense is not based on chemical magnetoreception, what is it based on?

- Magnetite (Fe_3O_4) is a possible mechanism
- Simplest idea: magnetite crystals function as microscopic compass needles; will align with ambient magnetic field
- Magnetite crystals might be coupled to secondary receptors such as stretch receptors or hair cells, which convert magnetic information into electrical signals.
- How can the magnetite hypothesis be tested?

One promising technique: **pulse magnetization**.

- Put animal into a solenoid; apply a strong, brief magnetic pulse to the animal
- Pulse is strong enough to alter the magnetic dipole moment of single-domain magnetite crystals.

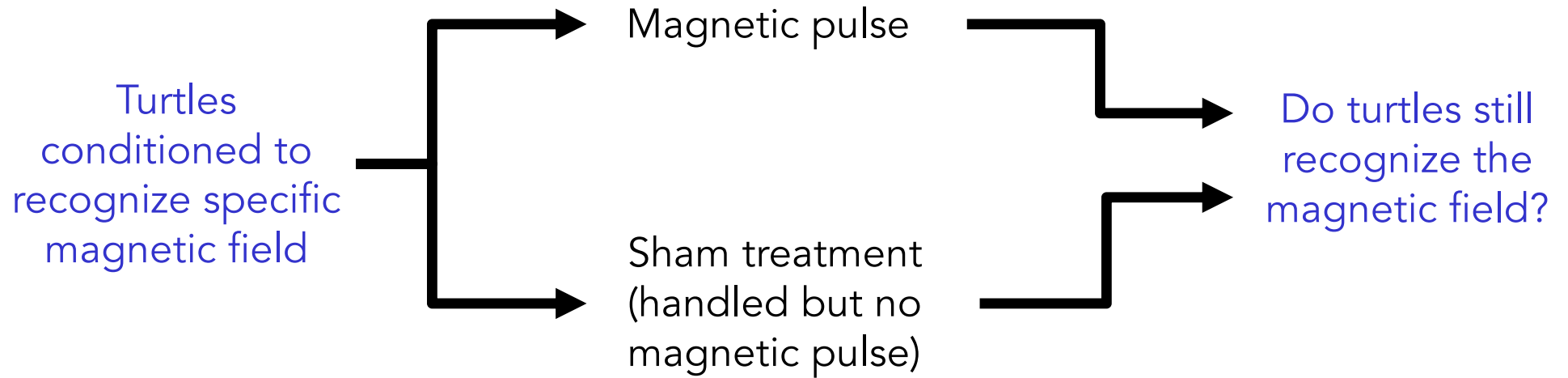


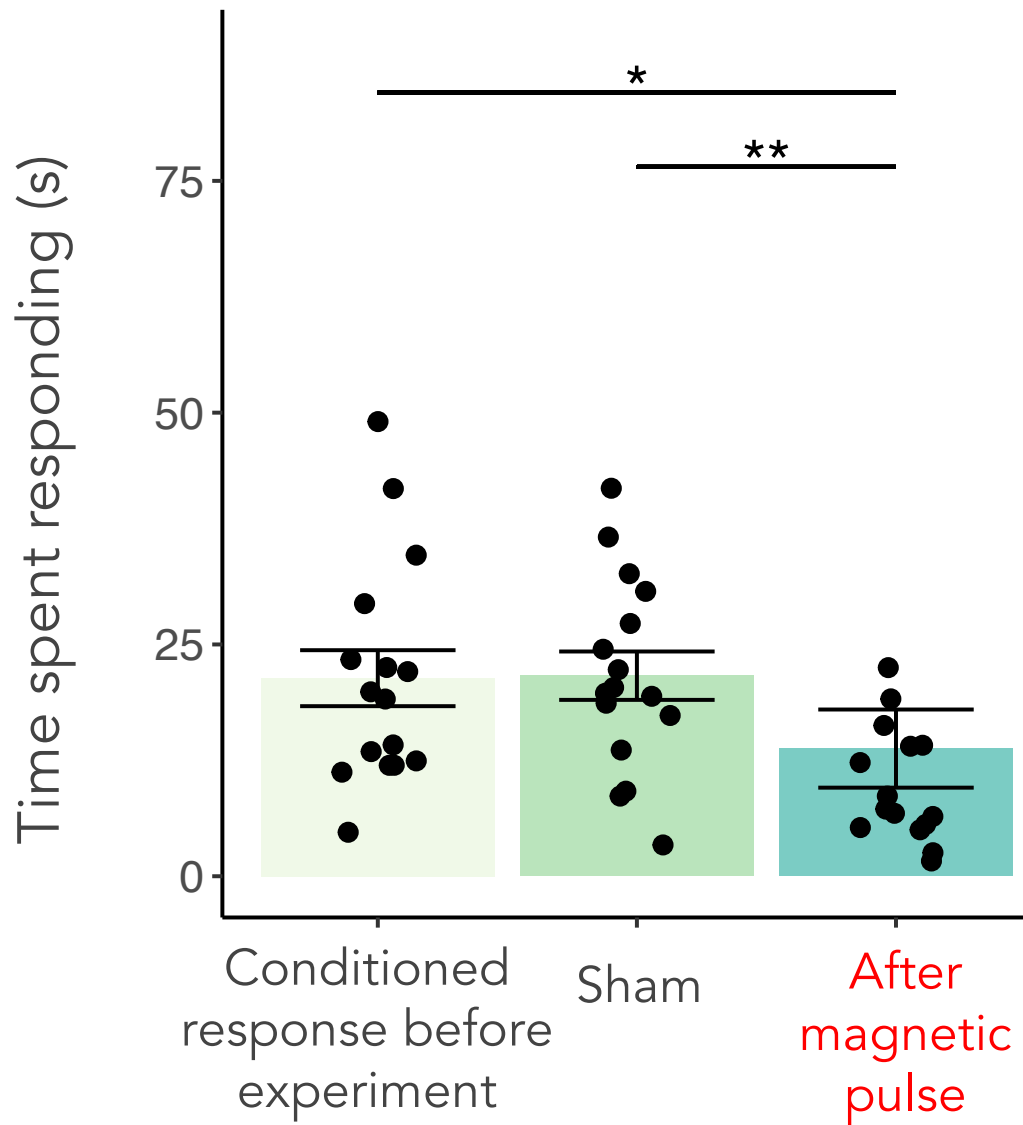
**Magnetic dipole
moment reversed**



might alter information
magnetic receptor
sends to brain

- Pulse magnetization might impair magnetoreception of the animal IF magnetic receptors are based on magnetite crystals.
- Moreover, theoretical considerations suggest that a magnetic pulse should not disrupt any other proposed magnetoreception mechanism (e.g., no expected effect on chemical magnetoreception).





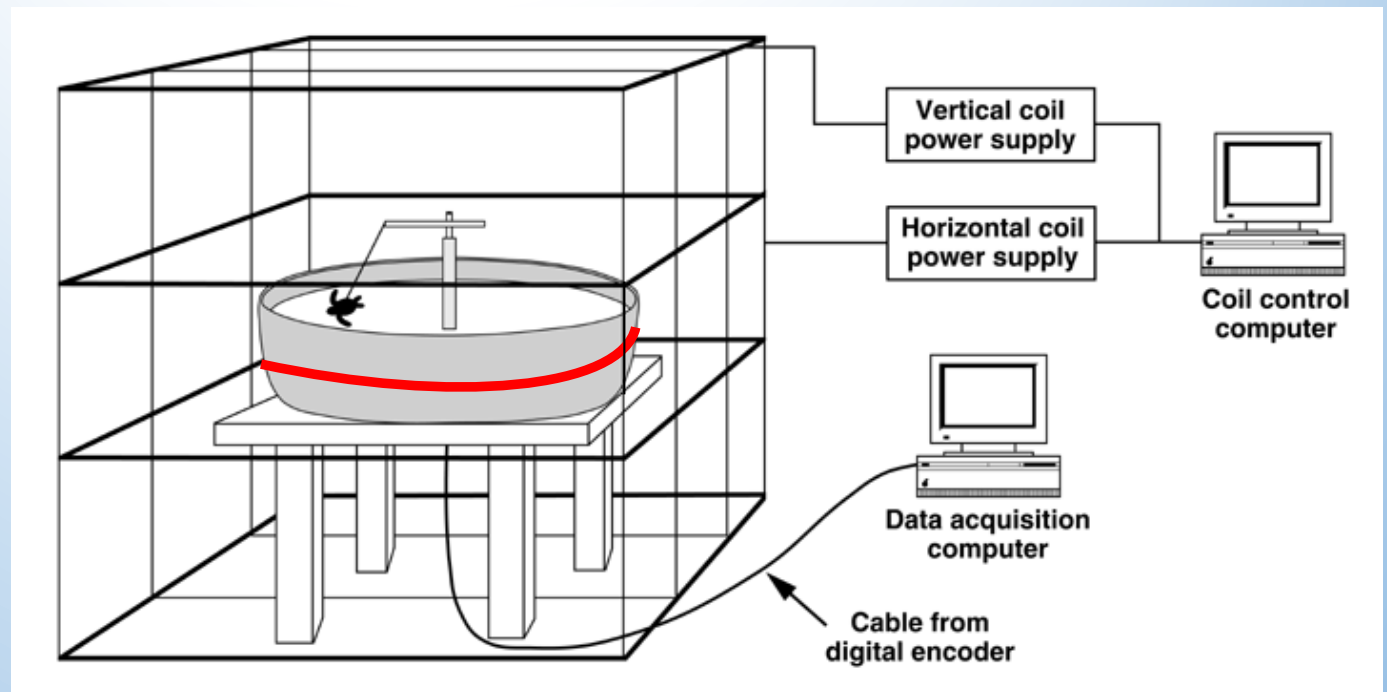
A magnetic pulse disrupts the turtle magnetic map sense, consistent with the magnetite hypothesis

Magnetic Compass Assay

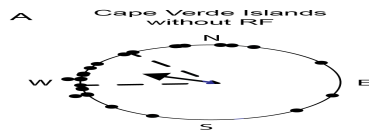
Is the **magnetic compass of turtles** disrupted by oscillating magnetic fields in the RF range?

