The Extended Sensorium

Magnetoreception

Part 2 of 2

by Benjamin Deniston

Proposed Mechanisms, Exposed Paradoxes

The question remains, how are these animals able to sense the magnetic field?

Certain mechanisms have been proposed and investigated which seem to be involved in the organisms ability to respond to the GMF, though how exactly these function is still unclear. As we will see, the evidence indicates that it is much more interesting than can be explained by the reaction of a single mechanism to a magnetic field.

Structures of the biogenic mineral magnetite have been found in various organisms, and have been studied as a possible way for organisms to detect the GMF. One report said that various forms of magnetite structures were so diverse that they were found in "species belonging to all major phyla."[10] However there is still no comprehensive picture of how exactly these structures might operate.

In attempts to test the nature of these magnetite structures, experiments were devised to determine if disrupting their magnetic polarity would affect the magnetoreception ability of the organism. In tests on birds, a strong, very short magnetic pulse was employed at the beaks of Australian Silvereyes, under the hypothesis that this would alter the magnetization of the magnetite (for birds the magnetite structures are found in the beak). The pulses were 3 to 5 milliseconds in length, and around 10,000 times the strength of the natural magnetic field. As expected, prior to the pulse, the birds oriented to their appropriate northerly migratory direction. After the pulse, their orientations were shifted east 90°. The eastern tendency lasted about three days, followed by about another 7 days of general disorientation, after which the birds were able to regain their normal migratory ability.

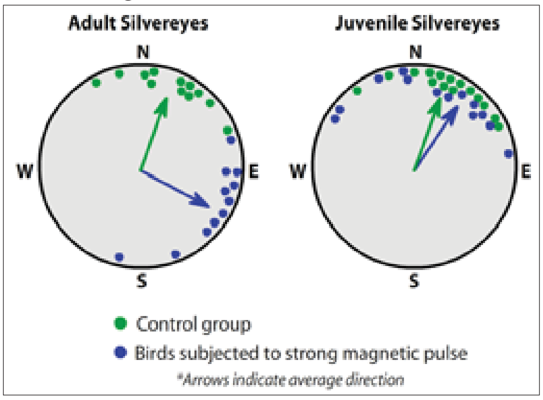

Image 8: Image adapted from "Magnetic orientation and magnetoreception in birds and other animals," Wolfgang and Roswitha Wiltschko, J Comp Physiol A (2005) 191: 675-693.

These results were not uniform, however. What was interesting is that only *adult* birds which had migrated before in their lifetimes were affected by the pulse. *Juvenile* birds of this species, which had never experienced a migration, were not affected by the magnetic pulse and most had no difficulty finding their proper migratory direction.

The conclusion drawn was that this indicated that the magnetite structures could play the role of some form of magnetic map, built up over time. The experienced birds seemed to rely upon this map, whereas younger birds had not developed a map, but could still orient to the magnetic field by use of another mechanism.

In an elaboration of this initial experiment, adult birds were subjected to the same intense magnetic pulse, but then, prior to having their migratory ability tested, they had a local anesthetic applied to their beak (the location of these magnetite structures thought to be related to a magnetic map-type function). In this case, with the anesthesia numbing the beak, the birds could again orient in their proper migratory direction with no problem, despite the fact that they had been subjected to a strong magnetic pulse.

Thus, evidence indicates that the magnetite structures located in the beak are likely involved in the magnetoreception capabilities of birds, but they can not account for everything. The birds were clearly able to rely on another aspect of magnetic sense, relating to the "inclination compass" ability discussed above (given its light-dependent nature and relationship with the eye, instead of the beak).

Further tests on other animals have shown that this light dependence is not limited to birds. For example, similar tests were tried with salamanders. But simply covering either the left eye, or the right eye, or both, did not disrupt the salamander's ability to use its inclination compass ability. It was only when the pineal gland (the so-called "third eye") was covered, even with both eyes open to the light, that the salamanders became disoriented.

In the mid 1970's, experiments with certain chemical reactions in the laboratory showed a sensitivity to low level magnetic fields. The reactions required light, and the resulting chemical reaction could be changed by the application of an external magnetic field. Such experiments were supposedly explained by certain spin chemistry models.

