Magnetoreception

by Benjamin Deniston

The impressive migratory and homing ability of birds has long drawn attention. Detailing the wide range of impressive cases has quickly grown from papers to books. The ability to consistently navigate incredible distances (migrating from the Arctic to the Antarctic and back every year, in some cases!) with impressive speed and accuracy has drawn extensive wonder and experimentation as to how exactly they are able to do this.[1] Through the 1950s, '60s, and '70s, tests were performed to determine how homing pigeons, among other birds, were able to do this. It was shown that they are able to use a number of impressive sensory capabilities, from being able to "hear" extremely low frequencies (down to 0.1 Hz for pigeons), to seeing both ultraviolet light and linearly polarized light, to using the positions of the Sun and stars to orient themselves. Pigeons are sensitive to changes in air pressure, with an accuracy of the pressure difference due to altitude changes as small as 10 meters. In fact, the studies of how the birds were able to utilize the position of the Sun were important in building significant interest in "biological clocks"[2] in the late 1950s, because determination of direction based on the location of the Sun requires some ability to "know" the "time of day," another ability demonstrated in these birds.

Even with this impressive array of sensory capabilities, tests indicated that there was more to the birds' sensorium than even this array of abilities. For example, when homing pigeons were conditioned to a day-night light cycle shifted six hours ahead, this shifted their "biological clocks" six hours, such that, when released into normal daylight, their directional sense was correspondingly shifted ~90° (6:00 to 24:00 corresponds to 90° to 360°), because their seeing the position of the Sun was correlated to a shifted sense of time.[3] But, when the same experiment was conducted on overcast days, the pigeons were able to navigate homeward with no problems, despite the light-dark conditioning which had shifted their "biological clock." This was the case even when the birds were released in a location completely unfamiliar to them, such that they had no indication of where they were being taken (at least no "indication" in terms of the traditional five senses).

Other tests with overcast conditions and/or impaired vision (as with frosted goggles which allowed the birds to see no more than a few meters) further indicated that the birds had another dimension of sensory capability. Experiments in the early 1970s, with magnets and magnetic fields, quickly showed an ability expected by some for over a century: that the birds had some sort of magnetic sense. The questions remained, and still remain: "How exactly is this magnetic sense utilized? What are they detecting and how are they detecting it?"

The Geomagnetic Field (What We Know)

To situate the experimental investigations, we have to start with a presentation of what is known about the measurable structure of the geomagnetic field (GMF), even if there might be limitations to what we know. Even in the simplest sense, the GMF is more interesting than can be measured by the polarity compass that we are most accustomed to.

For clarity, we will take the investigation in successive degrees of resolution. In the most basic view, the GMF is a dipole field, having a single north and single south pole, opposite each other (though in the GMF they are not exactly opposite). Here, in the hypothetically uniform dipole magnetic field, every location on the Earth will not only have a polarity (measured as *declination*, the angle between geographic north [or south] and magnetic north [or south]), but also two other components. There will also be a specific *intensity* (because the field is more intense at the poles and becomes less intense as one moves towards the magnetic equator), and an *inclination* (or dip), which measures how many degrees away from parallel (with the

