How have migratory birds evolved to use the Earth's magnetic field for navigation?

A research investigation to determine the most probable theory for magnetoreception in migratory birds

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Abstract

Through gradual extensions of annual movements, in search for food or breeding opportunities, the evolution of avian migration has occurred within several species of birds, including the homing pigeon and the European robin.[1] The theory of evolution was first established in the nineteenth century after being proposed by Charles Darwin.[2] Despite this theory being poorly received (due mainly to religious reasons), it has prompted scientists to discover how several organisms have adapted to their surroundings and the benefits of their evolution.[3] The majority of students are taught at a young age the basic fact that birds migrate when the seasons change. Few question how these birds know which direction to head. Those who do are given a fundamental explanation, excluding the complexities involved in this mechanism. Magnetoreception is the term used to describe how birds orient themselves using the magnetic field generated by the motion of the liquid iron outer core of the Earth.[4] The purpose of this research essay is to increase awareness of the current hypotheses for how magnetoreception works and to encourage education of the topic to allow for further progression in this field of study.

Introduction

Currently, there are two main competing theories behind magnetoreception: a magnetite-based theory and a light-dependent theory. The first theory states that migratory birds have magnetite receptors on their beaks, allowing for detection of the Earth's magnetic field. The second theory, first proposed by Klaus Schulten, suggests a series of chemical reactions are used in navigation. Scholars, including Peter Hore and Henrik Mouritsen, have provided significant evidence to suggest that the light-dependent form of magnetoreception is the most likely hypothesis. Whereas, Semm and Beason have also provided noteworthy evidence for the magnetite-based theory. Mouritsen has even suggested that both the magnetite-based magnetoreception and the light-dependent magnetoreception could simultaneously be correct. Despite a recent surge in experimentation and studies of the topic, a universally accepted theory is yet to be found. To determine which theory is most probable, this research essay will examine the magnetite-based theory; the light-dependent theory and an overview of other possible explanations for navigation in birds. Also included is some statistical analysis of Wolfgang and Roswitha Wiltschko's experimentation. The evolutionary journey will also be explored, to gauge a thorough understanding for why this mechanism has been established, not only in birds, but in other species too. It can be concluded, by looking at the findings below, that aspects of both theories are probable so both mechanisms could be part of the process of magnetoreception. However, there are various factors which could potentially disprove both mechanisms so further investigation would be required to prove a singular hypothesis is accurate.

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[1] TheCornellLab. "The Evolution of Bird Migration." *All About Birds*, 11 April 2017, https://www.allaboutbirds.org/news/the-evolution-of-bird-migration/#:~:text=One%20leading%20theory%20holds%20that,behavior%20along%20to%20their%20offspring. Accessed 31 March 2021.

[2] National Geographic Society. "Theory of Evolution." *National Geographic*, 7 June 2019, https://www.nationalgeographic.org/encyclopedia/theory-evolution/#:~:text=The%20theory%20of%20evolution%20is,Wallace%20in%20the%20nineteenth%20century. Accessed 31 March 2021.

[3] Dubochet, Jacques. "Why is it so difficult to accept Darwin's theory of Evolution." *BioEssays*, vol. 33, no. 4, 2011, pp. 240-242. *Wiley Online Library*, https://onlinelibrary.wiley.com/doi/full/10.1002/bies.201000142. Accessed 4 April 2021.

[4] Science Magazine. "We Don't Know: Magnetoreception." *YouTube*, 1 December 2016, https://www.youtube.com/watch?v=tdXb_4EkYtU. Accessed 28 March 2021.

1 Magnetite-based Magnetoreception

1.1 Magnetite

Magnetite, Fe_3O_4, is a mineral found in an array of organisms, including insects, fish and birds.[5] A common linkage between organisms possessing this mineral is that the majority are able to navigate large distances, mostly without error. The fact that these organisms have all evolved to have magnetite existing within their body suggests that it provides a selective advantage. Many scientists, including P Semm and R C Beason, believe that magnetite allows organisms to self-locate, using the Earth's magnetic field. Below is an explanation of the current theory behind this magnetite-based magnetoreception and the findings of several experiments which have taken place, in consideration of magnetite's potential selective advantage.

1.2 Theory

One theory for magnetoreception is that birds have magnetite on their beak, which suggests that the iron mineral crystals in the upper beak of birds allow for navigation using the Earth's magnetic field.[6] Magnetite is the most magnetic naturally occuring metal that has been found on Earth.[7] This is probably why many scientists believe it could play a key role in magnetoreception of birds.

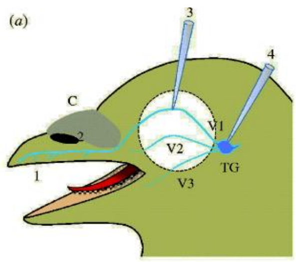

Figure 1 *shows a simplified diagram of a migratory bird, with site 2 representing the accumulation of iron.*

Scientists, Semm and Beason were some of the first to provide evidence supporting the magnetite-based theory, suggesting that the trigeminal nerve system was significant in transmitting information from the magnetite receptors in the beak to the brain.[8] In 1990, they found that the trigeminal system responded to changes as small as 200nT (nanoteslas) in the magnetic field.[9] Despite this compelling

[5] Kirschvink, Joseph L., et al. "Magnetite-based Magnetoreception." Current Opinion in Neurobiology, vol. 11, no. 4, 2001, pp. 462-467. Science Direct, http://web.gps.caltech.edu/~jkirschvink/pdfs/COINS.pdf. Accessed 30 March 2021.