The question was raised, "could such chemical reactions be occurring *within living organisms*, enabling them to sense the GMF?"

A few general characteristics of such a process could immediately be tested, to see if this would affect the magnetoreception ability of birds and other animals.

Most obvious was light dependence. As we saw, tests showed that birds required light for their "inclination compass" ability, but, in further tests, it was also shown that it only worked under specific colors and intensities of the light (this will be discussed in greater detail below).

A second experimental test was devised. Based on the spin chemistry model, it was claimed that an oscillating magnetic field (with rapid variations in its intensity), even if the changes are very slight, should disrupt the process, but only if the oscillation frequency is at just the right value. The idea then being, if the low-intensity oscillations in the magnetic field disrupt the magnetoreception of the animals, that would be evidence for this particular mechanism.

This effect of disrupting the magnetic sense was first demonstrated in birds, where magnetic field oscillations of amazingly weak intensity levels, variations as low as 5 to 15 nT (0.01% of the average normal intensity of the GMF), but at just the right frequencies (in the range of 0.1 to 10 MHz), did disrupt their magnetoreception, and lead to general disorientation.[11] This was also demonstrated with tests on cockroaches (yes, they have magnetoreception too), where similar extremely low intensity, but precise frequency oscillating magnetic fields disrupted their inclination compass ability, leading to general disorientation.

The interaction of the low-level oscillations with some process relating to the magnetoreception ability of the animals provides a useful piece of evidence. The disruption indicates a resonance, which means that the question can be inverted, and we can ask, "*what characteristics can we know about the quality of the affected process, based upon the characteristics of the low-intensity oscillation with which it is interacting?*"

At this point there are no definite conclusions that have been made about how this process functions for the organism. In fact, only within the last decade has there been evidence for a specific light receptor within the organism which could play this role. Absorbing light in the blue range of the spectrum, Cryptochrome was discovered in 1998 (initially for its likely role in circadian rhythms in plants).

Since then it has been found in a wide range of organisms. To test for its possible involvement in magnetoreception, experiments were performed with plants (*Arabidopsis thaliana*) and fruit flies. Both showed sensitivity to magnetic fields (certain characteristics of the plant's growth were shown to correspond to the magnetic field intensity; and the flies' magnetic sense could be used to train them to seek out a magnetic field, based on associating it with food), and in both cases the response to the magnetic field required light in the blue range of the spectrum. But, when genetic modifications of the flies and plants without the genetic material associated with cryptochrome were created, they were no longer responsive to the magnetic field at all.

The evidence indicates some relation to magnetoreception, but what exactly is occurring is still unclear, and even the biggest names in support of this model won't claim that anything is proven yet. Still, another potentially interesting point comes up here.

The light-dependent nature (as detailed more in the next section), and the characteristic disruption under a low intensity oscillating magnetic field of the proper frequency, are claimed to support the idea that this light-dependent mechanism could relate to some chemical process (interaction in the small).

However, we do not know if the quality of such an interaction would be replicable outside of a living process. That is, we can not assume that the characteristics of abiotic chemistry or physics, as presently understood, will be sufficient in expressing how the interaction of light and an external magnetic field in the small, *within the process of a living organism,* might provide a reading of the GMF, or at least be involved in doing so. It is important to not limit the investigation to models defined solely by abiotic physics.

Assuming that this aspect of magnetoreception does involve a chemical reaction, the following sets of tests could provide interesting experimental grounds for how the interaction of light and magnetism with chemical processes within living organisms might operate. In the least, these results below expose some fundamental problems in trying to pin the magnetoreception ability of organisms to a specific mechanism.

Light-Dependence

The experimental work discussed so far led researchers to two distinct mechanisms for magnetoreception, each with distinct characteristics. For example, here is a quote on magnetoreception from a 2008 book on photobiology,

"*Animals can detect different parameters of the geomagnetic field by two principal independent magnetoreception mechanisms: (1) a light-dependent process detecting the axial course and the inclination angle of the geomagnetic field lines, providing the animals with magnetic compass information (inclination compass), and (2) a magnetite-mediated process, providing magnetic map information (map sense).*"

- *Photobiology: The Science of Life and Light,*
2008 Springer Science+Business Media, LLC