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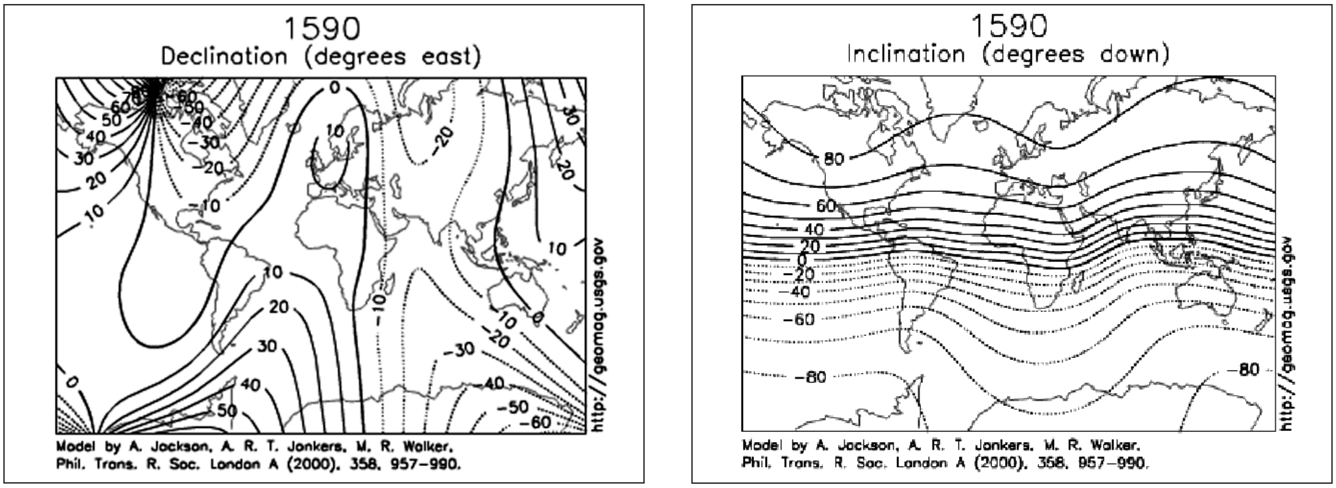
[1] It has also drawn man to utilize this capability. The domesticated homing pigeon has been bred to enhance this impressive navigational ability. Entire books have been written documenting the impressive capabilities of these birds, including the fact that the capability was so well trusted, that homing pigeons were used for military purposes up through World War II.

[2] See Peter Martinson's contribution in this issue, "Following the Beat of a Different Drummer."

[3] For example, if you are in a completely unfamiliar land, and you think it is 7:00 a.m., and you see the Sun just above the horizon, you would determine that direction is east; however, if you, instead, for whatever reason, think that it is 7 p.m., and see the Sun in the same location above horizon, you would be inclined to think that direction is west.

FIGURE 1



1590
Declination (degrees east)

1590
Inclination (degrees down)

Model by A. Jackson, A. R. T. Jonkers, M. R. Walker, Phil. Trans. R. Soc. London A (2000). 358, 957–990.

Declination and inclination global maps from the USGS. These maps are animated; see http://www.larouchepac.com/node/17191

surface of the Earth) the magnetic vector is (**Figure 1**).

For example, imagine you had a compass needle that could spin freely in three dimensions; at the north magnetic pole, the needle would point straight down to the Earth (90° inclination), but as you moved south, the inclination would gradually change until it pointed parallel with the surface of the Earth at the magnetic equator (0° inclination). Even though the GMF is much more complex than a simple uniform dipole field, these three values can be measured at every location in the GMF.[4]

However, when we increase the resolution, the structure of the GMF is much more intricate than a uniform field. Everywhere on the surface of the Earth there are variations in the structure of the GMF. Some variations are larger, related to the large scale-structure of the GMF as a whole, but there are also uncountable smaller variations of a variety of sizes, typically attributed to different densities of metallic components within the Earth's crust (referred to as magnetic "anomalies"). For example, one of the largest magnetic anomalies is found in Kursk, Russia (450 km south of Moscow), where the intensity jumps four-fold, compared to the expected GMF intensity for that location, and the declination (polarity) varies from +60° to −110°, when 8° should be expected. Another extreme case is found off the southern coast of Finland (near the island of Jussarö), where there is a sharp jump in intensity, and variations in the declination are enough to have caused many shipwrecks in the past, when a magnetic compass was all that could be relied upon.

These, however, are among a limited number of outstanding cases, and most of the anomaly variations are much smaller, though they are everywhere. Because there are at least some magnetic minerals in nearly every rock type, if we increase our resolution of measurement enough, the entire surface of the Earth is blanketed with these small anomalies of low intensity (variations of the expected GMF intensity by +/−0.1% to 2.0%).