[6] Mouritsen, Henrik. "Henrik Mouritsen on The biology of magnetoreception in night-migratory songbirds." *YouTube*, 24 May 2019, https://www.youtube.com/watch?v=iU-5XyvOj-k&t=1947s. Accessed 30 March 2021.

[7] Science Magazine. "We Don't Know: Magnetoreception." *YouTube*, 1 December 2016, https://www.youtube.com/watch?v=tdXb_4EkYtU. Accessed 28 March 2021.

[8] Kirschvink, Joseph L., et al. "Magnetite-based Magnetoreception." Current Opinion in Neurobiology, vol. 11, no. 4, 2001, pp. 462-467. Science Direct, http://web.gps.caltech.edu/~jkirschvink/pdfs/COINS.pdf. Accessed 30 March 2021.

[9] Wiltschko, Roswitha, et al. "Magnetoreception in birds: different physical processes for two types of directional responses." *HFSP Journal*, 21 March 2007, https://www.tandfonline.com/doi/pdf/10.2976/1.2714294/10.2976/1?needAccess=true. Accessed 31 March 2021.

evidence, studies so far have suggested that the magnetite-based receptors are only responsible for transmitting information based on magnetic intensity (and thus location), rather than direction.[10]

1.3 Mouritsen's experimentation on Eurasian reed warblers

In 2009, an experiment conducted by Henrik Mouritsen showed that when the trigeminal nerve was cut, European robins lost none of their ability to navigate.[11] Further experimentation in 2010-11 suggested that migratory species of birds rely on the trigeminal nerve to sense their location.[12] Mouritsen's studies used Eurasian reed warblers to determine the effects of removing the trigeminal nerve.[13] Eurasian reed warblers normally migrate from Kaliningrad, Russia to southern scandinavia. During their migration season, the warblers were removed from their habitat in Russia, in an eastern direction. Those with their trigeminal nerve removed still migrated northeast (similar to their normal migration pattern), but did not migrate to southern scandinavia. Whereas, those with their trigeminal nerve intact migrated northwest to southern scandinavia. This shows that the trigeminal nerve does play a role in magnetoreception but is not solely responsible for navigation.

1.4 Conclusions of the magnetite-based magnetoreception theory

This evidence suggests that the magnetite present in the bird's beak does hold importance in the mechanism of magnetoreception. However, due to the findings of Mouritsen's experiment, it would be hard to conclude that this theory is completely correct. It is perhaps more likely that the magnetite receptors in a birds beak are only used for sensing their location (similar to how a human would use a map) and another mechanism is used as the bird's chemical compass. This can be explored further.

2 Light-dependent Magnetoreception

2.1 Overview

The second theory for magnetoreception suggests cryptochrome absorbs photons of light, leading to the formation of a radical pair, which transmits a signal to cluster N (within the brain), allowing the bird to direct themselves. A radical is used to describe an atom with an uneven number of electrons, where all radicals have a slightly magnetic charge. A radical pair is formed when a molecule (cryptochrome) is hit by energy (photons of light). Radical pairs are unstable so tend to form recombinant molecules or new products. The ratio of the recombinant molecules to products is resultant of the position of the Earth's magnetic field. This information is transmitted to cluster N in the brain, where the orientation of flight is dependent, based on the bird's normal migration patterns.

2.2 The Radical Pair Mechanism

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[10] Wiltschko, Roswitha, et al. "Magnetoreception in birds: different physical processes for two types of directional responses." *HFSP Journal*, 21 March 2007, https://www.tandfonline.com/doi/pdf/10.2976/1.2714294/10.2976/1?needAccess=true. Accessed 31 March 2021.

[11] Moskvitch, Katia. "Beak-to-Brain Nerve May Help Birds Navigate." *Science Mag*, 27 June 2013, https://www.sciencemag.org/news/2013/06/beak-brain-nerve-may-help-birds-navigate. Accessed 30 March 2021.

[12] Moskvitch, Katia. "Beak-to-Brain Nerve May Help Birds Navigate." *Science Mag*, 27 June 2013, https://www.sciencemag.org/news/2013/06/beak-brain-nerve-may-help-birds-navigate. Accessed 30 March 2021.

[13] Moskvitch, Katia. "Beak-to-Brain Nerve May Help Birds Navigate." *Science Mag*, 27 June 2013, https://www.sciencemag.org/news/2013/06/beak-brain-nerve-may-help-birds-navigate. Accessed 30 March 2021.

A brief explanation of the radical pair mechanism has been provided alongside this research document, for those unfamiliar with the mechanism, which can also be accessed here.