The experimental evidence presented here indicates that the receptive ability associated with the map-like magnetoreception ability of birds is associated with the beak, and is disrupted by a strong magnetic pulse. The "second," supposedly independent, vision-related function (the "inclination compass") has distinct, different characteristics. First of all, it is light-dependent, and limited to the right eye specifically. It is not polar, but determines the inclination of the magnetic field; it operates in a narrow window of intensity levels (unless the bird is conditioned to a different level); it is disoriented by low intensity MHz-range oscillating magnetic fields; it is not affected by anesthesia of the upper beak, and is not affected by a strong magnetic pulse. However, despite the seeming distinctness, experimentation indicates a complex interaction between the two. To get to that, the nature of the light-dependence of the "inclination compass" has to be examined.

First it was shown that the light-dependent process in the birds' right eye *would only work under certain colors of light*.

If birds were tested in light from the blue-green side of the spectrum, they would be able to orient to their migratory direction without problems. For the extensive tests with European Robins in blue or green light, they would orient to the north in the spring and to the south in the autumn, just as if they were in the wild. Even in UV light (at 373 nm) the robins were able to find their proper orientation. However, when yellow and red light were used the birds could not orient in the proper directions, and showed a general chaotic disorientation (see image 9 for 6 tests in 6 different colors of light).

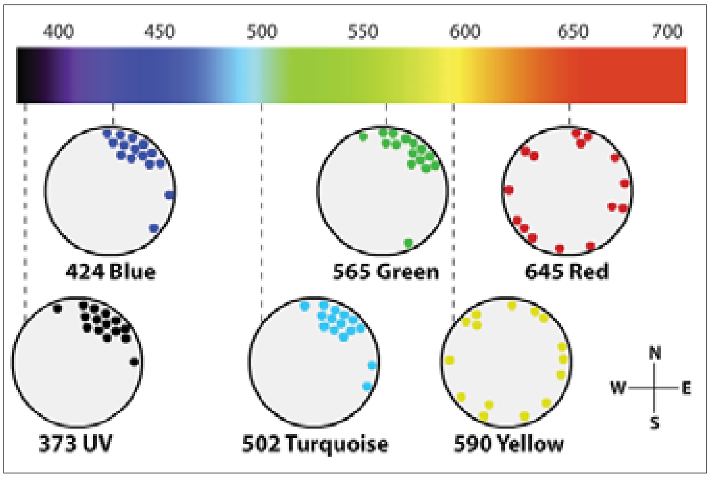

Image 9: Image adapted from "Magnetic orientation and magnetoreception in birds and other animals," Wolfgang and Roswitha Wiltschko, J Comp Physiol A (2005) 191: 675-693.s

In each of these cases single color (monochromatic) light was used.

This indicates that the light-dependent magnetoreception is only activated by the UV to green part of the spectrum, and fails to operate properly in the yellow to red range. As we saw above, this light-dependent response is related to the inclination compass, where the birds use the inclination of the magnetic field to determine direction (e.g. if the inclination of the field is inverted the birds will go in the opposite direction, even though the directions of the north and south components of the magnetic field remain the same direction). Also, recall that this light-dependent magnetoreception is disrupted by a very low intensity oscillating magnetic field of the proper frequency. These characteristics were tested, and demonstrated for monochromatic UV, blue, turquoise, and green light tests (see image 10).

However, these monochromatic tests were all performed at rather low light intensities. For each of the different tests using monochromatic light, the intensity level was roughly equivalent to the brightness experienced around a half hour before sunrise, or after sunset. Tests