Though invisible to us, these magnetic structures are as real and dependable as the minerals and other processes with which they are associated. Consider the geographic topology surrounding your hometown. In your mind's eye, you recall those distinguishing characteristics, its hills and valleys, mountains and cliffs, or, perhaps, the remarkable flatness of its plains. So too, does any location in the GMF have its distinct, memorable, and probably beautiful topography. It surrounds us at all times; we just don't see it. But, other species do.

In addition to these relatively fixed structures,[5] there are regular and irregular variations induced from above. The effects (gravitational and electromagnetic) of the rotational relationship of the Earth with the Sun, along

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[4] A few simple variations of these three values are also used. The general properties measured are the same, though the metric can be different. Instead of declination (polarity), inclination, and intensity, two other the sets of components are also used: horizontal intensity, vertical intensity, and declination; and x (north-south intensity), y (east-west intensity), and z (vertical intensity).

[5] In truth, the magnetic anomalies are only as fixed as are mountains, valleys, and plains. As the crustal structure shifts and changes, so do the magnetic anomalies. Even more interesting, the large-scale structure of the GMF changes, including reversals of the dipole field, where the magnetic poles actually swap their respective locations on the globe, although much of the "how" and "why" is still highly speculative.

with the rotational effects of the Moon (gravitational) induce slight (sometimes unnoticeable), but regular variations in the GMF qualities measured at the surface of the Earth. Much of this is attributed to the effect on, and generation of, electrical currents in the atmosphere, ionosphere, magnetosphere, and related structures which generate magnetic fields which interact with the GMF. Even if, on a relatively weak level of intensity, the class of regular variations in the GMF (daily, lunar, annual, etc.) could provide a temporal landscape, a periodic indicator, for life. Along with these expected influences, much more rapid micro-pulsations add another dimension of variation. Also, irregular activity from the Sun (solar flares, coronal mass ejections, solar wind shutdowns,[6] etc.) and other extraterrestrial interactions[7] sporadically induce fluctuations in the magnetic field at the surface of the Earth.

So, with this known degree of variation in the structure of the GMF, it is no surprise to learn that there is no single quality of the GMF that living organisms respond to; rather, a variety of distinct qualities of the GMF have been shown to influence living organisms. Presently, the magnetoreception ability of birds is the best studied, so that will be both the starting point and the bulk of this present report, with cases from other animals added in where relevant. But don't let that fool you: The wide range of living organisms which respond to the GMF—from single celled bacteria, to plants, to crustaceans and insects, to vertebrates including fish, reptiles, amphibians, mammals and birds—poses the likelihood that some form of magnetic perception is a rule, and not an exception, for life.

Unfortunately, in trying to determine how organisms can do this, the investigations are generally dominated by a "bottom-up" methodological approach, characterized by, first, asking, "How does magnetism act in non-living experiments of physics?" And second, seeking out particular mechanisms with those properties within living organisms. This unjustly constrains the investigation of a living process to the domain of the non-living, whereas the crucial experimental work of Louis Pasteur, especially as elaborated in the unique work of Vladimir Vernadsky, demonstrated that life cannot be reduced to non-living phenomena.[8] This challenge will come up in a specific, more developed context towards the end of this paper.

First, the proper geometry of experimental evidence will have to be created in the mind of the reader.

An 'Inclination Compass'

What follows is not intended to be chronological presentation of the history of the development of our understanding of magnetoreception, nor is it a complete record of the experimentation conducted. Rather, the composition is structured to build to the crucial questions relevant for this report as a whole.