Biophysicist, Klaus Schulten, first proposed the idea of cryptochrome's involvement in magnetoreception in 1978.[14] He suggested that the magnetic field of the Earth resulted in a chemical reaction within the bird, triggering a biological signal.[15] Initially, this theory was not widely accepted within the scientific community as many did not believe that the Earth's magnetic field was strong enough to break chemical bonds within a bird. However, Schulten counter-argued this by suggesting how 'the radical pair mechanism' may be involved in the magnetoreception of birds.[16]

Professor Peter Hore has proposed an analogy to help to explain the radical pair mechanism. The direction the 'block of granite' falls is determined by the 'fly'. The analogy works as the 'fly' would usually be unable to move 'the block of granite' However, due to the instability of the 'block of granite', the 'fly' is able to determine the way the 'block of granite' falls. Similarly, the Earth's magnetic field would not normally be able to cause a chemical reaction, but due to the instability of the radical pair, the magnetic field can determine the formation of recombinant molecules or the formation of new molecules. As described by Peter Hore, the ratio of recombinant molecules to the ratio of new molecules is what determines the orientation that the bird travels.[17]

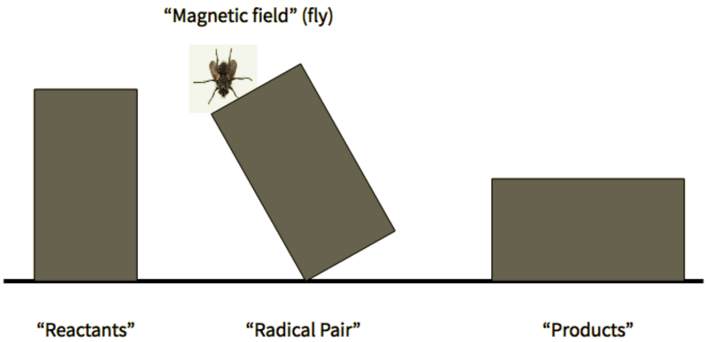


Figure 2 *shows Peter Hore's analogy of how a fly tipping over a block of granite could represent the Earth's magnetic field being strong enough to determine whether the radical pairs form a recombinant molecule or if the radical pairs form two new molecules.*

2.3 The Role of Cryptochromes

14 Yong, Ed. "How birds see magnetic fields - an interview with Klaus Schulten." National Geographic, 24 November 2010, https://www.nationalgeographic.com/science/article/how-birds-see-magnetic-fields-an-interview-with-klaus-schulten. Accessed 28 March 2021.

15 Up and Atom. "Quantum Biology [Part 3] - How Birds (Might) Navigate With Quantum Mechanics." YouTube, 13 March 2020, https://www.youtube.com/watch?v=NW7VUFgwqg8. Accessed 28 March 2021.

16 Adams, Betony, et al. "An open quantum system approach to the radical pair mechanism." *Scientific Reports*, 24 October 2018, https://www.nature.com/articles/s41598-018-34007-4#Abs1. Accessed 28 March 2021.

17 Hore, Peter. "Peter Hore on Radical Pair mechanism of Magnetoreception." *YouTube*, 24 May 2019, https://www.youtube.com/watch?v=FytxLiHlah4. Accessed 30 March 2021.

Cryptochromes are a class of flavoproteins, found in both plants and animals, which are thought to be a necessary component for detection of magnetic fields.[18] They act as photoreceptors and have shown to be most sensitive to blue light.[19] It is believed that cryptochromes have evolved from photolyases (DNA repair enzymes).[20] Both use the absorption of light to perform their individual functions and their tertiary structures share many similarities (as shown in ***Figure 3***), for example both have an α-helical FAD binding domain (which is needed for the formation of radical pairs). It could be assumed that the possession of cryptochrome provides a selective advantage as it is a product of evolution. In the case of migration, organisms containing cryptochrome potentially have a selective advantage as it allows them to carry out magnetoreception.

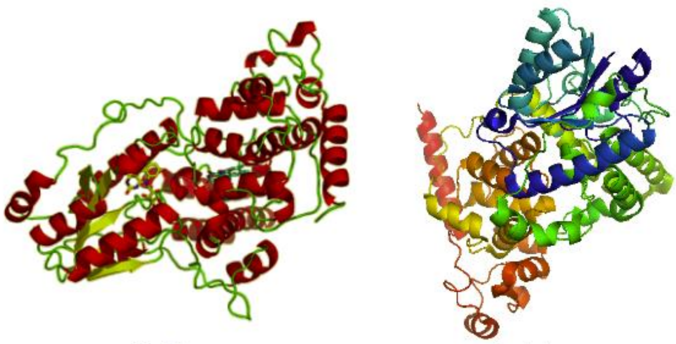


Figure 3 *shows a comparison between the structure of photolyase and the structure of cryptochrome*

The cryptochromes in a bird's retinal ganglion cells enable migratory birds to navigate using the Earth's magnetic field.[21] A study has shown that the expression of Cryptochrome 1 (Cry1) is higher in migratory birds in comparison to non-migratory species, providing strong proof that cryptochromes play a crucial role in chemical magnetoreception in birds.[22]

18 Lin, Chentao, and Takeshi Todo. "The cryptochromes." *Genome Biology*, 2005. *Genome Biology*, https://genomebiology.biomedcentral.com/articles/10.1186/gb-2005-6-5-220. Accessed 31 March 2021.

19 Lin, Chentao, and Takeshi Todo. "The cryptochromes." *Genome Biology*, 2005. *Genome Biology*, https://genomebiology.biomedcentral.com/articles/10.1186/gb-2005-6-5-220. Accessed 31 March 2021.

20 Lin, Chentao, and Takeshi Todo. "The cryptochromes." Genome Biology, 2005. Genome Biology, https://genomebiology.biomedcentral.com/articles/10.1186/gb-2005-6-5-220. Accessed 31 March 2021.

