BIOL 487 – Computational Neuroscience

Final Project – J. Romero

Avian magneto-receptive home-point navigation: A 2-Dimensional representation and analysis

Introduction

Migratory birds have been leveraging the earth's magnetic field for large scale special navigation since well before the era of man. They exhibit time-dependant migratory patterns, with increased migratory readiness in the hours of dusk and dawn, causing early observers to posit that their migratory navigational cues are stellar (ie. The use of the sun and/or moon as bearings) [1]. Indeed, the dawn/dusk migratory readiness signs, as shown in figure 1, point observers from simpler times to an explanation for avian navigation that is similar to our own primitive techniques.

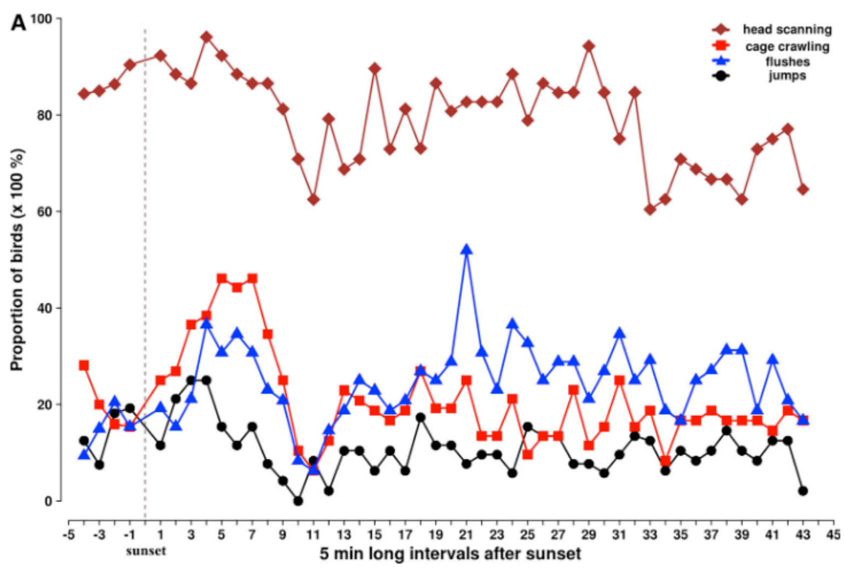

Figure 1: Migratory readiness indicators timed relative to sunset [1]

However, more recent investigations have uncovered the real reason for bird's restlessness during the dawn and dusk hours – specifically as they relate to the true 'north star' of avian navigational systems, the earth's magnetic field [2].

When it comes to the understanding the mechanisms behind Avian magnetoreception systems, none have championed the area of research better than Wiltschko and Wiltschko at the university of Frankfurt [3], [4], [5]. The latter of these cited papers is a more recent summation of the findings over the past few decades. The current knowledge-based can be summarized by splitting avian magnetoreception into two mechanisms with two distinct receptors.

1. The first receptor is the ‘compass’ receptor found in the retina of migratory birds. It functions via a radical pair mechanism occurring in a cryptochrome found in the cone cells that oxidizes in two stages [5], [6].
    a. Stage 1 occurs only in the presence of high-energy incident photons, that is, the environmental light must be above a certain intensity threshold as well as below a wavelength threshold (see figure 2).
    b. Stage 2 is the magneto-sensitive process whereby, depending on the orientation to an external magnetic field, the chemical result from stage 1 can oxidate into either singlet or triplet products. This is enabled by the spin characteristics of the redox reaction which then yields key ratio concentrations of triplet and singlet products that is later interpreted by the nervous system via the optic nerve (See figure 3) [5].

The nucleus of basal optic root, as well as the tectum opticum have been implicated as the cite for the processing of the information, though the research is too preliminary to make any concrete comments. Instead, it is understood that the magnetic-visual cues are integrated with other sensory information in the higher brain centres to provide a strong navigational model for strong migratory navigators [5].