We used a different behavioral assay in which turtles use their magnetic compass to swim westward.





- Loop antenna (red) generates RF oscillating magnetic fields
- Experiments were carried out with turtles in complete darkness
- Experiments were carried out under conditions in which turtles are known to use their magnetic compass to orient westward.



Control turtles
(no oscillating
magnetic fields)



Turtles tested with
RF oscillating
magnetic fields

Goforth et al., in review



Oscillating magnetic fields in the RF range disrupt the magnetic compass of sea turtles, consistent with the chemical magnetoreception hypothesis.



The same oscillating fields do not impair the magnetic map sense of turtles. A strong magnetic pulse, however, does.



Results are consistent with the interpretation that turtles have **two different magnetic senses**: a magnetic compass sense based on chemical magnetoreception and a magnetic map sense that is based on magnetite.

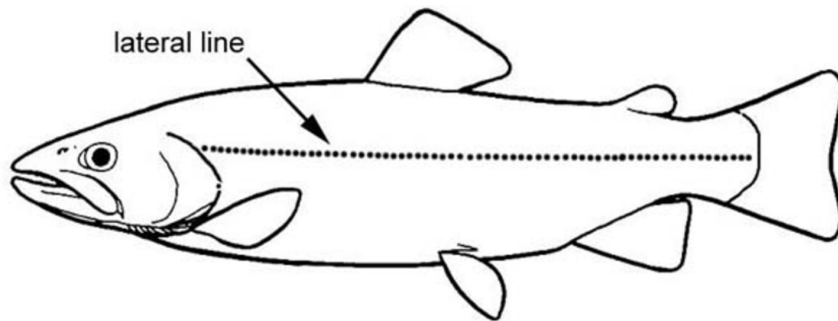


The turtle compass cannot be fully explained with current theories of chemical magnetoreception and cryptochromes; those require light, while the turtle compass functions in total darkness.

Investigating Magnetoreception Using Neurobiological Approaches

There is no established model system for studying the neurobiology of magnetoreception.

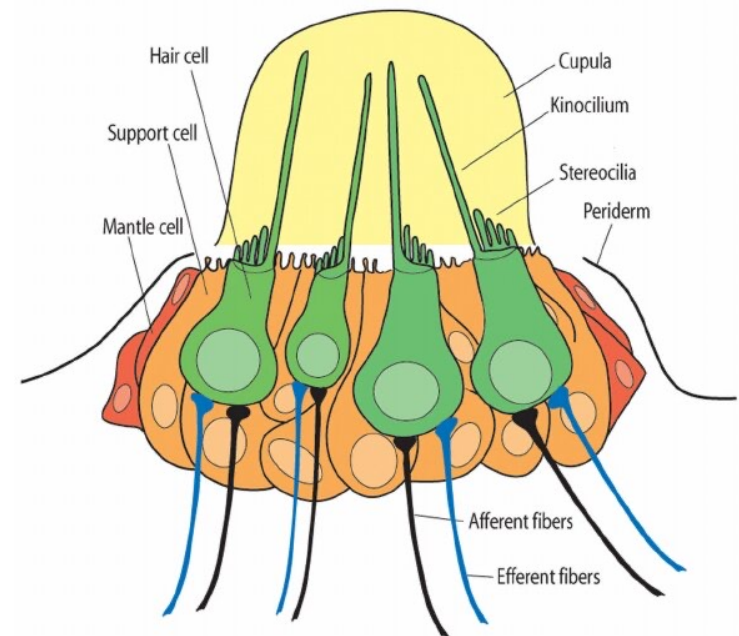
- Sea turtles are a great system for behavior, but not for neurobiology (they are protected species).



Many fish can sense magnetic fields

Many also have lateral lines composed of rows of sensory structures known as **neuromasts**

- Neuromasts contain highly-sensitive hair cells
- known to detect water movements and sound
 - might detect other sensory cues, including magnetic fields
 - consistent with this, magnetite has been detected in the lateral lines of several fishes



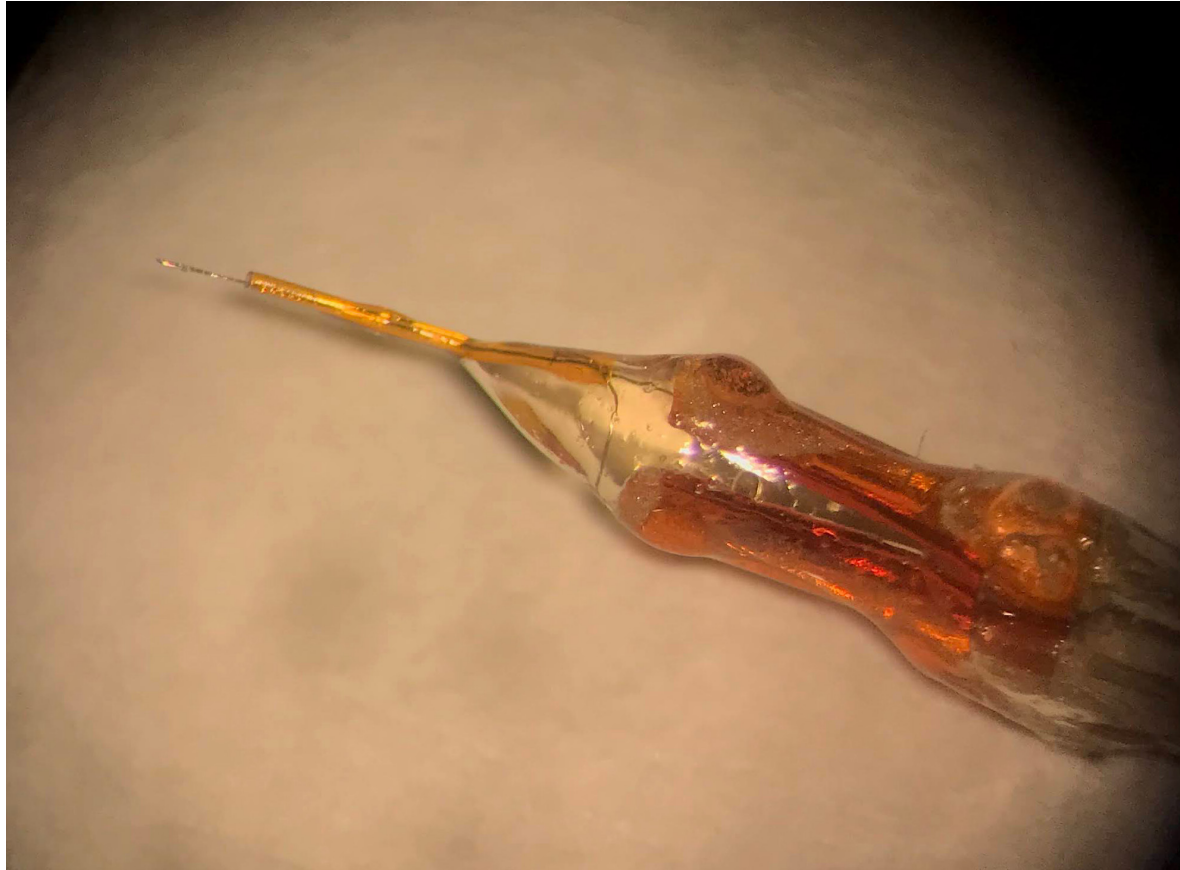
Neuromast of lateral line
from Chiu et al., 2008 [PubMed: 18408970]

oyster toadfish
(*Opsanus tau*)

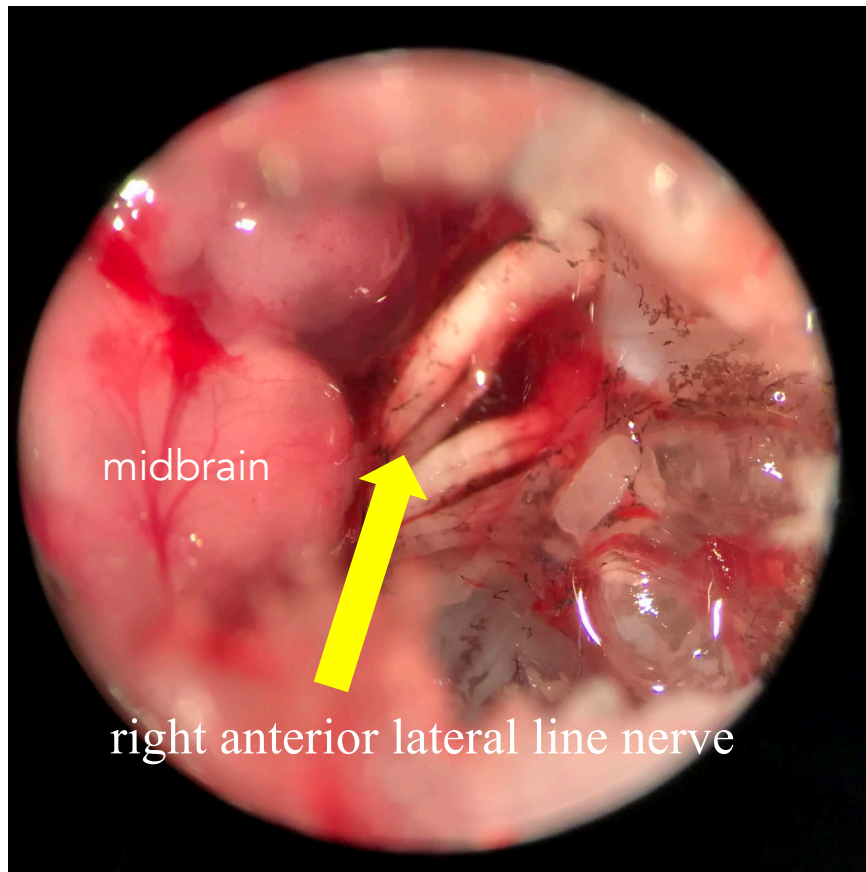


- The toadfish has been a model system for lateral line neurobiology
- Collaborating with Al Mensinger, Univ. Minnesota – Duluth.