21 Fusani, Leonida, et al. "Cryptochrome expression in the eye of migratory birds depends on their migratory status." *The Journal of Experimental Biology*, 2014. *The Company of Biologists*, https://jeb.biologists.org/content/jexbio/217/6/918.full.pdf. Accessed 28 March 2021.

Damulewicz, Milena, and Gabriella Mazzotta. "One Actor, Multiple Roles: The Performances of Cryptochrome in Drosophila." Frontiers in Physiology, 5 March 2020, https://www.frontiersin.org/articles/10.3389/fphys.2020.00099/full. Accessed 28 March 2021.

Pinzon-Rodriguez, Atticus, et al. "Expression patterns of cryptochrome genes in avian retina suggest involvement of Cry4 in light-dependent magnetoreception." *The Royal Society*, 28 March 2018, https://royalsocietypublishing.org/doi/10.1098/rsif.2018.0058#:~:text=Cry4%20has%20been%20described%20in,27%2C28%2C39%5D. Accessed 29 March 2021.

22 Fusani, Leonida, et al. "Cryptochrome expression in the eye of migratory birds depends on their migratory status." *The Journal of Experimental Biology*, 2014. *The Company of Biologists*, https://jeb.biologists.org/content/jexbio/217/6/918.full.pdf. Accessed 28 March 2021.

FAD, within cryptochrome, is thought to absorb blue light photons, resulting in the formation of a radical pair.[23] This also results in a change in the 3D structure of cryptochrome (see ***Figure 6***).[24] There is a limited number of cells which can transmit information from the eye but it is currently unknown how the cryptochrome signal is transmitted to the brain, but it is thought that cluster N is responsible for detecting this change.[25]

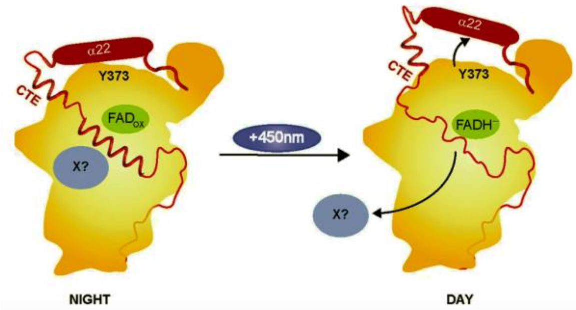
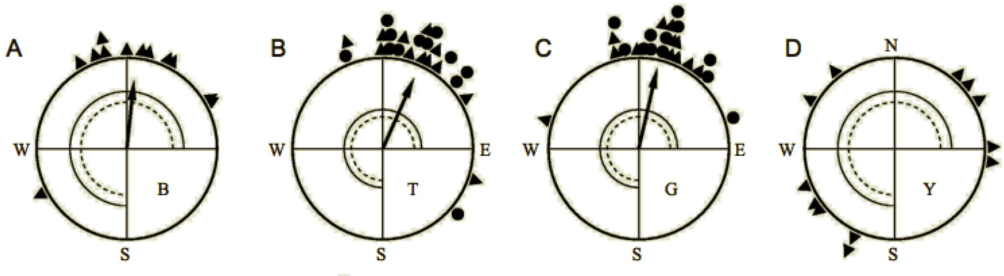


***Figure 4** shows the structural change in cryptochrome, once being hit by light energy.*[26]

Wolfgang Wiltschko and Roswitha Wiltschko have carried out a study, testing the navigation abilities of birds in different wavelengths of light.[27] Their experimentation has proved that magnetoreception is wavelength-dependent to an extent, by studying the direction European robins flew in different wavelengths of light.[28] The results show that the European robins oriented well in the blue, turquoise and green wavelengths. However, they did not orient well in the yellow wavelength, perhaps suggesting that absorption of yellow light does not significantly assist in the navigation abilities of birds.



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[23] Up and Atom. "Quantum Biology [Part 3] - How Birds (Might) Navigate With Quantum Mechanics." *YouTube*, 13 March 2020, https://www.youtube.com/watch?v=NW7VUFgwqg8. Accessed 28 March 2021.

[24] Up and Atom. "Quantum Biology [Part 3] - How Birds (Might) Navigate With Quantum Mechanics." *YouTube*, 13 March 2020, https://www.youtube.com/watch?v=NW7VUFgwqg8. Accessed 28 March 2021.

[25] Up and Atom. "Quantum Biology [Part 3] - How Birds (Might) Navigate With Quantum Mechanics." *YouTube*, 13 March 2020, https://www.youtube.com/watch?v=NW7VUFgwqg8. Accessed 28 March 2021.

[26] Franz-Badur, S., Penner, A., Straß, S. *et al.* Structural changes within the bifunctional cryptochrome/photolyase *Cra*CRY upon blue light excitation. *Sci Rep* 9, 9896 (2019). https://doi.org/10.1038/s41598-019-45885-7.Accessed 30 March 2021

[27] Wiltschko, Wolfgang, and Roswitha Wiltschko. "Light-dependent magnetoreception in birds: the behaviour of European robins, Erithacus rubecula, under monochromatic light of various wavelengths and intensities." *Journal of Experimental Biology*, 2001, pp. 3295–3302. *Journal of Experimental Biology*, https://jeb.biologists.org/content/jexbio/204/19/3295.full.pdf. Accessed 30 March 2021.