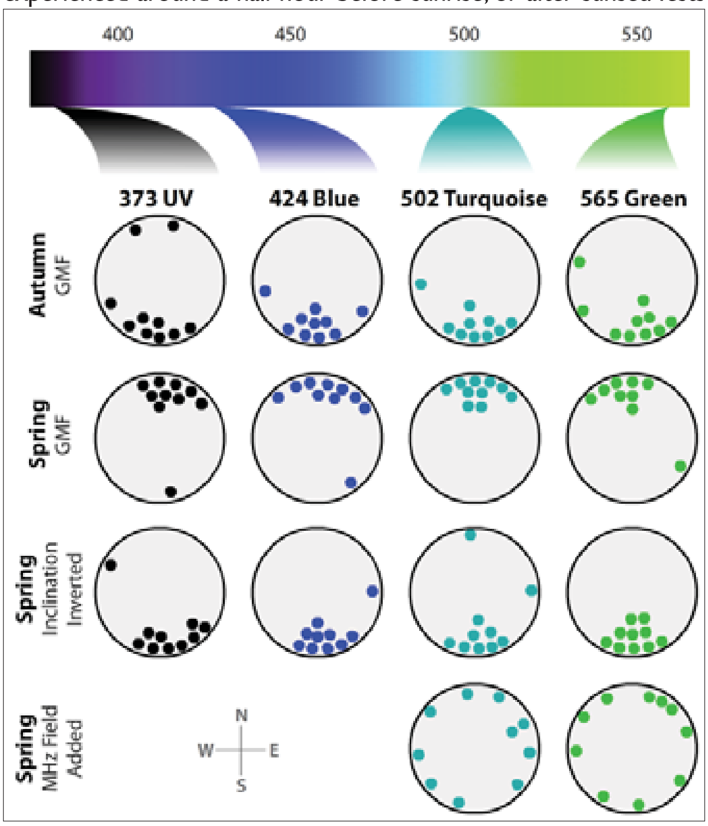

Image 10: Image adapted from "Directional orientation of birds by the magnetic field under different light conditions," Roswitha Wiltschko, Katrin Stapput, Peter Thalau, and Wolfgang Wiltschko; R. J. Soc. Interface (2010) 7, S163-177.

with birds in bright daylight, where they experience the entire visible spectrum at the same time, showed that they have no to trouble using this light-dependent magnetic sense in the bright daylight. But, using the narrow ranges of the monochromatic lights, they showed interesting problems with increased light intensity.

Still at intensity levels far below that experienced on a sunny day, using monochromatic light the birds started showing peculiar responses. In tests with robins under green light, at a low intensity ("8*10^15 quanta/s/m^2"), they oriented in their proper migratory direction, north in this case. When the intensity of the green light was increased ("36*10^15 quanta/s/m^2") they showed general disorientation. When increased further ("54* 10^15 quanta/s/m^2") a curious response emerged, they showed a tendency to orient either east or west specifically. When the intensity of the green light was increased more ("72*10^15 quanta/s/m^2"), they now preferred either north or south. Even with the highest intensity tested here ("72*10^15 quanta/s/m^2"), it is still only the level of brightness experienced around sunrise or sunset. This new phenomenon was identified as an "axial preference" (see image 11).

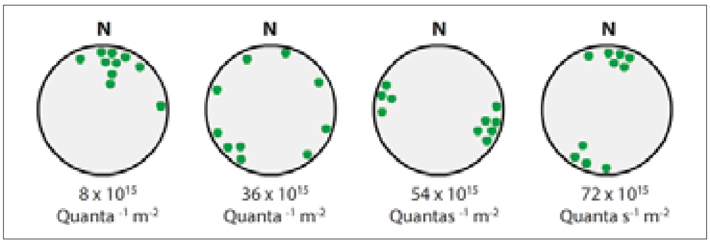

Image 11: Direction of birds at successively higher levels of intensity of green light. Image adapted from "Directional orientation of birds by the magnetic field under different light conditions," Roswitha Wiltschko, Katrin Stapput, Peter Thalau, and Wolfgang Wiltschko; R. J. Soc. Interface (2010) 7, S163-177.

Because the intensity was still far below that of noon on a normal day (where the birds have no trouble orienting in their navigational direction), this could not be just an over-saturation of the birds' vision. At least, not in a simple sense. And this is more than general confusion, because the birds were not just generally disoriented, but predominately choose a certain axial direction, one different than their expected migratory direction. Again, the axial direction changed with different intensities, and it was found that to get the same axial direction at different colors (e.g. east-west under green light and then under blue light) the intensity level had to be different. It was shown to get a general east-west directional response in successive colors (UV, blue, turquoise, and then green; in that order), the respective intensity had to be higher in a corresponding manner (see image 12).

It is worth noting that this relationship of the intensity and color roughly corresponds to the sensitivity of the different light cones of birds. That is, the intensity level at which a certain fixed-axis response is induced gets lower as you move from green towards UV light, just as the sensitivity of the birds' receptor cones is said to increase as you move from green to UV light.