Extensive study has attempted to narrow down exactly what aspects of the GMF are being detected by the animals, usually limited to investigations of the three factors of the GMF discussed above. Animals have shown responses to each of those factors, as well as combinations thereof, indicating that they can sense all of these qualities.[9]

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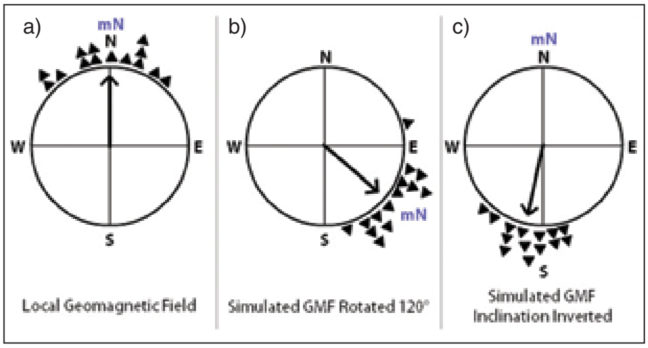
[6] For example, for two days in May 1999, the Sun basically stopped emitting solar wind (the constant flow of charged material flowing from the Sun), with output levels falling to less than 2% of normal. This was by far the most extreme reduction ever witnessed, and is, still, a completely anomalous event. See http://science.nasa.gov/science-news/science-at-nasa/1999/ast13dec99_1/.

[7] For example, see Sky Shields, "Unheard Melodies," in this issue, where he discusses the large-scale effects of the interaction of meteors with the Earth's ionosphere and atmosphere.

[8] For the work of Pasteur referenced here, see the LaRouchePAC-TV video, "Louis Pasteur: The Space of Life" (http://www.larouchepac.com/node/13732), and for the work of Vernadsky, see his "The Physical States of Space" (http://www.21stcenturysciencetech.com/Articles%202008/States_of_Space.pdf), and "The Problems of Biogeochemistry II: On the Fundamental Material-Energetic Distinction Between Living and Nonliving Natural Bodies of the Biosphere" (http://www.21stcenturysciencetech.com/translations/ProblemsBiogeochemistry.pdf).

[9] Although the experimental work leans heavily on the ability of animals to detect magnetic fields as such, often using synthetic magnetic fields generated with man-made electromagnetic systems, we cannot simply limit our understanding of animal sensation to this. It cannot be assumed that the laboratory magnetic fields generated for these tests embody all of the characteristics that animals are sensitive to. What we do know is that we can simulate a limited component of the sensorium that animals are responsive to, but we don't know how or in what way that component is limited with respect to their full sensorium, which is interconnected and organized in ways that we don't yet realize. For example, entire classes of organisms have demonstrated abilities to sense (and in some cases produce) electrical currents and fields, which, though notable in itself, also takes a new dimension of interest because of the intimate relation of electrical and magnetic fields (again, noting that extensive investigations of this interrelationship have been limited to abiotic expressions). In that context, consideration must be given to the electrical nature of living organisms, expressed throughout their structure, as well as the sensitivity of living organisms to extremely low-frequency electromagnetic fields. Without fully knowing how the electrical nature of an organism functions, nor exactly how organisms are sensitive to these low-frequency fields, among other considerations,

FIGURE 2



Orientation behavior of migrating European robins during Spring time. The triangles indicate the direction of individual birds, and the large arrows indicate the averaged direction. Image adapted from Wolfgang and Roswitha Wiltschko, "Magnetic orientation and magnetoreception in birds and other animals," ***Journal of Comparative Physiology****, A (2005) 191: pp. 675-693.*

For example, birds have shown the ability to determine compass direction, though not the way you might think.

European robins, under caged test conditions, will consistently show their expected desire to head north in the Springtime. If prevented from seeing the Sun, or any landmarks, the birds are still able to consistently orient themselves northward, suggesting that they are given indications by the natural geomagnetic field. In attempting to determine how they do this, and what specific characteristics they respond to, various experimental conditions were tested.

If an artificial simulation of the local GMF was created, simulating all the same conditions of the GMF (only in terms of the three components discussed above), but rotated 120° to the east, then the birds showed that they wanted to go in that corresponding roughly southeast direction (**Figure 2b**). Initially, it seemed that the birds were determining their direction by a desire to head towards magnetic north, as they following the 120° shift.

However, we get a totally different response when a new artificial simulation is tried. When magnetic north still points towards geographic north, as in the GMF, but the inclination is inverted (pointing above, rather than below the horizon), then the birds go in the exact opposite direction, predominantly heading towards magnetic south (**Figure 2c**).