[28] Wiltschko, Wolfgang, and Roswitha Wiltschko. "Light-dependent magnetoreception in birds: the behaviour of European robins, Erithacus rubecula, under monochromatic light of various wavelengths and intensities." *Journal of Experimental Biology*, 2001, pp. 3295–3302. *Journal of Experimental Biology*, https://jeb.biologists.org/content/jexbio/204/19/3295.full.pdf. Accessed 30 March 2021.

***Figure 5** shows the results of the experiment conducted by Wolfgang Wiltschko and Roswitha Wiltschko, studying the orientation behaviour of European robins when exposed to different wavelengths of light (B=blue; T=turquoise; G=green; Y=yellow).*[29] *The experiment was carried out in laboratory conditions, where the direction and length the birds flew were recorded.*

2.4 Statistical Analysis of the Wiltschko Experiment

*The raw data has been provided alongside this research document, which can also be accessed **here**.*

Pages 7-12 show a statistical analysis carried out from the data collected by Wolfgang and Roswitha Wiltschko. The experimentation they performed has been used by many scholars to explain this theory of magnetoreception so its inclusion within this document is important to illustrate how current theories have evolved. The outcomes of the statistical analysis were unexpected, prompting the formation of further questioning around the topic. However, there are several factors which could have contributed to the unforeseen results, which will be explained below. It should be noted that in the documents provided by Wiltschko, there were no units for length given, so the decision has been made to graph the data with the length in arbitrary units.

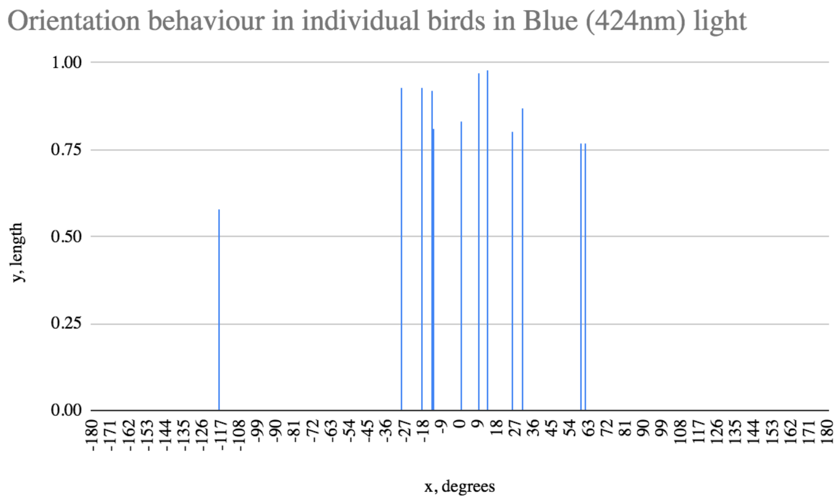

***Figure 6** shows the direction the individual birds travelled in blue light (in degrees) against the corresponding length (a.u) the bird travelled (where 0° = North; 90° = West; ±180° = South; -90° = East). The calculated standard deviations were 47.16 (for degrees) and 0.113 (for length).*

[29] Wiltschko, Wolfgang, and Roswitha Wiltschko. “Light-dependent magnetoreception in birds: the behaviour of European robins, Erithacus rubecula, under monochromatic light of various wavelengths and intensities.” *Journal of Experimental Biology*, 2001, pp. 3295–3302. *Journal of Experimental Biology*, https://jeb.biologists.org/content/jexbio/204/19/3295.full.pdf. Accessed 30 March 2021.

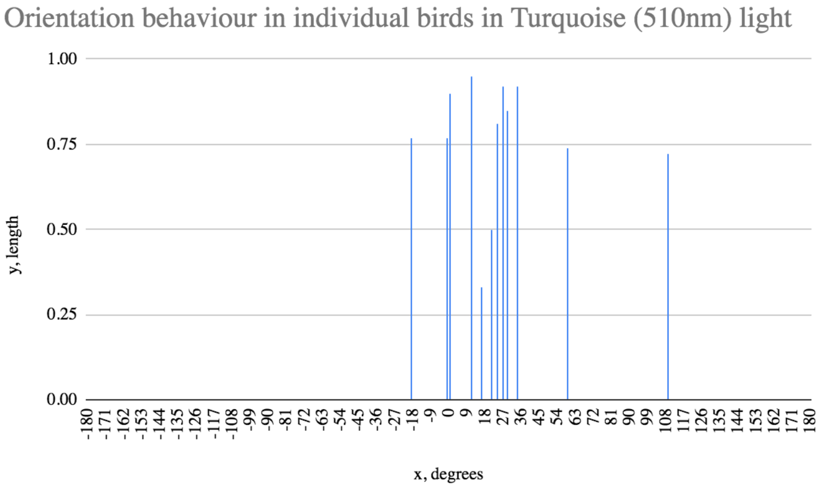

Figure 7 *shows the direction the individual birds travelled in turquoise light (in degrees) against the corresponding length (a.u.) the bird travelled (where 0° = North; 90° = West; ±180° = South; -90° = East). The calculated standard deviations were 32.80 (for degrees) and 0.184 (for length).*