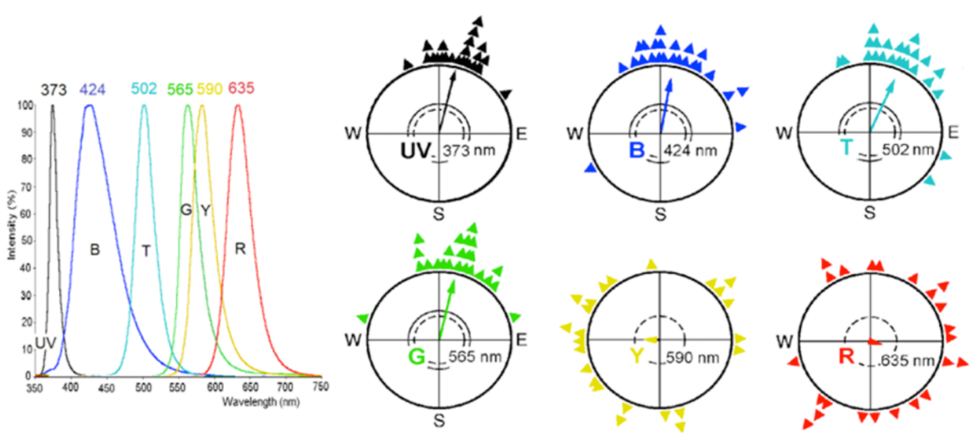

Figure 2: Light dependant characteristics to the precursor reaction that enables the radical pair mechanism. On the left is the spectra of LEDs used in the tests. On the right is the reorientation behaviour in the presence of this light observed in European Robins under each of the narrowband [5].

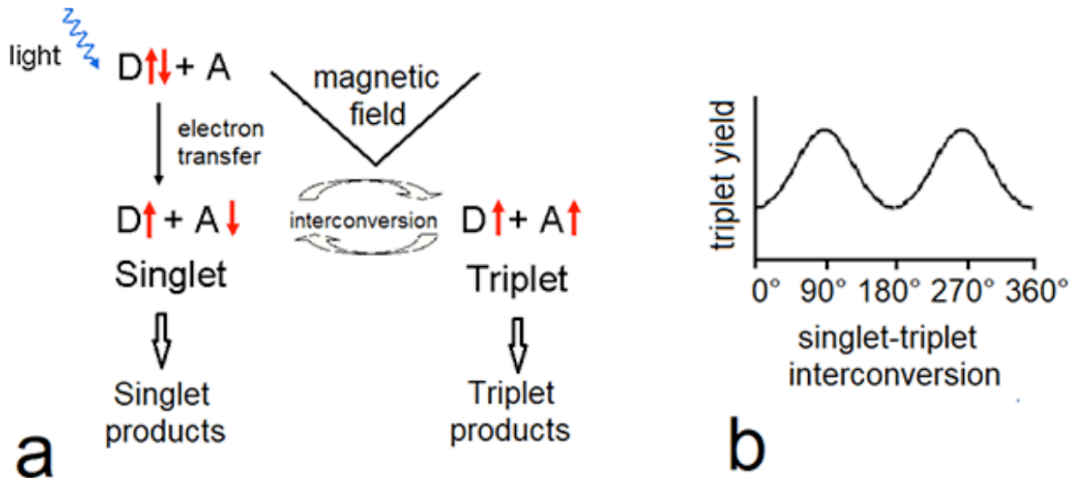

Figure 3: Triplet and Single Conversion schema for the latter stage of the radical pair mechanism occurring in the cone cells of birds. The left (a) shows how the second-stage decomposition of the relevant cryptochrome can occur with and without a normal orientation to an external magnetic field. The right (b) shows how the relative yields of single or triplet products serves as the orientational cue in avian magnetoreception [5].

2. The second receptor is found in the upper beaks of birds and function in a more straight-forward way. This receptor is enabled by magnetite (naturally occurring Fe_3O_4) clusters embedded in the upper dermal layer of the beak. Electrophysiological studies and behavioural observations have indicated that these receptors are mediated through the trigeminal nerve responding in the ophthalmic branch to changes in magnetic intensity[3]. Interestingly, experiments using strong magnetic pulses can potentially alter the magnetization of these iron-rich magnetite structures. These disruptions alter the bird's ability to navigate which suggests that this receptor is imperative in the higher order environmental mapping that enables long distance migration[3].