This indicates that the Robins don't determine their navigational direction by the magnetically polarity, but rather determine the inclination of the GMF, and use that to determine their migratory direction. For example, the inclination in the Northern Hemisphere points in a downward direction, and the amount it points downward depends on how close you are to magnetic North Pole.

Every species of bird that has been tested for this particular "inclination compass" has shown this specific ability. Sea turtles and salamanders also possess an inclination compass, whereas the only mammals tested for this ability (mole rats), as well as insects and crustaceans, did not respond to the inclination changes, but demonstrated a "*polarity* compass" (orientation based on the direction of magnetic north/south). Further tests were performed to determine how those that did, were able to use this inclination compass.

For example, intensity was tested. For robins that live in a local geomagnetic field of ~46,000 nanotesla (nT), it was shown in experimental tests with artificial geomagnetic fields, that they could not orient to their normal migratory direction if the intensity were either increased or decreased by ~20-30%. This showed that the intensity window at which the birds respond with their inclination compass is rather narrow. But, if the birds were exposed to a higher-intensity magnetic field for three days prior to testing, they could then orient properly at the higher intensity level, as well as at the normal intensity level, though not at an intermediate level, which they had not yet become accustomed to.

It was also shown that the magnetic compass function of birds is dependent on the right eye, specifically. When only the right eye was covered, they could not determine their migratory direction. But with the left eye covered, they could determine their migratory direction by using their right eye.

`Non-Compass Use of the Geomagnetic Field'

As we saw above, there is evidence demonstrating that animals can do much more than detect the inclination of the magnetic field to determine direction. From observations of their ability to navigate and home, it is clear that they need to know more than just a direction. Tests have long shown that birds could be released in locations completely unfamiliar to them, even when they were given no indication of what direction they had been taken in, and they could still find their way directly back home. This clearly requires, in addition to

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it is presumptuous to expect that we could grasp the extent of the "magnetoreception" capabilities of living organisms.

being able to determine direction (compass), some way for the birds to determine their location. Using a compass to determine which way is north won't do you much good in trying to find your home, if you don't know where you presently are. For birds, among other animals, it has been demonstrated that this ability is also a magnetic sense.

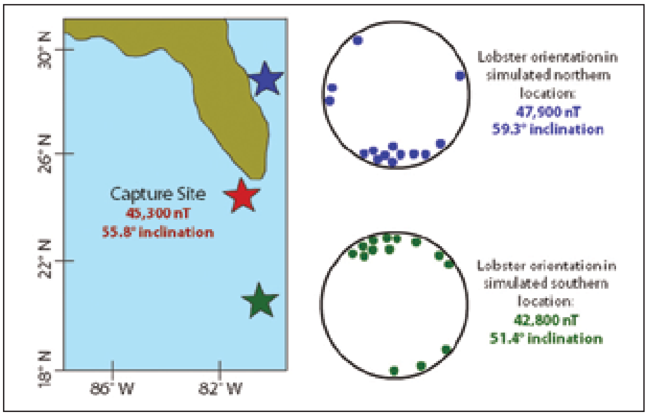
In addition to inclination, the other components of the GFM discussed, intensity and polarity (declination), change continuously as you move throughout the GMF.

To test the ability for animals to utilize these components to determine their position, numerous experiments were set up, including with lobsters. Captured off the tip of Florida, their home location has a specific GMF intensity, inclination, and polarity. They were kept in one location, but two groups were tested in two different magnetic environments generated to simulate the GMF at two different locations. One group was exposed to magnetic conditions which simulated a location directly north of their home, while the other group was exposed to a simulation of the magnetic conditions of a specific location directly south. No other stimuli were provided to simulate any difference in location. In the first group, the lobsters predominantly attempted to head south, which would be the direction of their home, if they were actually at the location indicated by the simulated magnetic conditions. Likewise the second group, exposed to magnetic conditions simulating a location south of their home, attempted to head north, even though they were geographically in the same location as the first group. In both cases, the synthetic magnetic indicators appeared to be enough to trick the lobster into "thinking" they were at the location that would be associated with those magnetic conditions (**Figure 3**).