Microwire Electrode

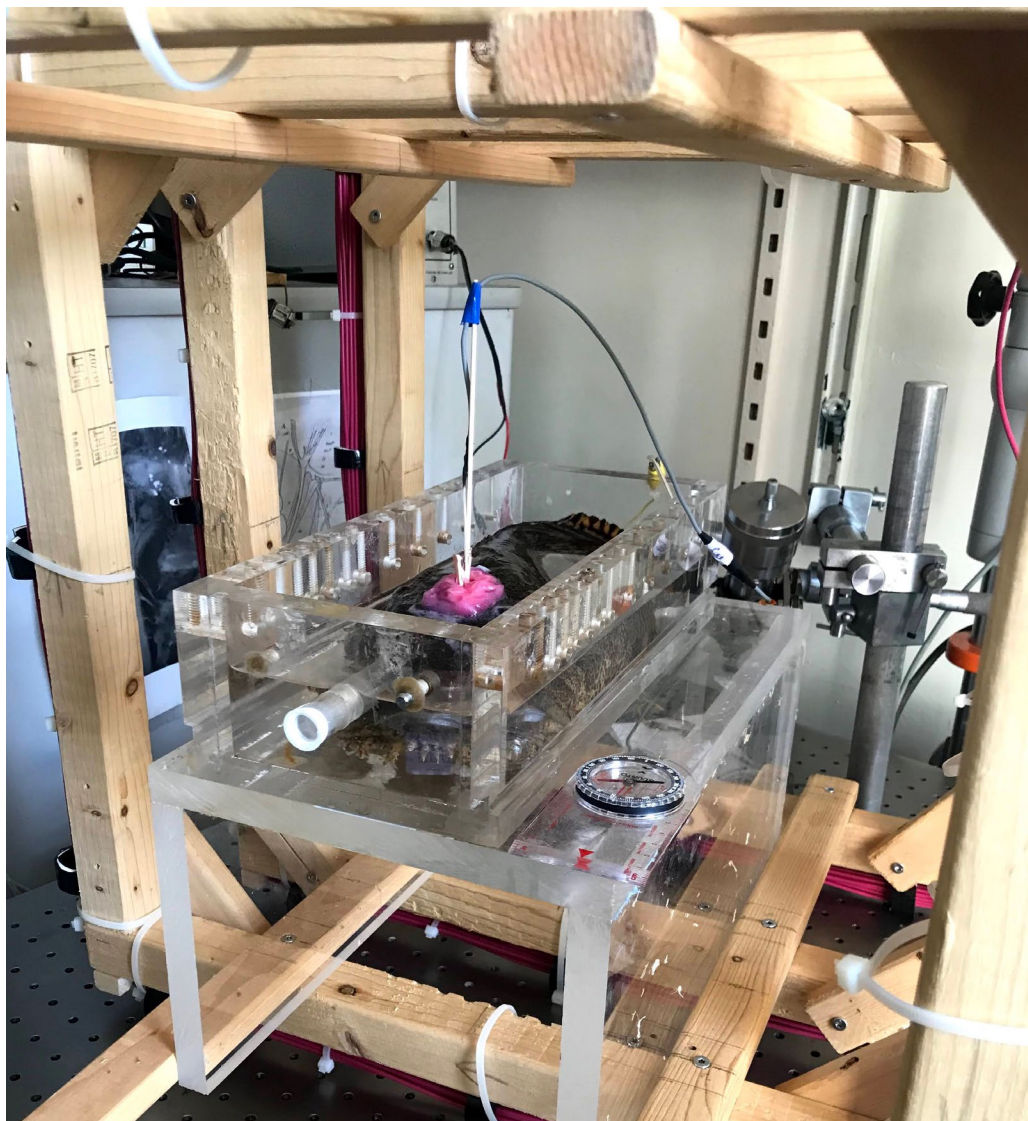


Toadfish Electrophysiology

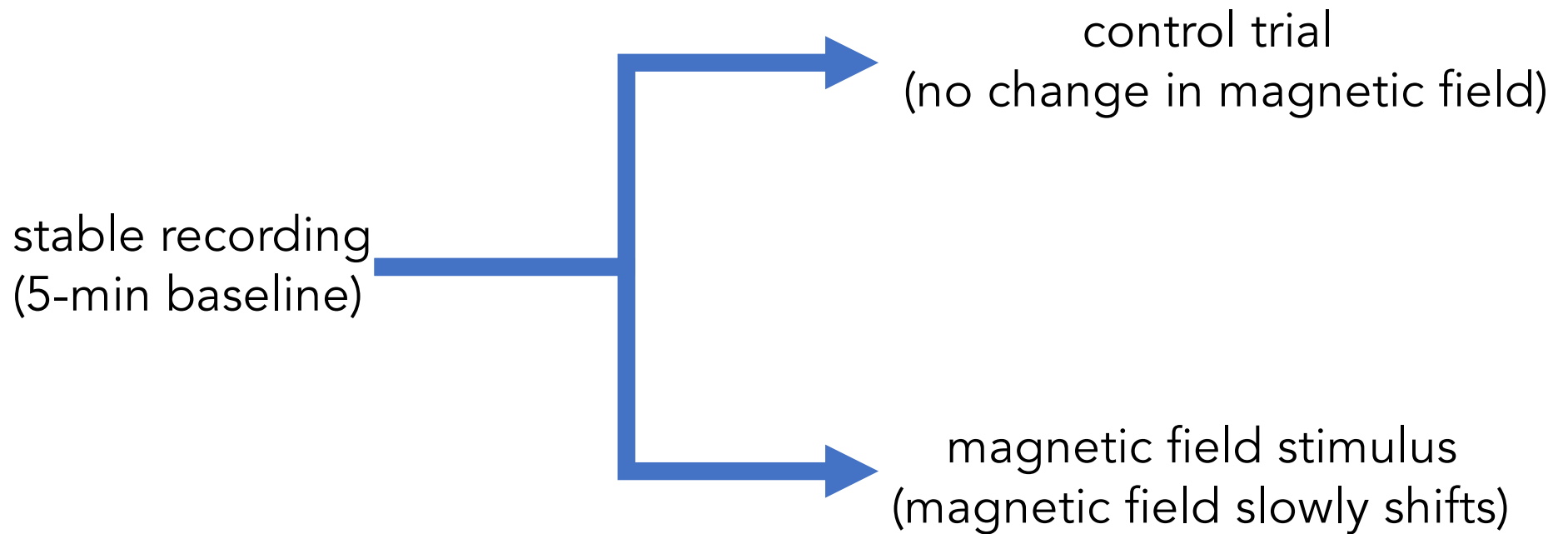


Approach:

- Record from lateral line nerve while altering magnetic field around the toadfish
- Determine if there are neurons in the nerve that show changes in electrical activity in response to changes in the ambient magnetic field.

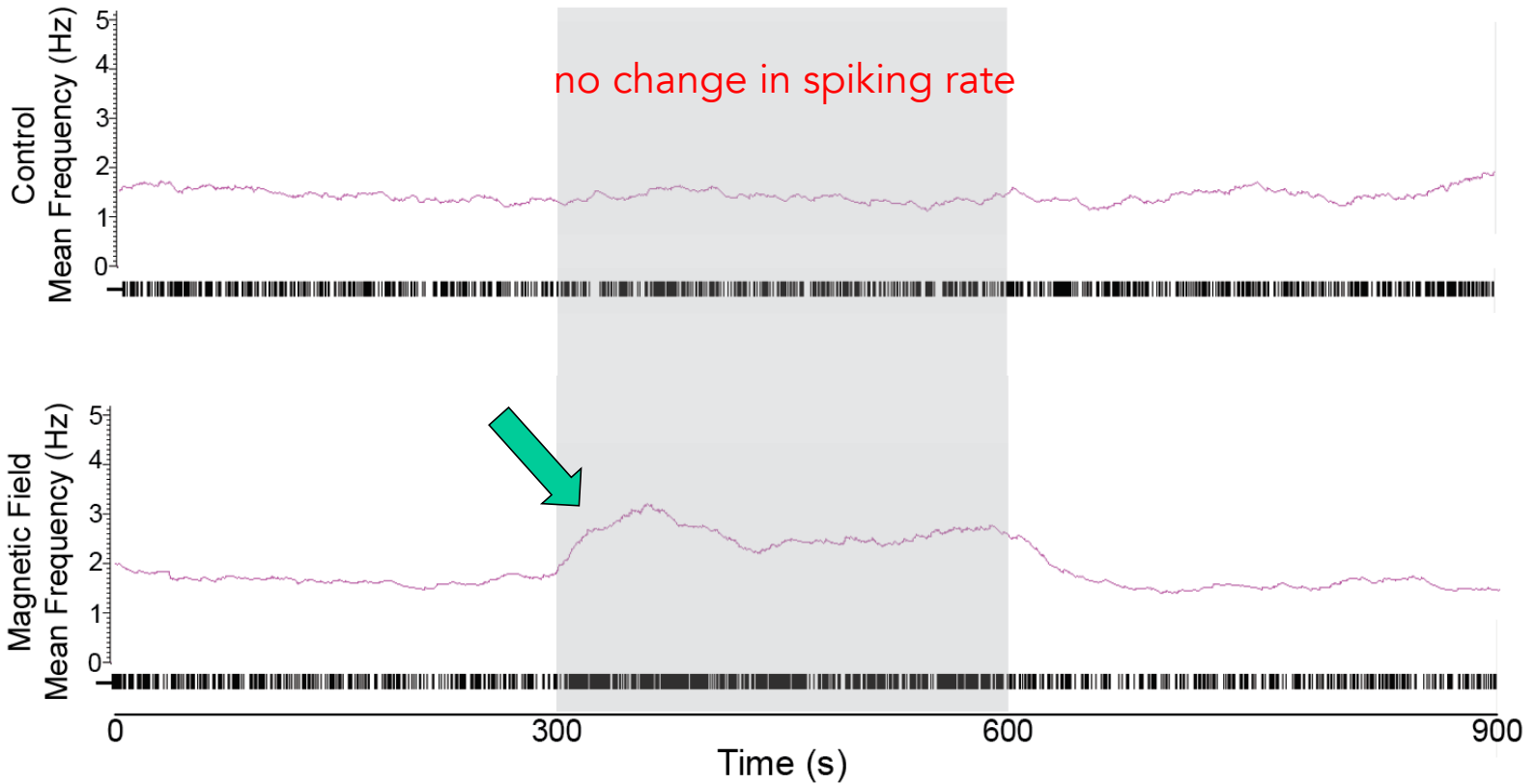


Procedure for electrophysiology trials



Initial results are promising (analysis is ongoing)