   This receptor is believed to function as a sort of magnetometer for the bird; perfectly complimenting the orientational compass in the retina by providing a reference for the magnetic field's intensity at any given point [5].

This project endeavours to explore a home-point navigational model for migratory bird species by implementing a neural network capable of interpreting and learning geomagnetic cues to direct itself toward the home point. As well, we will briefly explore the reorientation behaviour (as shown on the right side of figure 2) by using a winner-take-all synapse model to suggest that birds are very capable of orienting themselves in the direction of magnetic field lines. Indeed, it seems the receptor mechanisms describes above provide enough information to navigate point-to-point anywhere on earth; likewise, it is the navigational mapping and recall capabilities (especially of point-to-point capable species) that have the most relevance and keen interest for this project.

Methods

In order to maintain a manageable scope for this experiment, the decision is made to explore the same point-to-point navigational systems aforementioned but in a 2-dimensional space. This choice does bring its own challenges, namely with regard to representing a magnetic field in 2-dimensional space, but the pros far outweigh the cons, especially when we compute the large network and datasets necessary for the experiment.

<u>Generating a magnetic field representation</u>

We begin by defining a function that can generate a vector field to represent the magnetic field in 2-dimensional space. As a simple starting point, we consider a rudimentary representation of a magnetic field for which all points on the plane point northward (+y), this would be given by…

$$\vec{B} = B_0 * \hat{j}$$

Where B_0 is the strength of the magnetic field at any given point as it is uniform at all points in space and ĵ is a unit vector pointing in the positive y direction which represents northward.

The vector field that can be created from the equation above does not provide any locational information as it is uniform along the plane. We can vary the strength along the y-axis and point the vectors inward to provide a gradient for geomagnetic navigation. This field can be created using this equation…

$$\vec{B}(x, y) = (B_0 + \alpha * y)\hat{j} - \left(\beta * y * \frac{x}{|x|}\right)\hat{\imath}$$

Where α determines the rate at which the magnetic field increases with increasing y and β determines the rate at which the magnetic field lines converge with increasing y.

Lastly, we take add an x-dependence to the $\hat{\imath}$ component so that there is variability in the x-axis beyond defining the left or right side of the y-axis, this would be given by…

$$\vec{B}(x,y) = (B_0 + \alpha * y)\hat{\jmath} - \left(\beta * y * \frac{x}{|x|} * \left(X_{dependance} * x\right)\right)\hat{\imath}$$

It's important to note that the above equation, as it was implemented to generate a 2-dimensional vector field using Python's Numpy library, is not an direct implementation of the magnetic field equations that inspired it [7], nor is it a planar slice of a real 3-dimensional magnetic field. This is because it is impossible to accurately model a 3-dimensional magnetic field in 3-dimensions as it varies in all 3 dimensions at almost all points in space (the axial planes being the exception and not useful for a realistic representation of a navigational model).