Mixing Colors

A last set of tests pushes the understanding of the nature of the magnetoreception capability in birds to an unexpected paradox.

What we have seen is that under low-level monochromatic light from the UV to green range, the light-dependent magnetic response of birds functions, but it does not function under yellow-red light, under which the birds become generally disoriented, orienting randomly without any preferred direction.

Now, in a new set of tests, when low-level turquoise light is added to low-level yellow light, a new response appears. The birds do not choose their natural migratory direction, as under the turquoise alone (or under normal daylight), but they are not simply in a general disorientation, as occurs under the yellow light alone. Rather they all choose to orient in one specific direction that is not the expected migratory direction. They all tend to a south-east direction, in both the spring and autumn, whereas under normal light conditions, they oriented south in the autumn and north in the spring. Because of this same direction in both spring and autumn, this was identified as a "fixed-direction response."

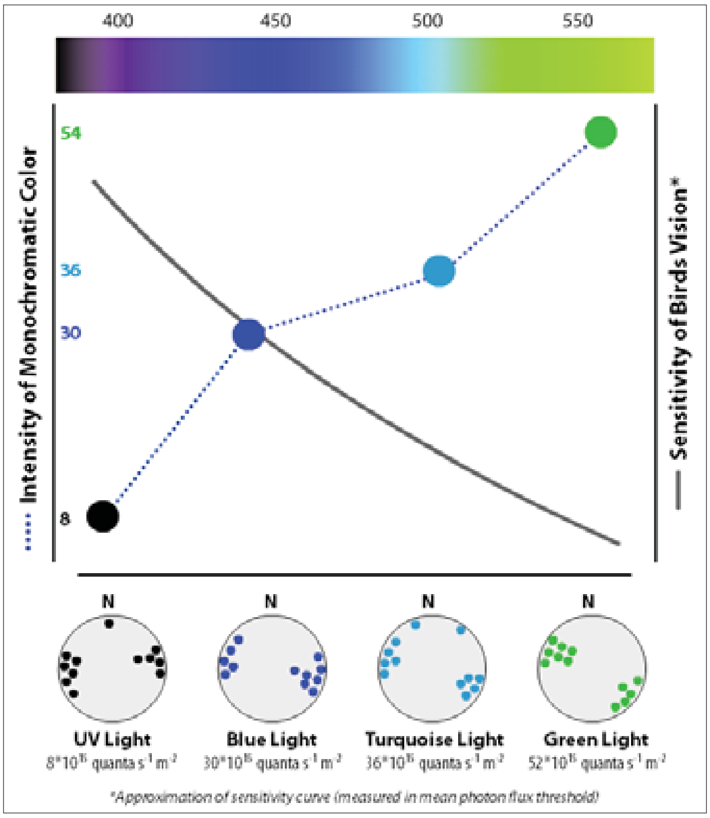

Image 12: Comparison of the general change in the sensitivity of birds' vision at different colors of light, with the intensity at which the same "fixed-direction" response is induced at different colors. Image adapted from "Directional orientation of birds by the magnetic field under different light conditions," Roswitha Wiltschko, Katrin Stapput, Peter Thalau, and Wolfgang Wiltschko; R. J. Soc. Interface (2010) 7, S163-177.

First of all, this indicates that yellow light dose not simply have a null effect for the birds, but does interact with the magnetic reception process in some way. Next it was demonstrated that the actual direction of the "fixed-direction response" depended upon what colors are mixed with the yellow. For example yellow-blue induces south, yellow-green north, and yellow-turquoise east-southeast.

Now things get strange.

So the fixed-direction response is light-dependent, because the light quality determines its direction. However, the following set of tests demonstrate that it shows characteristics *opposite* of the normal light-dependent magnetic orientation of birds discussed above. Recall that normal light-dependent magnetic orientation was shown to be dependent on the inclination of the magnetic field and not the polarity (declination). However this fixed-direction response of the birds was shown to be the same when the inclination was inverted, but it was reversed when the polarity was reversed. That is, showing the opposite characteristics of the normal light-dependent response. (see image 13)

Again, it might be tempting to dismiss this by saying that the birds are just confused. But what is interesting is that there is an order to their confusion, in that they still consistently are choosing certain directions.