Control
(no change)



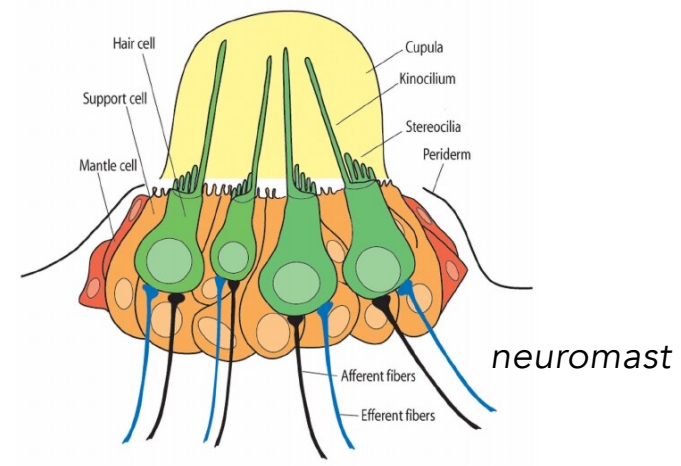
Magnetic
Field

5-min baseline

Initial electrophysiology results

Results suggest that a population of neurons in the anterior lateral line nerve responds to a changing magnetic field

Might eventually lead to identification of a magnetic receptor



oyster toadfish
(*Opsanus tau*)



New project: Neural activation studies using ribosomal proteins as markers

- ❖ Relatively new method of identifying brain regions involved in processing sensory stimuli



Used poison frogs from Central America

- these frogs have a magnetic sense
- methods for pS6 staining have been worked out
- colleague (Sabrina Burmeister) works with them

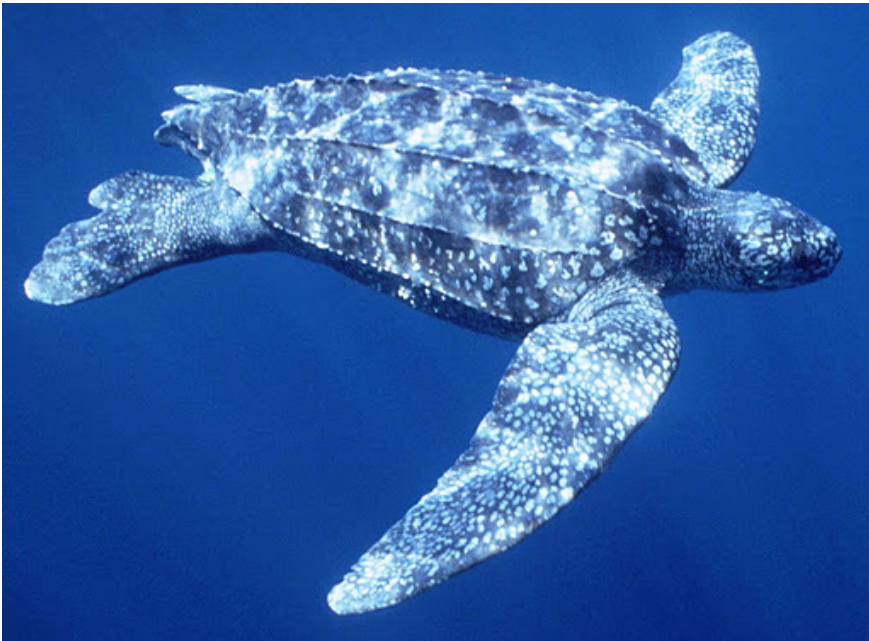
Objective: Identify where in the brain magnetic stimuli are processed, using a favorable neuroanatomical system.

Use computational techniques to study animal navigation, with the goal of uncovering new strategies and concepts with engineering relevance

Project leader: Sonke Johnsen, Duke University

One objective: Investigate the navigational strategies of open-ocean navigators by analyzing telemetry tracks.

- focus on species too large to study in the lab



leatherback sea turtle

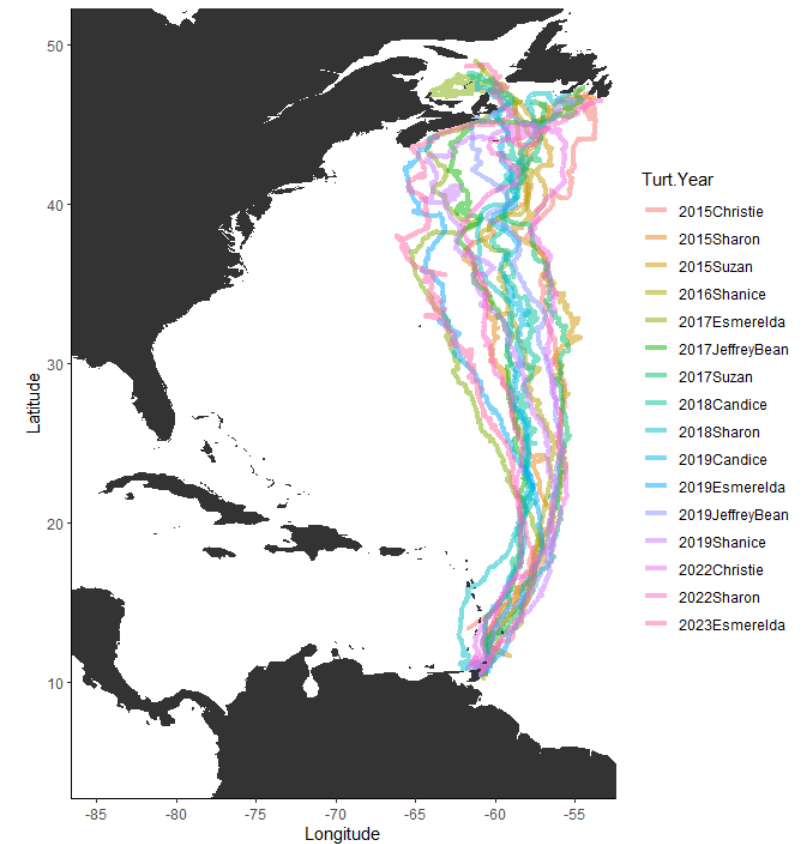


northern elephant seal

Leatherback Sea Turtle Telemetry

Acquired leatherback telemetry tracks from Mike James (Fisheries and Oceans, Canada)

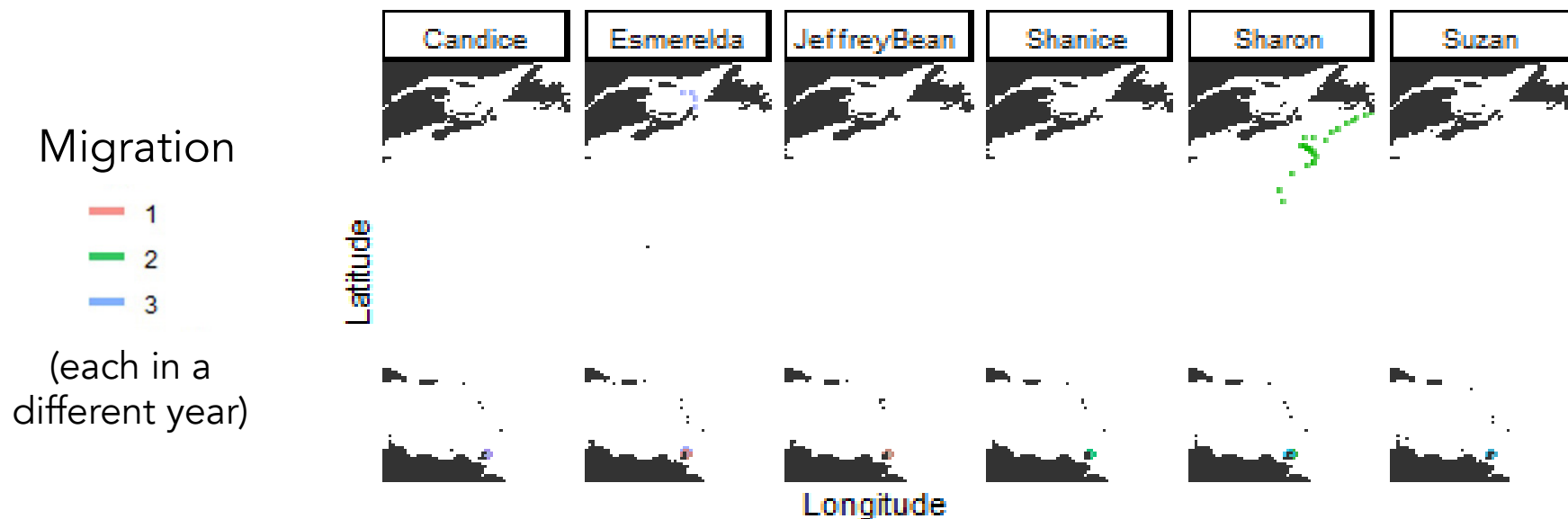
Leatherbacks migrate from nesting grounds in Trinidad to foraging grounds in Nova Scotia, Canada (>2,000 miles)



Turtles are long-lived; some individuals have been tracked on multiple migrations over a period of years.