Some birds have demonstrated an even more sophisticated ability to use the magnetic conditions of the GMF to not only determine their relative location, but also respond to the geographical characteristics associated with that location. They will react as if they had encountered those geographic conditions, even if only provided with the associated magnetic conditions.

The Autumn southerly migratory route of the central European pied flycatchers takes them from central Europe, not directly south, but first southwest, towards the Iberian Peninsula, allowing them to avoid the Alps. Then, after a certain distance, they make a roughly 90° change in direction, heading southeast. This helps to avoid the Sahara Desert. Domestically raised birds of this population were tested in caged environments, where they remained in the same geographic location for the entire test period. During the appropriate migratory time, they showed an orientation to head in the expected southwest direction. They continued the desire to head in this direction only until they were subjected to an artificial magnetic field that simulated the magnetic conditions in Northern Africa. Then they immediately changed their orientation 90°, heading southeast. There was no change in visual or other stimuli, only the magnetic conditions.

FIGURE 3



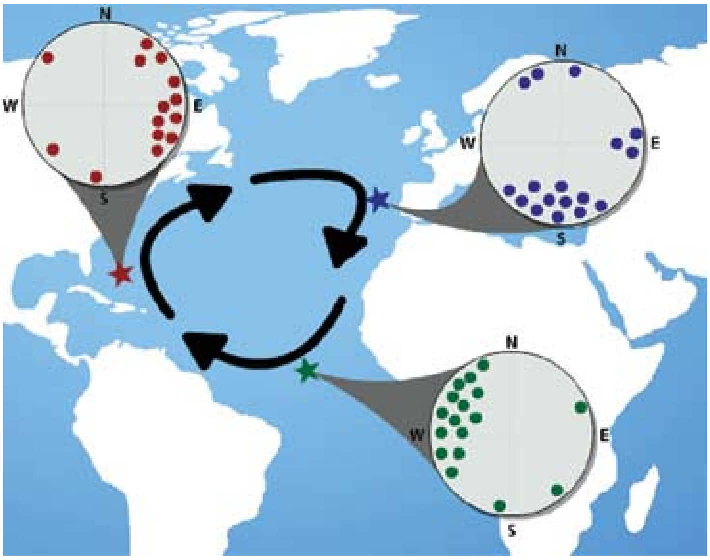
The circles indicate the direction of individual lobsters. Image adapted from Wolfgang and Roswitha Wiltschko, op. cit.

Note that there is nothing universal about the magnetic stimulation and the directional response of different species (i.e., there is nothing in the simulated magnetic environment in itself that indicates a particular direction for every animal). For example, if the lobsters were provided the same Northern African magnetic conditions, they would not have made the same directional change that the flycatchers did, but would have likely chosen the direction that would have brought them back to Florida.

Similar tests were performed with thrush nightingales caught in Sweden. In Autumn, while remaining in one location, they were provided with an artificial magnetic environment that simulated what they would have encountered on their regular migratory route, with no change in any other stimuli. Their eating habits and weight were monitored. They showed a slow, regular weight gain in the beginning period. However when the simulated magnetic environment matched that which would be felt in Egypt, the birds suddenly showed a dramatic increase in weight gain. This corresponds perfectly to their actual migratory trips, where they put on more weight prior to crossing the desert in Egypt, where there is a lack of food. In this experimental case, behavioral responses were induced solely by the magnetic stimuli associated with a geographic location, with particular relevance to their migratory patterns.