In fact, the fixed-direction response, though clearly light-dependent, seems to lose all the characteristics that were found to correspond to the normal light-dependent magnetic sense of the birds. What follows are the results of another series of experiments.

The normal light-dependent function was dependent upon the inclination of the magnetic field but not the polarity; the fixed-direction light-dependent response is polar and not sensitive to the inclination.

The normal light-dependent function was disrupted by low-intensity oscillations in the magnetic field intensity; the fixed-direction light-dependent response is not disrupted by those effects.

The normal light-dependent function functioned in a narrow intensity window (roughly +/- 20-50% of the local GMF intensity); the fixed-direction light-dependent response does not have a limited intensity window, but occurs over a wide range of intensities.

The normal light-dependent function is not disrupted when anesthesia is applied to the upper beak, that is the location of the magnetite structures associated with the "other" ability of the birds to perceive

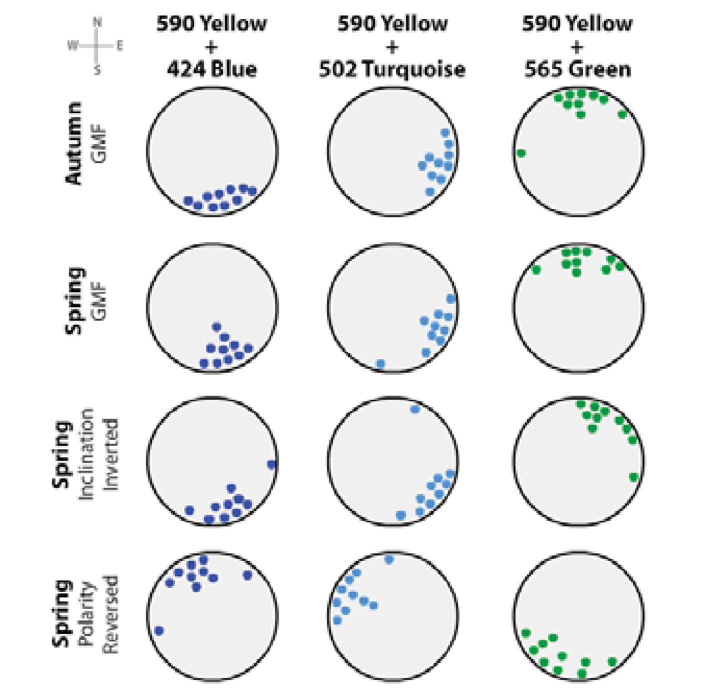

Image 13: Under each respective color pair the birds choose different fixed-directions, but in each color pair, they choose the same fixed-direction in both spring and autumn. When the vertical component of the magnetic field was inverted the birds did not respond differently, as is the case under normal light conditions. But, when the polarity direction is rotated 180° then the birds shift their fixed direction by the same 180°, even though they did not do this under normal light conditions. Image adapted from "Directional orientation of birds by the magnetic field under different light conditions," Roswitha Wiltschko, Katrin Stapput, Peter Thalau, and Wolfgang Wiltschko; R. J. Soc. Interface (2010) 7, S163-177.

the magnetic field. But when anesthesia is applied to the beak, the fixed-direction light-dependent response ceases to function, and there is a general disorientation as opposed to a fixed direction.

So even though it is clearly demonstrated that the fixed-direction response is, in some way, light-dependent, it also seems to rely on this other mechanism of the magnetite structures in the beak, which had no indication that it was light-dependent in any way (there is no light-dependence in any of the theories of how the magnetite structures might function).

Magnetoreception in the Sensorium

Inclination Compass	Fixed-Direction Responses
Inclination	Polar
Disrupted by Oscillating Field	Not Disrupted by Oscillating Field
Narrow Intensity Window	No Intensity Window
Disrupted by Anesthetic to Beak	Not Disrupted by Anesthetic to Beak

Image 14: Comparison of different light-dependent magnetoreception characteristics.s

An immediate implication from the preceding evidence is that there is some form of complex interaction between two magnetic reception abilities—or at least what had been presented as two distinct abilities. Perhaps it is wrong to view these as distinct. Rather they may be aspects of one system. For example, the human eye uses three different cones to detect different wavelengths of light, but you see the three different cone readings as one sense. Taking this into view, perhaps there are other mechanisms involved in magnetoreception as well, ones that we are not yet aware of, all of which could become integrated into one sense for the bird.