Different turtles follow different routes

Some turtles are remarkably consistent in their path year after year



How can an animal retrace its path in the middle of the ocean?

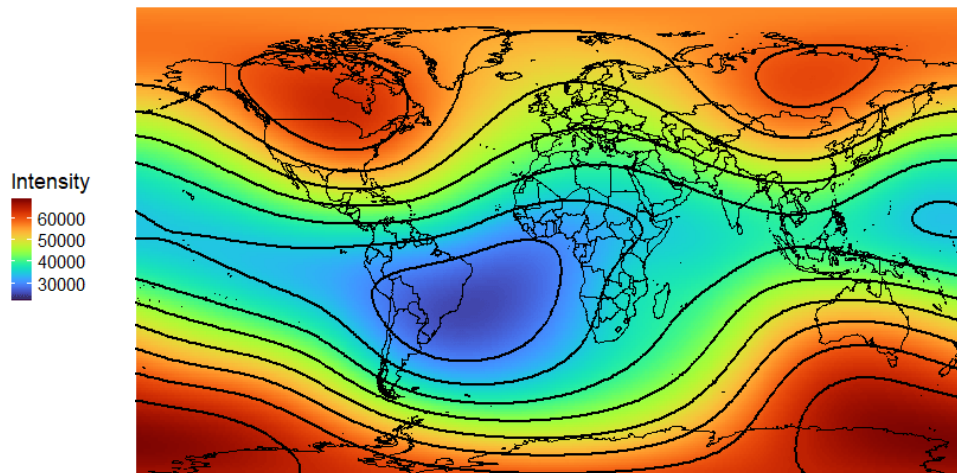
Is retracing a path in different years possible using magnetic navigation, given that the geomagnetic field changes over time?

Do we need to hypothesize use of alternative/additional non-magnetic cues to explain this capability?

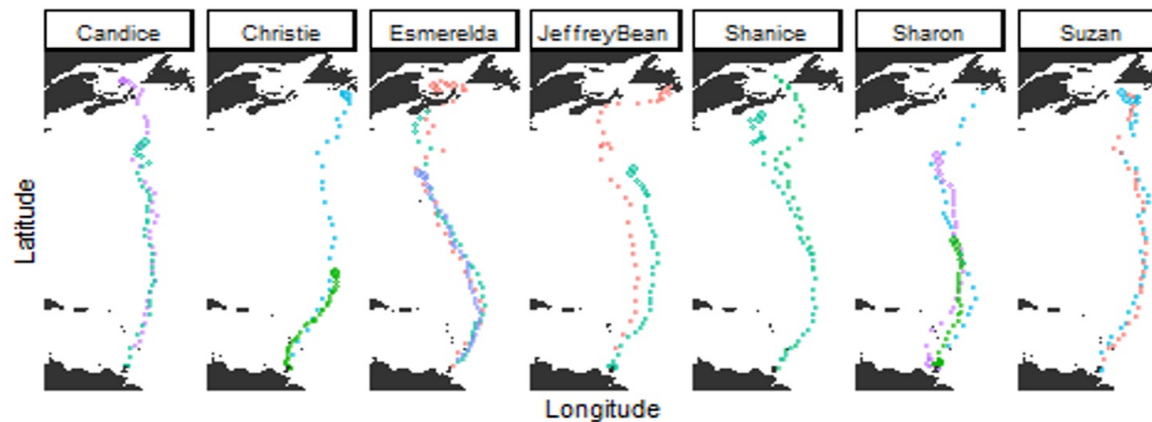


Note: Field drift (secular variation) is a potential problem not only for animals, but also for engineered magnetic navigation systems

Year: 1900



Animation of changing magnetic field intensity isolines from 1900-2024



Can path consistency be explained by magnetic navigation, given the magnetic field change?

Some possibilities:

- 1.) Leatherback turtles use an as-yet-undiscovered, non-magnetic cue for open-sea navigation (or in combination with magnetic navigation)
- 2.) Leatherbacks are deep divers and turtles may pay attention to magnetic anomalies on seafloor (these do not change)
- 3.) Turtles may break migration into segments, each with a fixed and recognizable endpoint (e.g., a seamount); use “magnetic signature navigation” for each segment

Investigate strategies and algorithms of long-range magnetic navigation using engineering approaches (simulations, robotics platforms)

Project Leader: Dr. Brian Taylor



Navigation Using Magnetic Signatures

- inspired by young loggerhead turtles, which migrate along a 10,000-mile circular pathway around the Atlantic Ocean.

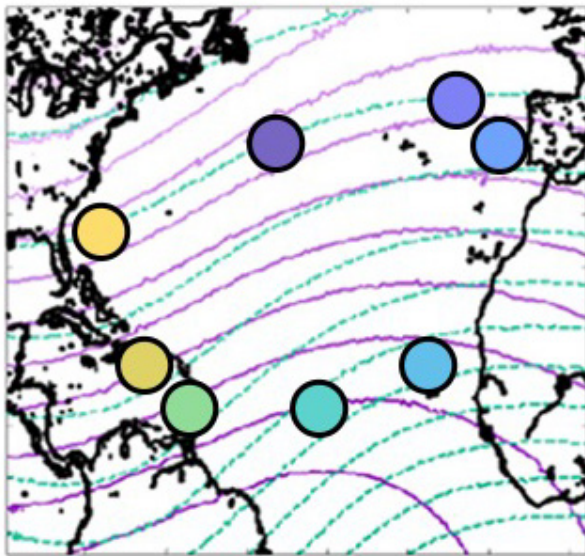


- young turtles inherit instructions that tell them what direction to swim when they encounter specific magnetic fields; in effect, the magnetic signatures serve as open-sea navigational markers

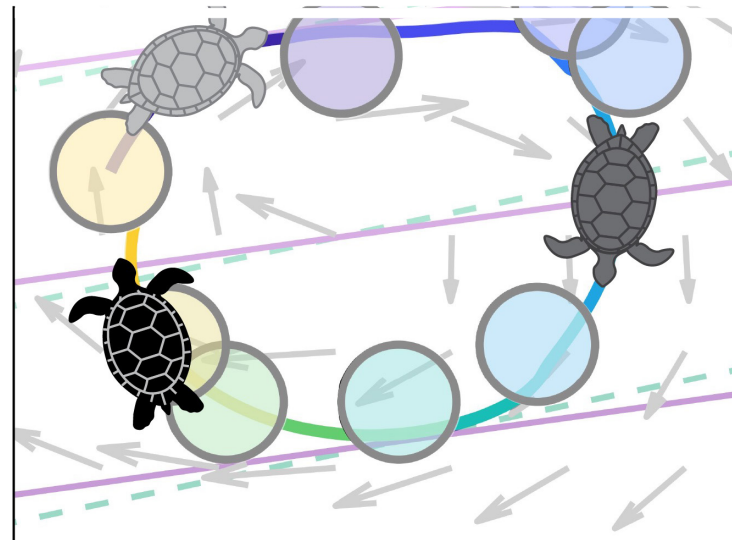
Simulations of long-range navigation (using magnetic signatures much as a turtle does)



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at CHAPEL HILL



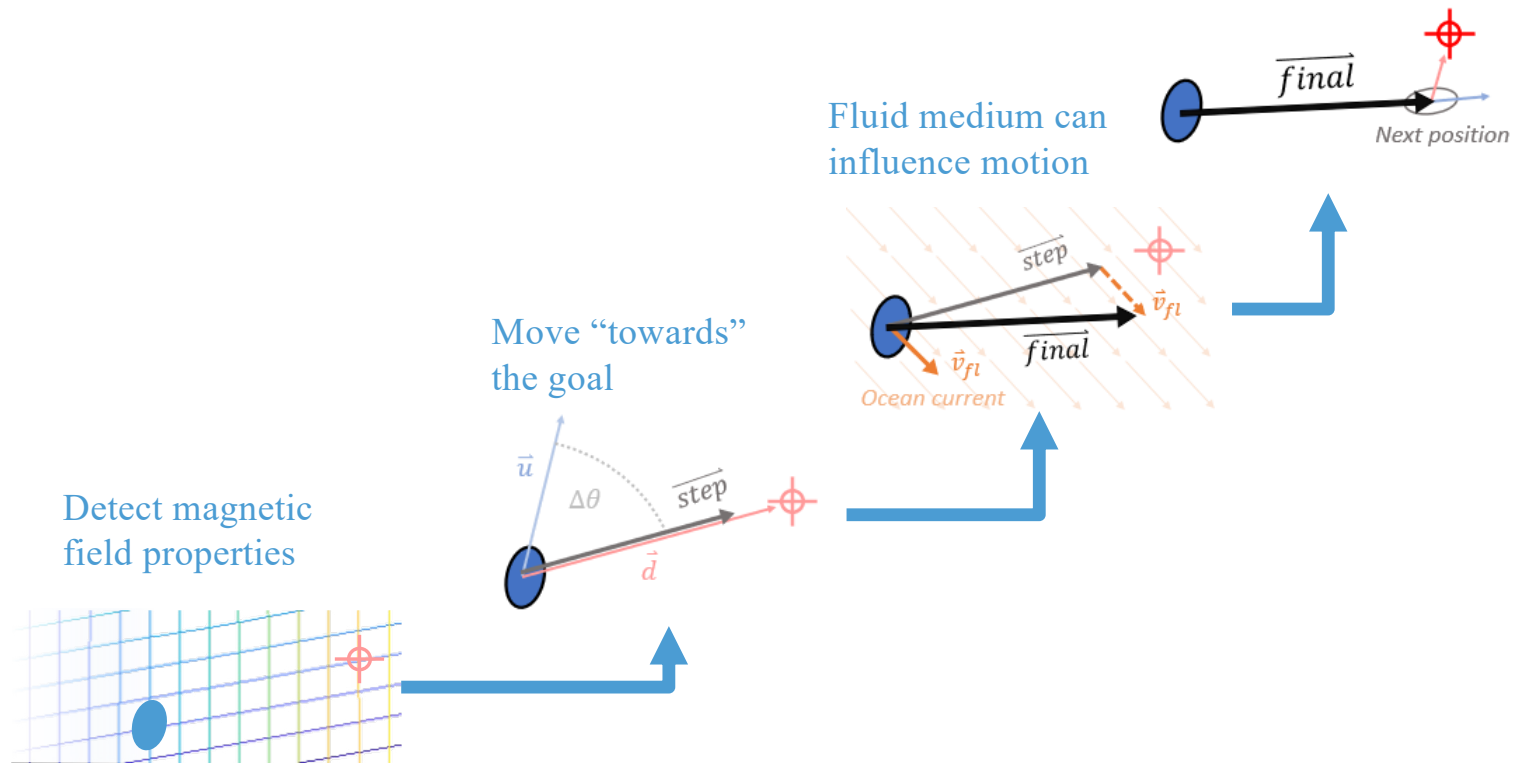
- Magnetic environment (curving isolines)
- Migration waypoints (colored circles)