This ability to use magnetic conditions as "magnetic markers" or "magnetic signposts," is not limited to birds. Juvenile loggerhead sea turtles from Florida show an interesting characteristic during the first years of their lives: They travel about the Atlantic Ocean, but always stay within the particular region known as the Atlantic gyre. So, hatchling turtles of this grouping were tested to see whether this ability depended upon magnetoreception. As in the cases of birds and lobsters, the turtles were kept in a single location, but were provided with three different artificial magnetic environments, simulating the magnetic conditions of three locations on the edge of the gyre. In each of the cases, the hatchling turtles oriented in the proper direction that would keep them within the gyre, had they actually been at the geographic locations that the simulated magnetic conditions indicated. As hatchlings, they obviously had never experienced the extent of the Atlantic gyre, so, in addition to the ability to navigate by magnetic conditions, they were seemingly born with some form of magnetic map of the Atlantic Ocean (**Figure 4**).

FIGURE 4



The three different locations the artificial magnetic conditions simulated. The circles indicate the direction of individual turtles subjected to the artificial conditions indicated. Image adapted from Wolfgang and Roswitha Wiltschko, op. cit.

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, 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 these structures might operate.

In attempts to test the nature of these magnetite structures, experiments were devised to determine whether 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 seven days of general disorientation, after which the birds were able to regain their normal migratory ability.

These results were not uniform, however. What was interesting is that only *adult* birds which had migrated before were affected by the pulse. *Juvenile* birds of this species, which had never experienced a migration, were not affected, and most had no difficulty finding their proper migratory direction (**Figure 5**).

The conclusion drawn was 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 another mechanism.

In an elaboration of this experiment, adult birds

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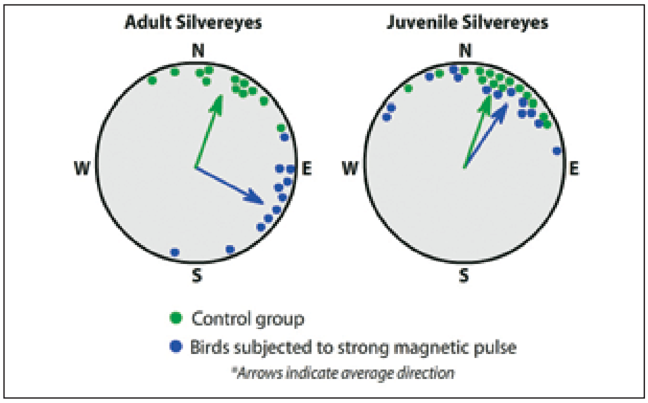
[10] See Wolfgang and Roswitha Wiltschko, "Magnetic orientation and magnetoreception in birds and other animals," *Journal of Comparative Physiology,* A (2005) 191: 675-693.

FIGURE 5



Adult silvereyes were disoriented by the magnetic pulse, but juveniles are not. Image adapted from Wolfgang and Roswitha Wiltschko, op. cit.

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 the magnetite structures). In this case, 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 cannot 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, salamanders. 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 1970s, 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, 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 was that 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, 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 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

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[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? Within 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, whose 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.

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, 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 whether the quality of such an interaction would be replicable outside of a living process. That is, we cannot assume that the characteristics of abiotic chemistry or physics, as presently understood, will be sufficient to express 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 not to 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. The results reported 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).[12]

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. In 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