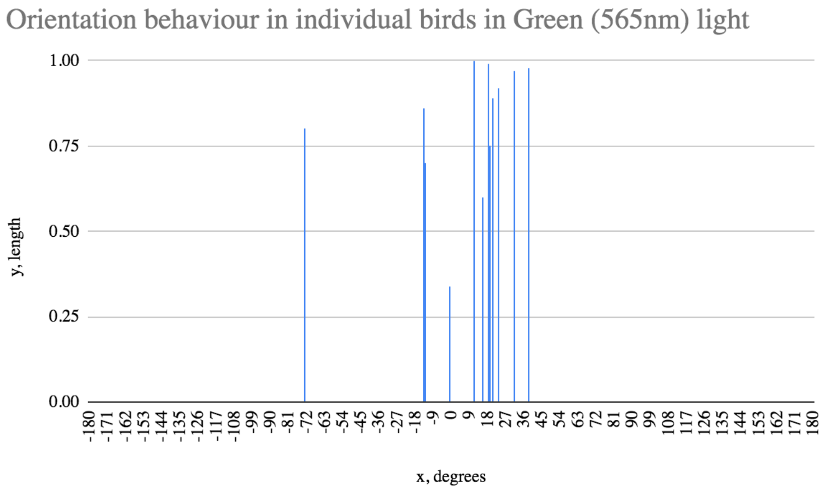

Figure 8 *shows the direction the individual birds travelled in green light (in degrees) against the corresponding length (a.u.) the bird travelled (where 0° = North; 90° = West; ±180° = South; -90° = East). The calculated standard deviations were 29.55 (for degrees) and 0.196 (for length).*

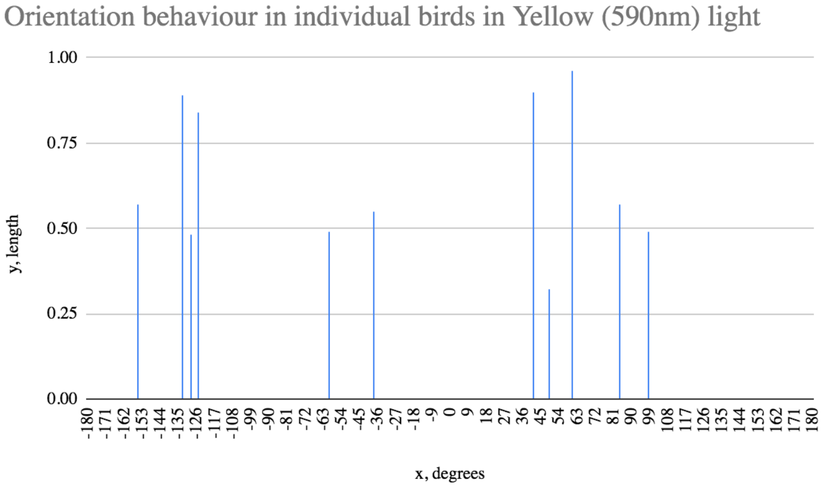

Figure 9 *shows the direction the individual birds travelled in yellow light (in degrees) against the corresponding length (a.u.) the bird travelled (where 0° = North; 90° = West; ±180° = South; -90° = East). The calculated standard deviations were 99.78 (for degrees) and 0.234 (for length).*

Before plotting each graph, there was an initial expectation that the data would follow a normal distribution. Some graphs, such as for the blue and turquoise, follow a weak normal distribution. Although, with a lack of symmetry and a characteristic bell shaped curve, no further tests were performed from these graphs. Instead, the graphs can be used to illustrate the general spread of the data. The data was then used to calculate the standard deviation of both the length and direction the birds travelled.

For each wavelength, the standard deviation was calculated (for both length and direction), to highlight the spread of the data. A high standard deviation indicates an inconsistency in the data, meaning the birds did not orient well. Whereas, a low standard deviation indicates consistency within the data, meaning the birds oriented well. After plotting the standard deviations for each data set, the product moment correlation coefficient (PMCC) was calculated and a hypothesis test for zero correlation was calculated.

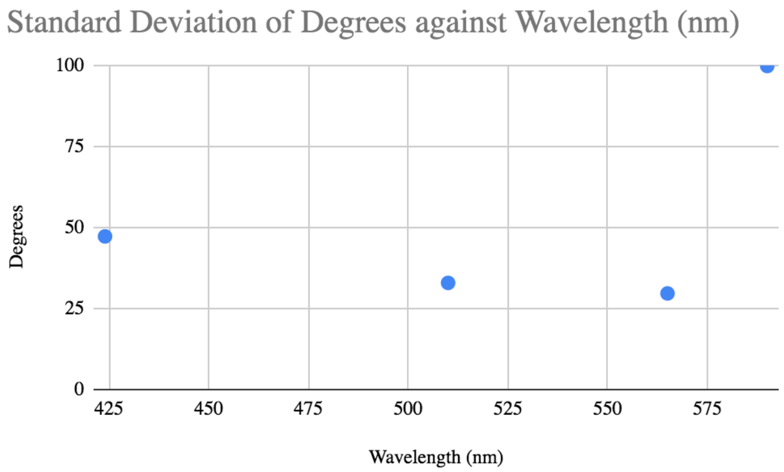

Figure 10 *shows the standard deviation of the direction (in degrees) against the wavelength (nm). The PMCC calculated was **r** = 0.416 (3s.f.), indicating a weak positive correlation.*