Simulations – Navigation with Magnetic Signatures (Agent-Based Models)



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Vary: Measurement noise, measurement frequency, ocean currents

Simulations that mirror the real world

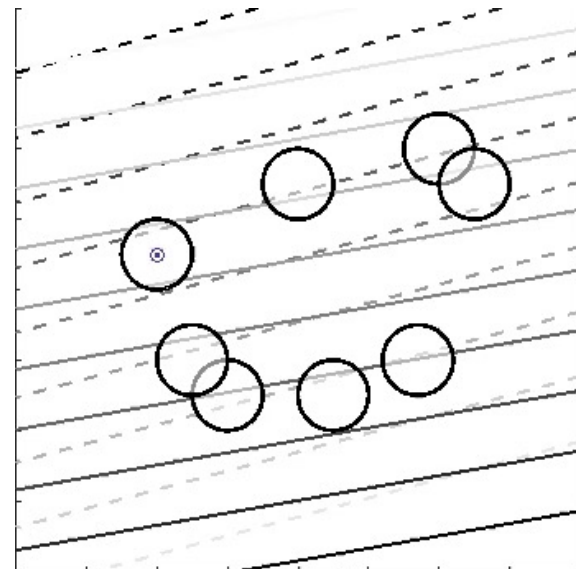


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Simulations have now been done under a variety of increasingly realistic conditions that include variations in:

- magnetic environment
- migration waypoints
- ocean currents

Navigational strategy appears valid and robust

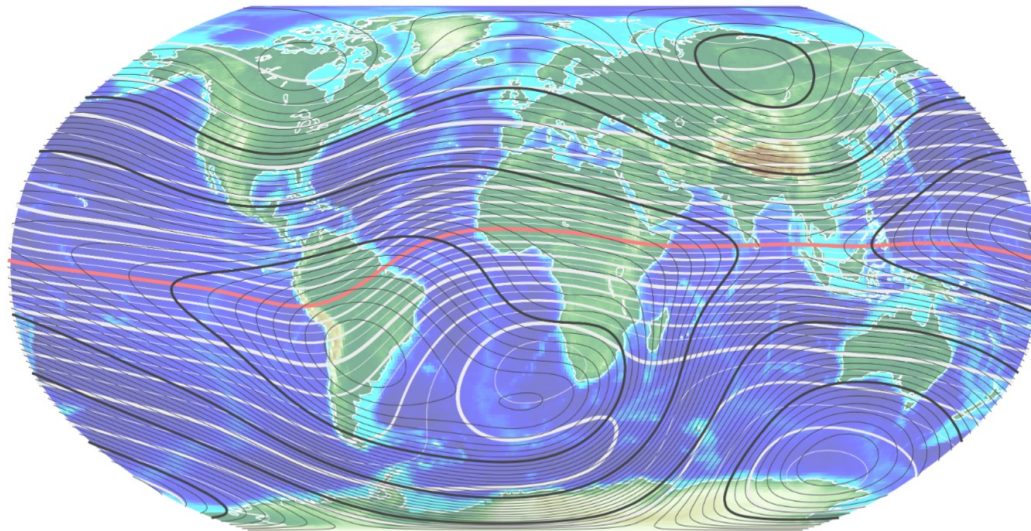


Taylor et al. 2021

Bioinspiration and Biomimetics

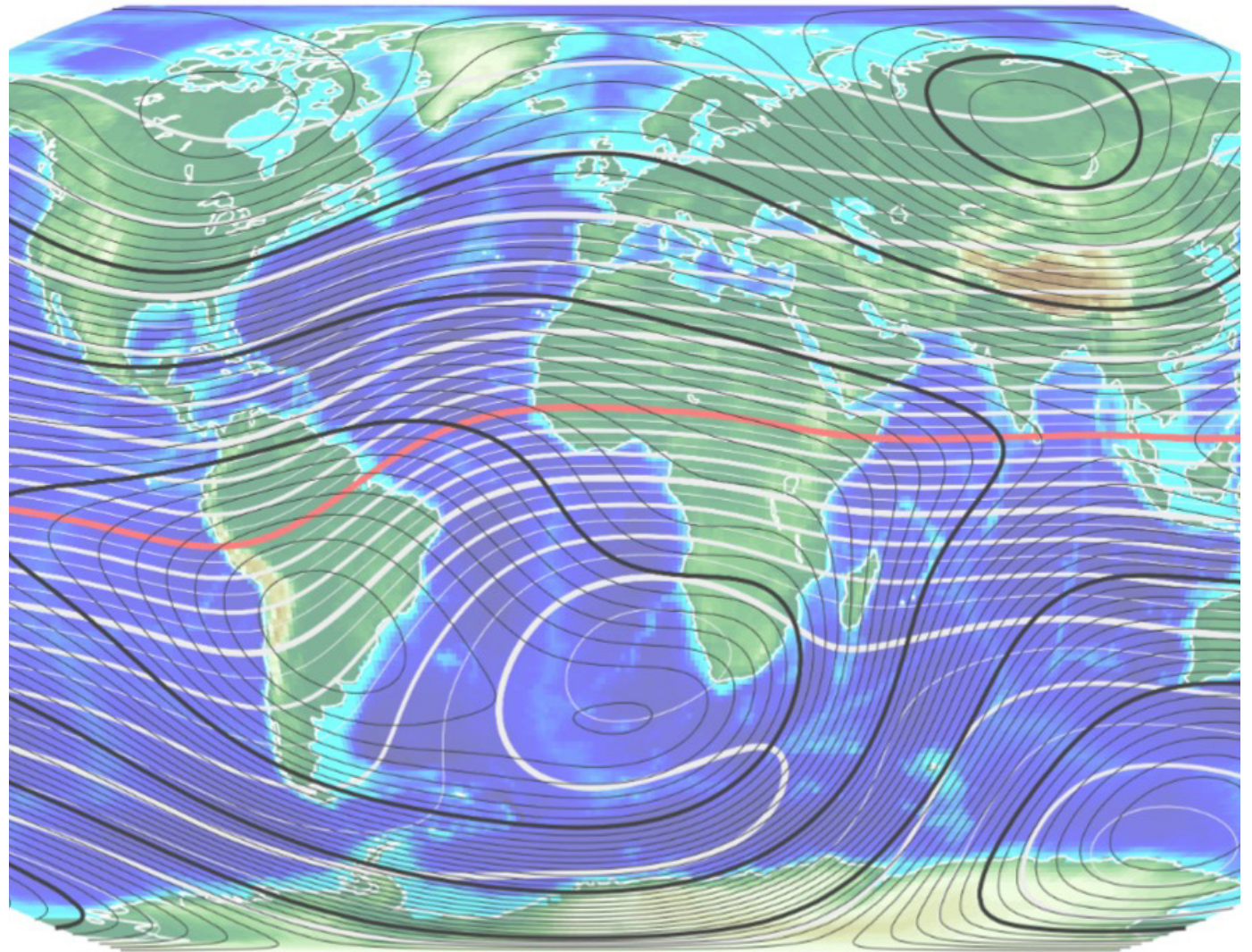
Behavioral Strategies/Algorithms

- The magnetic signature of a location can be defined as a combination of field intensity and inclination (angle of field lines relative to Earth's surface)
- Unlike latitude and longitude, patterns of magnetic isolines vary worldwide

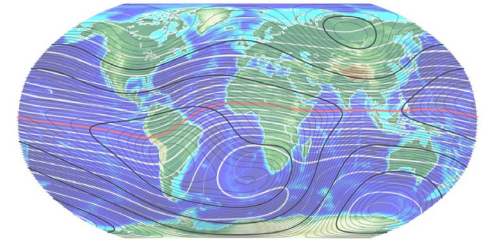


White lines: lines of
constant inclination

Black lines: lines of
constant intensity



Behavioral Strategies/Algorithms



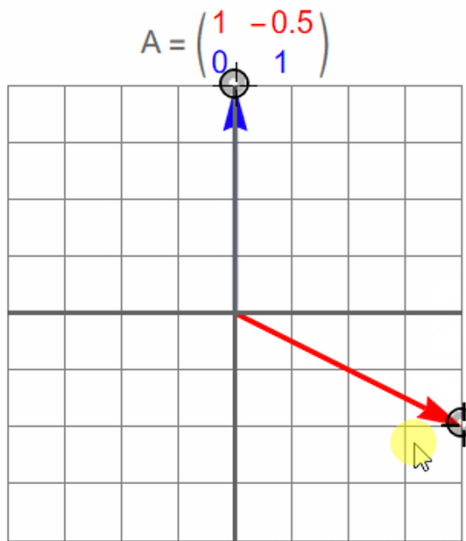
Can navigation using magnetic signatures be made to work anywhere on Earth or is it only possible in restricted geographic areas?