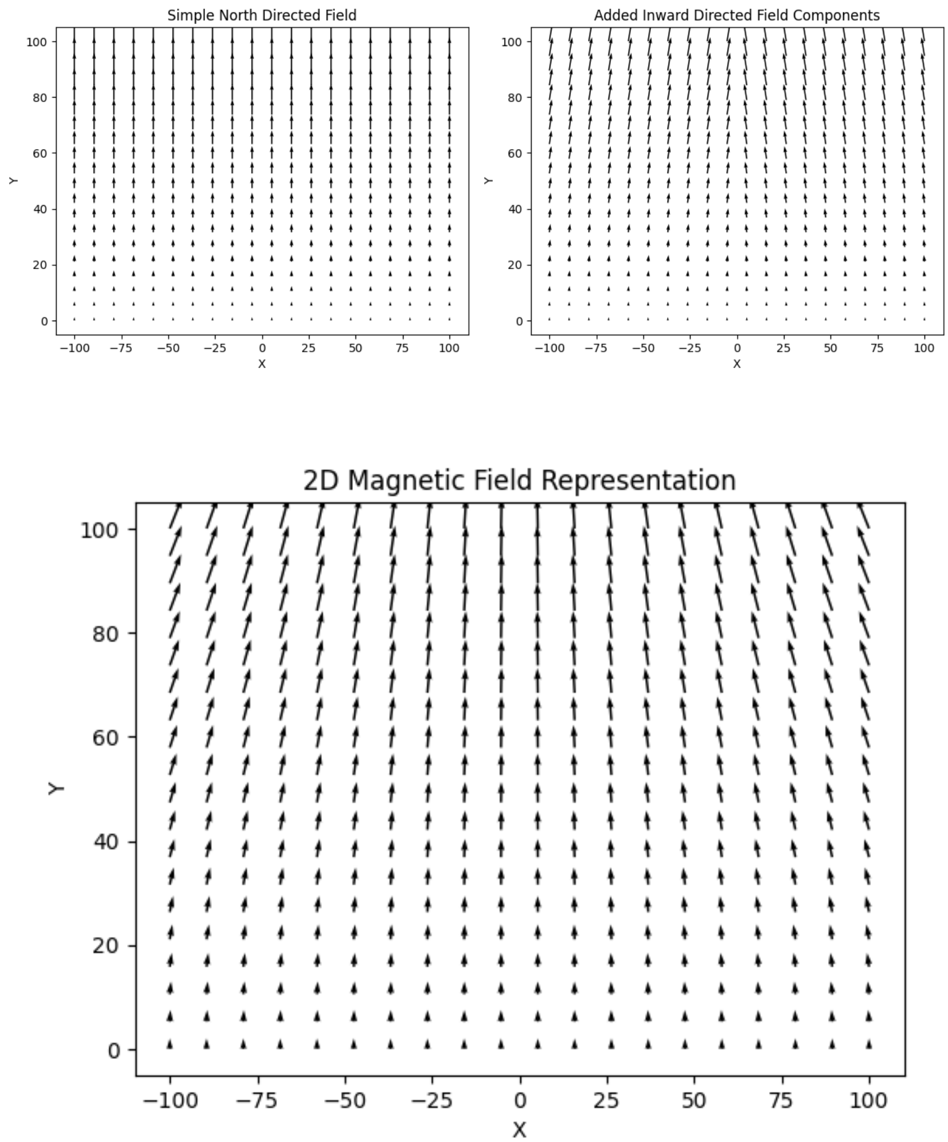

Figure 4: 2-Dimensional Magnetic Field Representation. Top right is the simple field that only increases intensity with y, the top right is the northward field with an inward inclination. The bottom graph shows the actual vector generated by the actual function which generated fields for all the experiments in this report.

Bird class and data generation function

The bird class used to represent a bird is defined in a relatively straight-forward way. A bird has a position (x and y coordinates) and direction (in radians from the x-axis $-\pi < \theta < \pi$). Crucially the bird class is set up with a retina model that is defined as a 3-point perpendicular line segment placed slightly ahead of the bird's centre point. The 'mag_view()' method can interpolate the magnetic field at the three retinal model points by taking the dot product to obtain 3 flux values.

These flux values are then normalizing (to between -1 and 1) to serve as a magnetic image from the bird's perspective in their position and direction.

The data used in these models is generated randomly on by the ‘generate_training_data’ which preforms the following actions.

- Generates a random home point that unique to every data set.
- Iterates for all the samples (n defined in call) to:
  - Place a bird at a random spot (oriented in the direction of the magnetic field at that point)
  - Records its position, direction, normalized magnetic image, normalized field strength (calculated from the vector field), the computed turn angle requires to orient to the home point.
- Lastly it returns the home point as well as the recorded values in a separate tuple.

<u>Modelling the bird’s reorientation behaviour</u>

The assumption that the bird model is capable of orienting toward the magnetic field is explored using a winner-take all synapse model whereby the circle surrounding each bird is divided into 8 directional categories. The central point from the magnetic flux image is then recorded and the 8 flux values are passed to the winner-take-all synapse model (with parameterized inhibition, excitation, and time constants) and tested for its accuracy in choosing the highest flux value, which is the highest dot product between the bird’s orientation in one of the eight categories and the magnetic field vector interpolated at the specific point of interest. Prior to testing how many iterations it takes for the model to be 100% successful, the synapse model’s parameters are iterated to find the optimal configuration for the task.