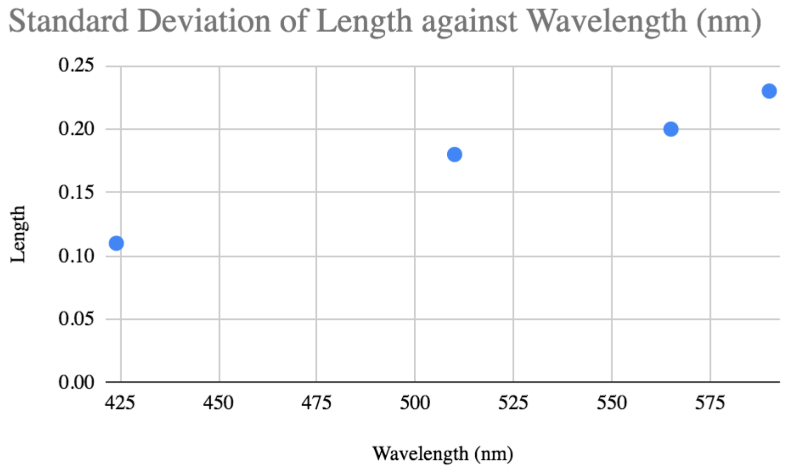

Figure 11 *shows the standard deviation of length (a.u.) against the wavelength (nm). The PMCC calculated was **r** =0.989 (3s.f.), indicating a strong positive correlation.*

Hypothesis Test for Zero Correlation between degree of orientation and wavelength

Null Hypothesis: There is no correlation between the standard deviation of the degree of orientation of individual birds and the wavelength of light.

Alternative Hypothesis: There is a correlation between the standard deviation of the degree of orientation of individual birds and the wavelength of light.

Sample Size = 12

Significance level = 0.05

From table of critical values, critical value of **r** for a 5% significance level, with a sample size of 12 is **r** = 0.4973

r > 0.4973

0.416 < 0.4973. The observed value of **r** lies within the critical region, so do not reject the null hypothesis.

At the 5% level of significance, there is insufficient evidence to suggest that there is a correlation between the standard deviation of the degree of orientation of individual birds and the wavelength of light.

Hypothesis Test for Zero Correlation between length of distance travelled and wavelength

Null Hypothesis: There is no correlation between the standard deviation of the length of distance travelled of individual birds and the wavelength of light.

Alternative Hypothesis: There is a correlation between the standard deviation of the length of distance travelled of individual birds and the wavelength of light.

Sample Size = 12

Significance level = 0.05

From table of critical values, critical value of **r** for a 5% significance level, with a sample size of 12 is **r** = 0.4973

r > 0.4973

0.989 >0.4973. The observed value of **r** lies within the critical region, so reject the null hypothesis.

There is evidence, at the 5% level of significance, that there is a correlation between the standard deviation of the length of distance travelled of individual birds and the wavelength of light.

Analysis of results

The tests for zero correlation had unpredicted outcomes. The scatter graph showing the direction the birds travelled against the wavelength of light did not have a significant correlation, which would imply that the directional aspect of magnetoreception is not wavelength dependent, contradicting the hypotheses of several academics. Contarily, the PMCC calculated for length against wavelength showed a significant positive correlation of 0.989. A correlation this high indicates that the relationship is not due to chance, suggesting that there is an aspect of magnetoreception which is wavelength dependent, thus proving that aspects of this theory are correct.

As described above, cryptochromes absorb blue wavelengths of light (~450nm) the best. ***Figure 12*** also shows this. However, the results have shown that European robins orient more consistently in the wavelength of 565nm, with the lowest standard deviation in orientation (29.55 degrees). Since cryptochrome is supposedly responsible for the formation of radical pairs, it would have been assumed that the blue wavelength would have the smallest standard deviation. Despite evidence that magnetoreception is wavelength specific (to an extent), there was no evidence to suggest that the wavelength affected the direction of the bird's flight. This could prompt further investigation for if there is another photoreceptor in the retina which could also perform a role in magnetoreception. On the other hand, these unexpected results could be resultant of a small sample size. Even though all outliers anomalies were ignored in calculations, the twelve robins used may not be representative of the whole population.

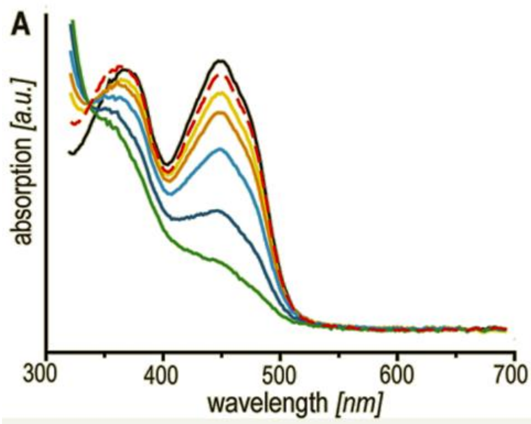

Figure 12 *shows and absorption spectra for cryptochrome 1a (Cry1a), See black line of graph*

2.5 Cluster N

Cluster N is located in the forebrain of birds. In studies calculating the activity of cluster N, it was found that it was more active in migratory birds during the night, compared to during the day time.[30] For non-migratory birds, there was no change in the activity of cluster N between the night and the day.[31] Another study has shown that where the eyes of the migratory birds were covered, there was no change in the activity of cluster N.[32] This suggests that cluster N allows night vision in migratory birds and that the detection of a magnetic field is reliant upon a light-activated mechanism.[33] A further study has shown that in European robins where their cluster N was destroyed, they could no longer navigate using their magnetic compass.[34] The difference in activity between migrants and non-migrants suggests that the migrants have evolved, where the ability of magnetoreception acts as a selective advantage.