Brian Taylor and Jeff Gill published a new model of magnetic navigation in which non-dimensional scaling factors can be altered (*Gill & Taylor, 2024, Bioinsp. Biomim.*)

- scaling factors determine weighting assigned to inclination and intensity when the agent computes direction to travel
- looked at whether scaling factors can be “tuned” to result in successful magnetic navigation in different parts of the world

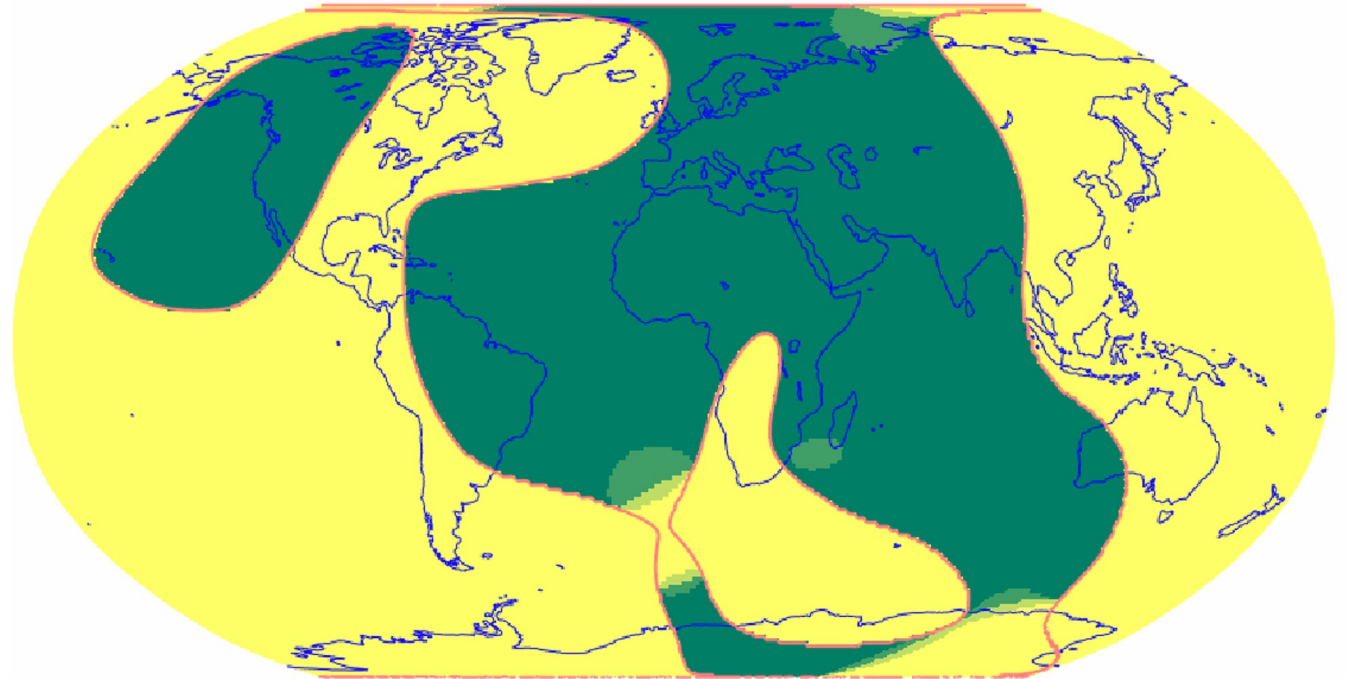
Short answer: YES! Scaling factors can be adjusted to optimize magnetic navigation in different global regions.

Scaling Factors



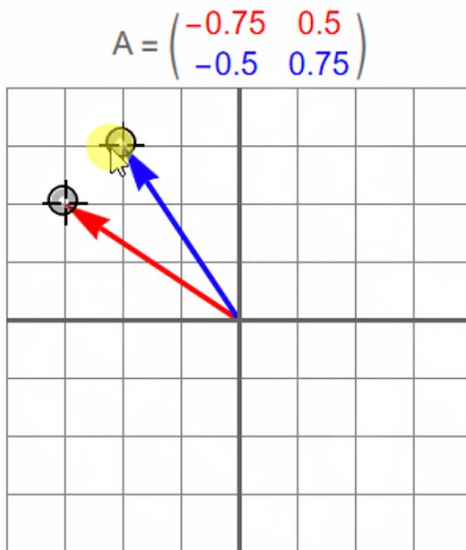
With this particular set of scaling factors:

- Green on map indicates areas where navigation is likely **successful**
- Yellow on map indicates areas where navigation is likely **unreliable**



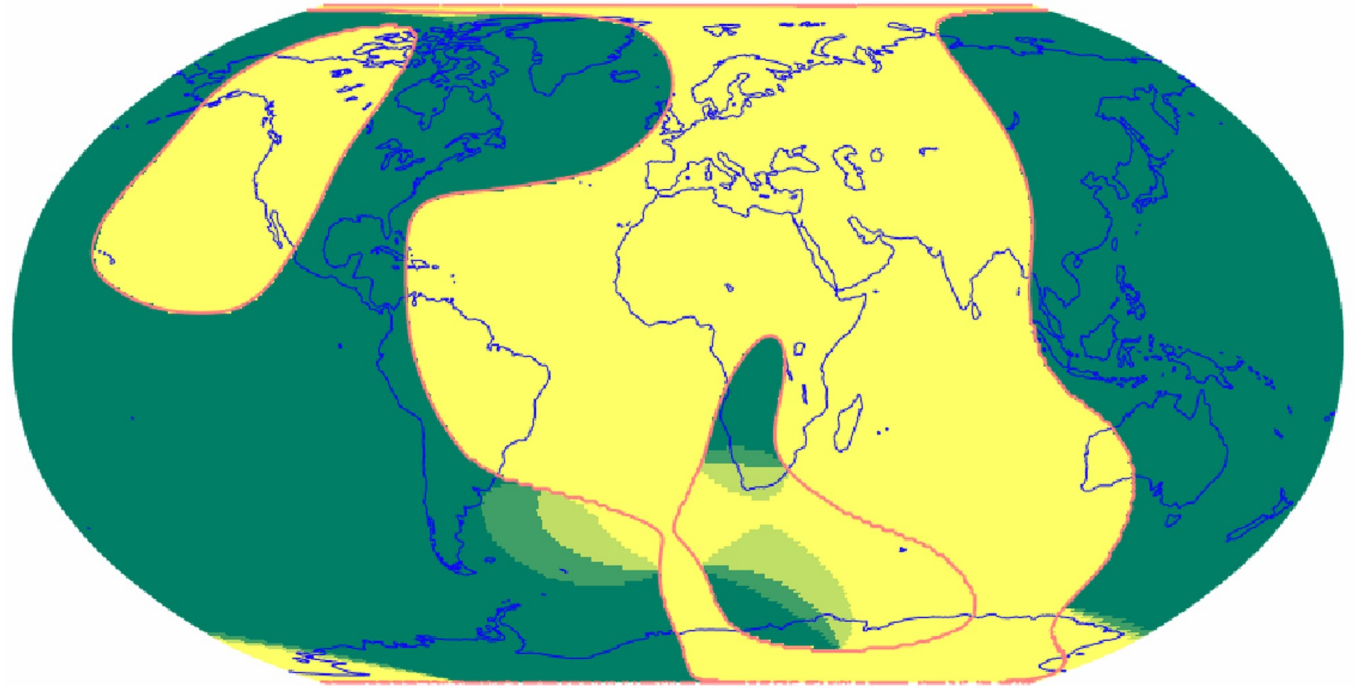
Gill and Taylor (2024) *Bioinspiration and Biomimetics*

Scaling Factors



With this particular set of scaling factors:

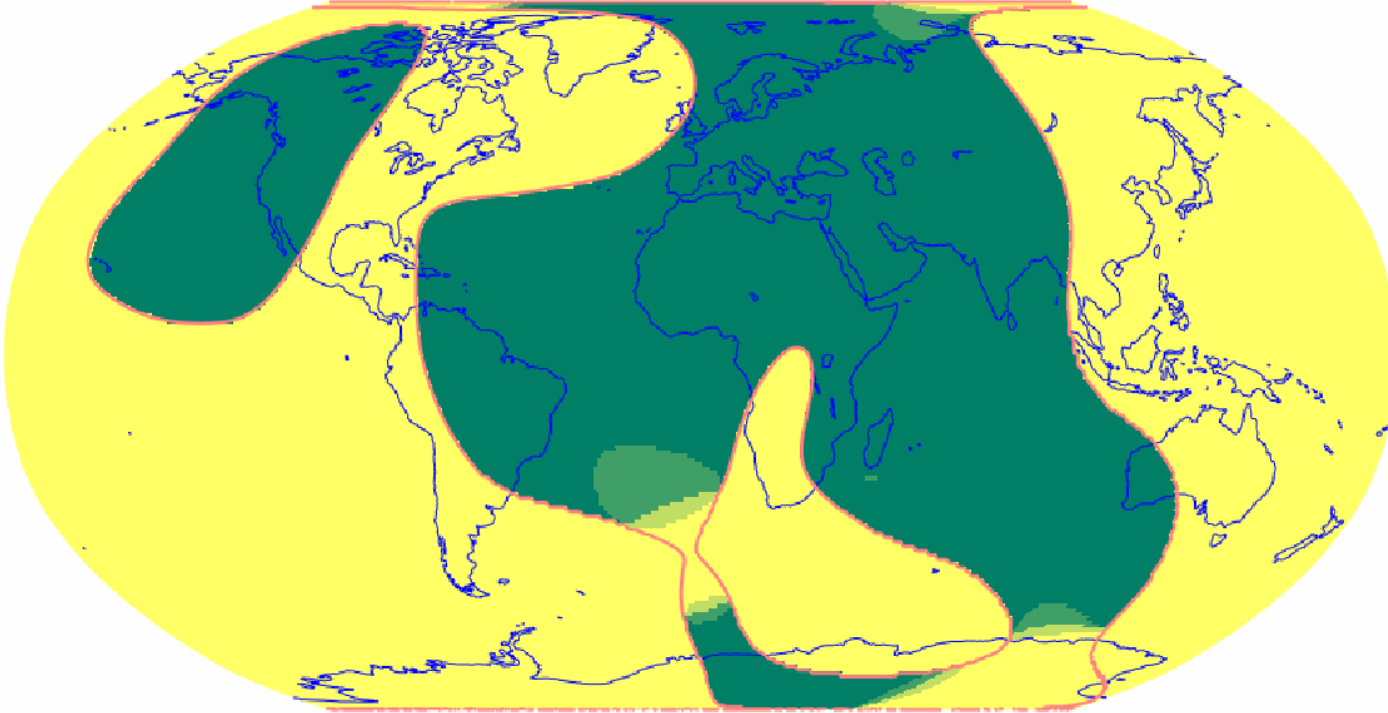
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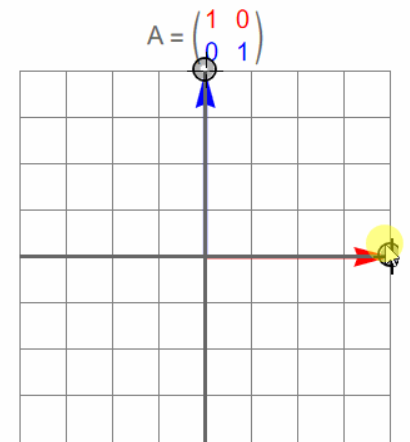
Gill and Taylor (2024) *Bioinspiration and Biomimetics*

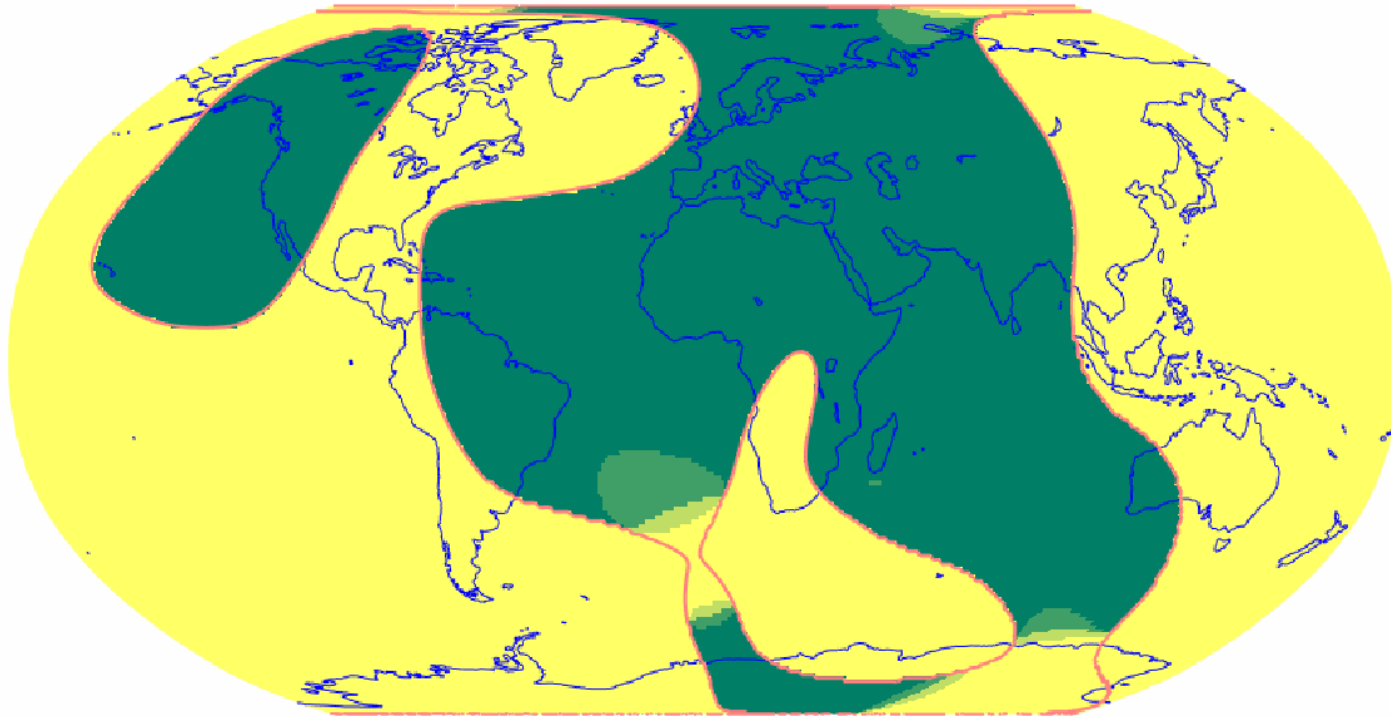
With this particular set of scaling factors:

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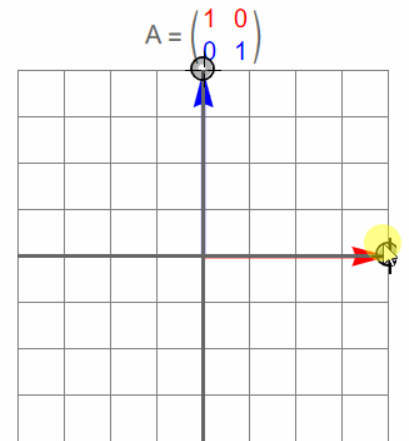


Scaling factors





Scaling factors



Key findings:

- There is no single combination of scaling factors that works everywhere
- Scaling factors can be “tuned” to allow magnetic navigation in nearly every part of Earth.

Acknowledgments

Turtle magnetoreception

Dr. Kayla Goforth, UNC Biology
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Dr. Reyco Henning, UNC Physics
Dr. Andrew Gavin, UNC Physics
Dana Lim, UNC Biology
Hazel Havens, UNC Biology

Fish neurobiology

Alayna Mackiewicz, UNC Biology
Dr. Al Mensinger, U. Minn - Duluth

Turtle telemetry track analysis

Dr. Bradley Wilkinson, Duke Biology
Dr. Jesse Granger, Duke Biology
Dr. Mike James, Fisheries & Oceans Canada

Engineering simulations and robotics

Dr. Jeff Gill, Case Western
Dr. Catherine Kehl, UNC Biology
Faye Piephoff, Case Western

Special thanks to:

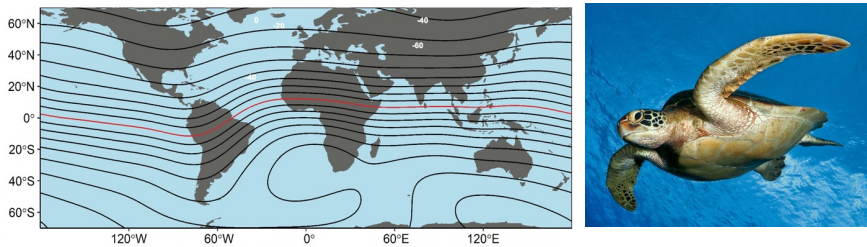


Dr. Pat Bradshaw

Magnetoreception in Marine Animals and Bio-Inspired Algorithms for Long-Range, GPS-free Navigation

Objective: Investigate how sea turtles and other aquatic animals detect Earth's magnetic field and use it to guide long-range navigation, with a view toward engineering bio-inspired, GPS-free navigation.

- Determine the capabilities, sensitivity, and bio-sensory basis of long-range magnetic navigation in sea turtles and other marine animals.
- Identify strategies and algorithms that lead to successful geomagnetic navigation in both engineered and biological systems.
- Use 'Big Data' analytics and machine learning to discover multi-modal strategies of animal navigation with engineering relevance.



Left: Isolines of magnetic inclination angle used by sea turtles as a proxy for latitude

Accomplishments:

- Evidence that sea turtles have two different magnetic sensing systems, each based on a different underlying mechanism.
- Development of electrophysiological and neuroanatomical techniques for studying how brains of animals detect magnetic fields
- Successful tests of bio-inspired magnetic navigation strategies using simulations and robotics platforms
- Evidence that collective navigation can enhance navigational precision.
- Demonstrated feasibility of magnetic navigation on other planets.
- Published 17 peer-reviewed papers, 3 Ph.D. dissertations.

Technical Approach:

- Use neurobiological and behavioral techniques to investigate the mechanisms that underlie magnetic field detection in marine animals and identify possible strategies of long-range navigation.
- Use engineering approaches (modeling, simulations, and robotics) to identify the strategies and algorithms that lead to successful long-range navigation in both biological and engineered systems.
- Analyze paths of long-distance marine migrants using 'Big Data' analytics and machine learning, with the goal of uncovering previously unknown navigational strategies and algorithms that can be leveraged for engineering purposes.

Uniqueness: This project represents a novel interdisciplinary approach to studying magnetoreception, merging techniques ranging from cellular neurophysiology and behavior to robotics and Big Data analytics. It is also the first attempt to acquire a detailed understanding of long-distance magnetic navigation that can be leveraged for engineering applications.

DoD Benefit:

- Advances in understanding the strategies and algorithms used by animals during long-distance magnetic navigation to specific goals, with applications for autonomous vehicles and navigation in GPS-denied environments.
- Improved understanding of biophysical mechanisms underlying magnetic field detection by animals, with potential applications for new technologies and distributed sensing.
- Novel strategies for facilitating navigation through uncharted terrain (including other planets) without requiring a map.