<u>Modelling the direct-to-home neural network model</u>

In process of obtaining a working model, it became clear that passing only the flux image to the model was not enough to ascertain the birds’ positions, let alone the bird’s position with respect to its direction with respect to the home point. This is because the normalized flux values only provide information about the magnetic field's orientation to the bird. I found that one must pass the model a representation of the strength of the magnetic field at each point *AND* make sure that the bird is oriented in the direction of the magnetic field to reduce the variability that comes with placing the bird at a random direction. Luckily, this follows naturally since above we used a winner take all model to orient the bird roughly in the direction of the magnetic field.

The generation of the point to home magnetic field navigation model can be done by simply following these steps:

1. Generate an adequate amount of training data, 100-thousand data points seemed to be the sweet spot.
2. Convert the data to Pytorch Tensors then create the appropriate data loaders for the model.
3. Initialize the network (sized parametrically). A hidden layer size of 200 and a depth of 3 produces the best output. Note that the network uses linear layers with a standard Relu activation function. Epoch count as low as 5 is fine. The optimal learning rate was found to be 0.0001 as the model uses Adam optimizer instead of stochastic gradient descent.
4. Train and test the network using the appropriate functions which also provide a graph of the training and testing mean squared error losses over the batches.

It's worth noting that the ideal hyperparameters (hidden_size=200, depth=3, learning_rate=0.0001) for the network were found by iterating over a smaller dataset of 10 thousand. As well, the magnetic field strength used to generate the vector field was iterated to find that the model improves with higher magnetic field strengths, though it is not clear if diminishing returns would be experiences for field strengths above 256.

Results

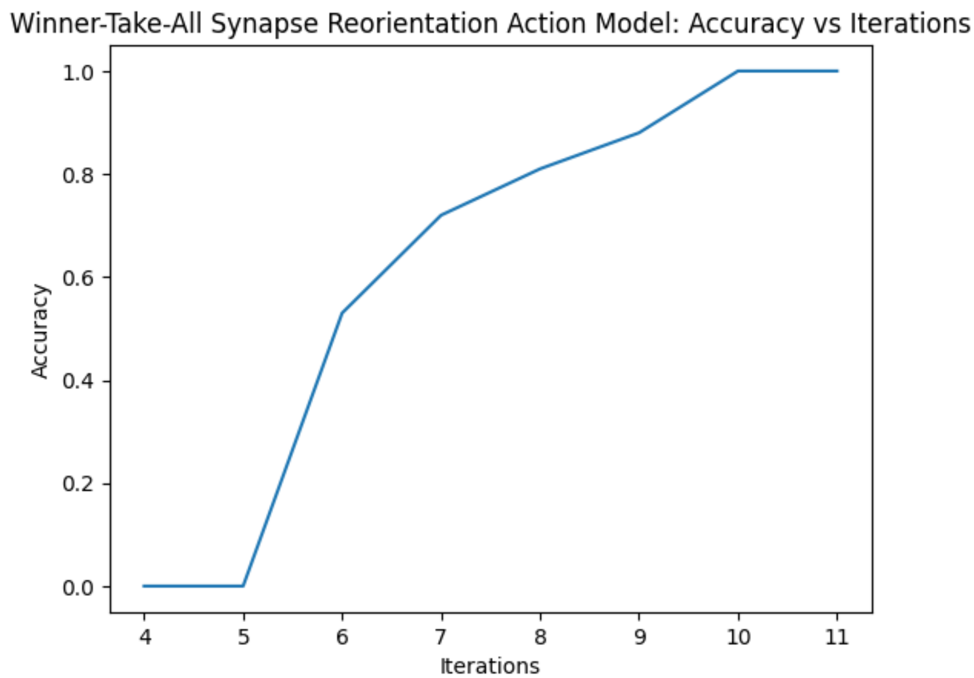

Figure 5: Winner-take-all Synapse Model Accuracy vs Iteration count. The model used a small 100-piece dataset and the task-specific ideal winner-take-all synapse parameters (inhibition=-1.2, excitation=1.1, time_constant=0.001) as obtained via iterative testing.