This also appears to go beyond just a magnetic sense as such. These sets of experiments with intensity of monochromatic light and mixing of different color lights, indicate some form of interaction between the bird's magnetoreception and their visual system. Recall two indications of this.

First, in tests with various intensities of light, certain fixed axis responses were induced, where the birds consistently chose to go in a specific direction, even though it was different than their expected migratory direction. Recall, that direction changed with the different intensity levels of the light, and the different color mixtures of light. When comparing the different colors and intensity levels at which a specific direction of fixed-axis response was induced (for example the desire to head east or west), there was a similar relationship between that intensity-color relationship, and the general sensitivity of the birds normal vision to different colors. That is, as the light source moves from green to UV light, the intensity level of light required to induce the same fixed-axis response (e.g. east or west) becomes less and less-- which generally corresponds to the fact that the receptor cones of birds are supposed to become more sensitive as you move from green to UV light. (See image 12 above)

In the second case, under low-intensity monochromatic light, the birds could properly orient to their migratory direction under light from UV to green, but under yellow and beyond they became generally disoriented, choosing no specific direction. The simple interpretation would be that magnetoreception requires light from the UV to green range to function, and it does not function under other wavelengths, implying that under yellow light the birds' magnetic sense is simply not activated. However it does not appear to be that simple. When two colors were mixed, for example green and yellow, the yellow no longer appeared to have a null effect, as the birds chose a particular fixed direction (which was different than their expected migratory direction)-- whereas, if the yellow did simply have a null effect, then it would be expected that the bids would still orient to their proper migratory direction under a green and yellow mixture. Also it is worth noting that the molecule proposed to be the one reacting to the magnetic field, cryptochrome, is responsive to light in the blue range, and not the yellow to red range. This leaves presently no mechanical explanation for why the addition of the yellow light would have any effect at all.

These results indicate that there is possibly some interaction between the birds' "vision" (as we tend to understand vision) and their magnetic sense. Perhaps they are not two distinct senses for the birds? Perhaps it is more of a mixture, maybe similar to what we call synesthesia in people, which we identify as seemingly unexpected mixtures between our senses.

The other useful point of departure for future investigation based on what has been presented here, is a potential basis for the study of light-field-chemical interactions within a living process.

If we leave behind the assumption that the reactions occurring within a living process can be reduced to the characteristics of the non-living, the evidence for some form of reactions in the very small being involved in magnetoreception can been seen in a new light. Perhaps the tests involving different colors and intensities could provide a new grounds for experimentation on interactions in the small within a living process.

However they are able to do it, this remarkable ability of the widest variety of living organisms to sense the invisible and changing landscape of the GMF surrounding us at all times, when taken to the extreme of present knowledge, presents questions which are likely more universal across all aspects of what we consider "senses."

When the exact mechanisms and processes by which different living beings are able to detect and utilize the magnetic field are sought out, the investigation leads to some of the same standing questions regarding what sense perception really is. The demonstrated paradoxical interaction between what are said to be different mechanisms for magnetic perception in birds, and the likely general interaction of vision, indicates that the senses are not self-evident and distinct "data readings" as one might be lead to believe.

Footnotes

[10] See *"Magnetic orientation and magnetoreception in birds and other animals,"* Wolfgang and Roswitha Wiltschko, J Comp Physiol A (2005) 191: 675-693.

[11] Imagine if the brightness of the lights in your room was decreased by one ten-thousandth of their current level, and then increased to the same amount above the initial level. If this was done in rapid succession, would you notice? With-in a magnetic field, this type of fluctuation in the intensity, even at such a low level of change, is enough to disrupt the magnetic sense under investigation here. This magnetic case falls under a class of "weak force" phenomena, where the significance is not determined by a scalar value of intensity, but by a geometric question of resonance, in which harmonization with the quality of a process is what enables an interaction. Contrast this with the failure of the limited conception that interactions are only determined by quantity levels, a "brute force" approach.