30 Mouritsen, Henrik, et al. "Night-vision brain area in migratory songbirds." *PNAS*, vol. 102, no. 23, 2005, pp. 8339–8344. *PNAS*, https://www.pnas.org/content/102/23/8339. Accessed 29 March 2021.

31 Mouritsen, Henrik, et al. "Night-vision brain area in migratory songbirds." *PNAS*, vol. 102, no. 23, 2005, pp. 8339–8344. *PNAS*, https://www.pnas.org/content/102/23/8339. Accessed 29 March 2021.

32 Mouritsen, Henrik, et al. "Night-vision brain area in migratory songbirds." *PNAS*, vol. 102, no. 23, 2005, pp. 8339–8344. *PNAS*, https://www.pnas.org/content/102/23/8339. Accessed 29 March 2021.

33 Mouritsen, Henrik, et al. "Night-vision brain area in migratory songbirds." *PNAS*, vol. 102, no. 23, 2005, pp. 8339–8344. *PNAS*, https://www.pnas.org/content/102/23/8339. Accessed 29 March 2021.

34 Theodoulou, Panagiota. "Quantum Effects in Biology." University of Leeds Library, https://resources.library.leeds.ac.uk/final-chapter/dissertations/physics/example1.pdf. Accessed 29 March 2021.

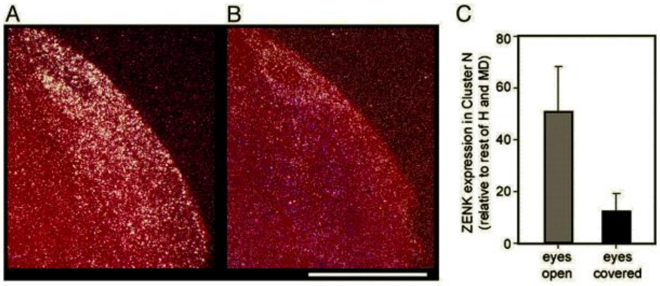

Figure 13 *shows that the ZENK (driven by neuronal activity) expression in cluster N in night-migrants is significantly greater when their eyes are open in comparison to when their eyes are closed. This can be taken as proof that the reactions which occur for navigation are light-dependent.*[35]

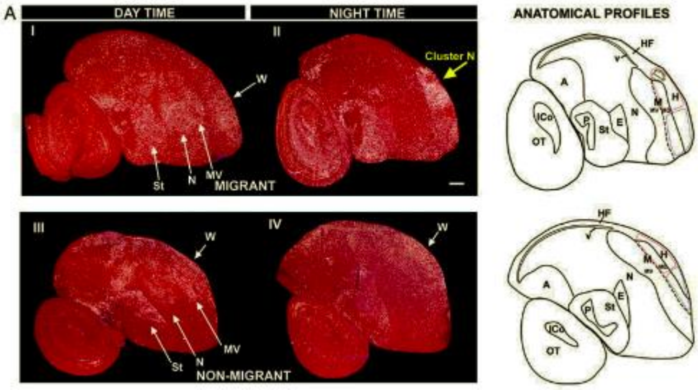

Figure 14 *shows that there is a greater change activity in cluster N (between day-time and night-time) in night-migratory birds that were awake at night, compared to the non-migrants. This suggests that the light-dependent reaction which occurs is used for navigation rather than for any other reasons.*[36]

2.6 Conclusions of the light-dependent magnetoreception theory

Overall, it can be concluded that the involvement of cryptochromes in magnetoreception is likely, given the evidence provided by the statistical analysis from Wiltschko's experimentation. It seems probable that there are still gaps in the research which need to be bridged in order to gauge a fuller understanding of the proposed mechanism. To conclude, the current limitations (such as the fact orientation of the birds is better in green wavelengths) make it difficult to convincingly state this theory as accurate, although this does not mean the theory should be dismissed as incorrect.

3 Conclusions

Having weighed up the evidence, it is unlikely that one theory alone is responsible for magnetoreception. From the information presented above, it is likely that the magnetite-based receptors are used for location detection and the light-dependent mechanism is used for detection of

[35] Mouritsen, Henrik, et al. "Night-vision brain area in migratory songbirds." PNAS, vol. 102, no. 23, 2005, pp. 8339–8344. PNAS, https://www.pnas.org/content/102/23/8339. Accessed 29 March 2021.

[36] Mouritsen, Henrik, et al. "Night-vision brain area in migratory songbirds." PNAS, vol. 102, no. 23, 2005, pp. 8339–8344. PNAS, https://www.pnas.org/content/102/23/8339. Accessed 29 March 2021.

direction. Through analysis of the data provided alone, there is also a possibility that another photoreceptor is involved in the absorption of light as, in the Wiltschko experiment, the birds oriented best in green light, despite the prediction that they would orient best in the blue light. However, there is insufficient evidence to claim this is true. This research has hopefully been able further awareness of the current hypotheses for magnetoreception and provide a new perspective of the likelihood and limitations of each theory.

4 Topics for Further Investigation

The mechanism of magnetoreception in other migratory organisms could also be investigated, as there are likely to be differences between the way this mechanism works due to their different eye anatomy. It would also be interesting to explore how well migratory organisms orient in other forms of radiation visible light. This could be carried out in a similar way to Wiltschko's experimentation, by exposing the organisms to ultraviolet light and infrared light, followed up by the calculation of their ability to orient.

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