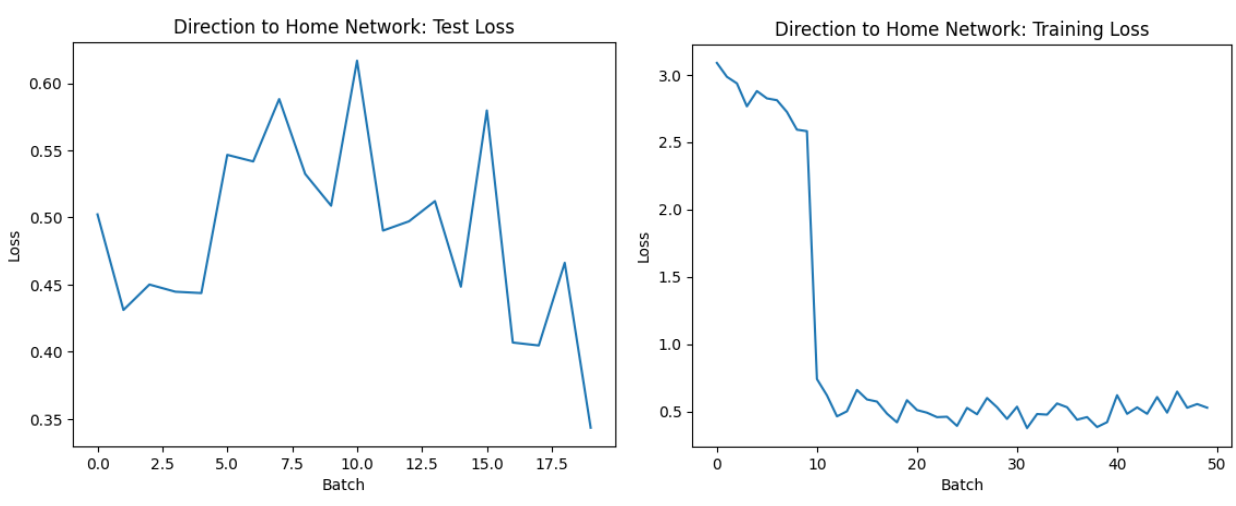

Figure 6: Point-to-home point Training (left) and Testing (right) loss using a large 100-thousand piece dataset and ideal hyper parameters. It's clear the model has learned the task to a reasonable extent.

For all code used in this project, please see the annotated Github Repository at: https://github.com/JRomeroRepositories/avian_magrec_nn

Discussion

We'll begin our discussion by recounting one of the great learning experiences of this experiment. Initially, the plan was not to include anything but the magnetic flux images as input for the model. In testing, I found that it was impossible for the model to learn the task no matter what changes were made to the network type, its size, and the size of the dataset used.

Upon further investigation, it became clear that the answer was to implement the biological parallel learning from birds as they always utilize a 2-receptor magneto-receptive navigation system. See, the first task was impossible to learn because the bird couldn't determine its position on the y-axis (see figure 4). This, presumably [3],[5], is carried out via the magnetite based receptor in the beak's of migratory birds which suggests that they must remember the strength, and likely other characteristics, of the magnetic field at different positions along their migratory routes. Given that many of these routes span thousands of miles along the earth's surface, it is plausible to assume that the perceived magnetic field (by the dermal, magnetite-based, receptor) is notably distinct longitudinally across the earth.

As well, it was clear that the task of determining the home-point direction while facing an arbitrary direction on the plane is too difficult of a task to train. To correct this, the birds needed to be oriented in the direction of the magnetic field at whatever position they were placed at. This is akin to a bird using the magnetic field to orient their bearings *BEFORE* choosing a heading to travel in.

As soon as these corrections were made, the model was able to learn the task with some reasonable efficacy and all that remained was to improve the output losses via idealized parameterization.

Given that the retinal receptor is light based, it would be interesting to further the experiment by adding a light-factor that weakens the perception of the retina model during the later hours of the day. Special consideration would need to be taken since the best angle of incidence for the retinal incident light that powers the compass functionality is during the hours of dusk and dawn.

Conclusion

It's clear that a computational investigation into the neural navigational frameworks employed by birds is merited as their receptors begin to become more keenly understood. Future experiments should use neural network models with a higher biological fidelity (eg. convolutional neural networks and/or more complicated models like RatSLAM)

References

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