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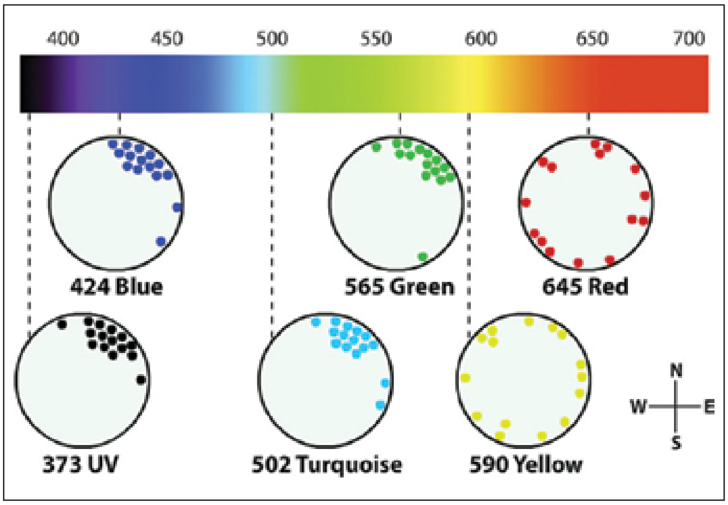
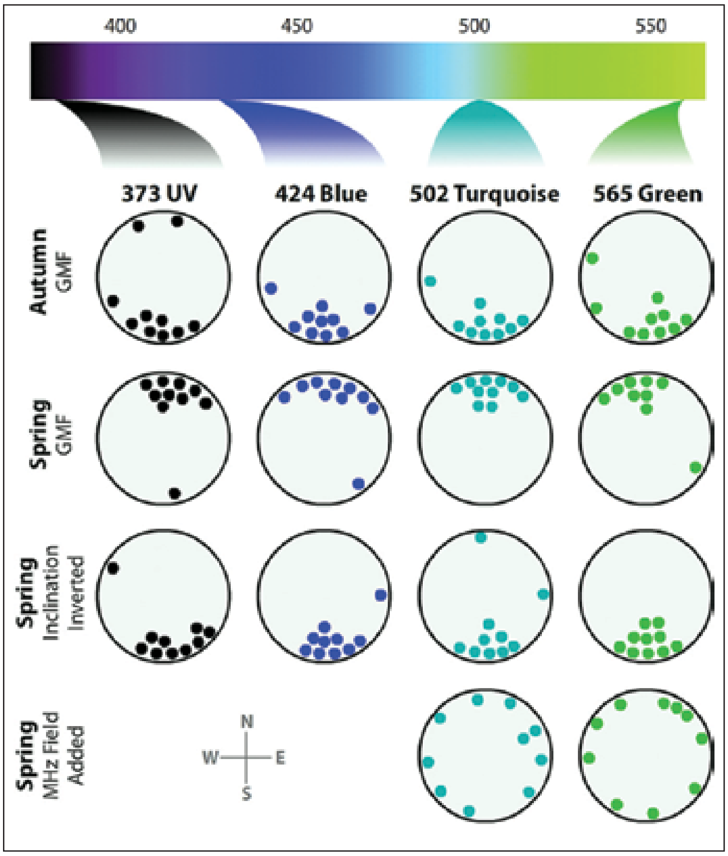
[12] *Photobiology: The Science of Life and Light* (Springer Science+Business Media, LLC, 2008)

FIGURE 6



Birds' orientation to different monochromatic colors of light. Image adapted from Wolfgang and Roswitha Wiltschko, op. cit.

FIGURE 7



Birds' orientation to monochromatic colors combined with a very low-intensity oscillating magnetic field. Image adapted from Roswitha Wiltschko, Katrin Stapput, Peter Thalau, and Wolfgang Wiltschko, "Directional orientation of birds by the magnetic field under different light conditions," R. J. Soc. Interface (2010) 7, pp. S163-177.

were used, the birds showed a general chaotic disorientation (**Figure 6**).

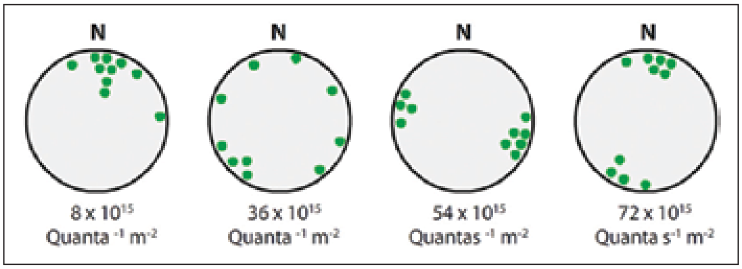
In each of these cases, single color (monochromatic) light was used.

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). 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 (**Figure 7**).

However, these monochromatic tests were all performed at rather low light intensities. For each of the tests using monochromatic light, the intensity level was roughly equivalent to the brightness experienced around half an hour before sunrise, or after sunset. Tests with birds in bright daylight, where they experience the entire visible spectrum at the same time, showed that they have no 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/^{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 iden-

FIGURE 8

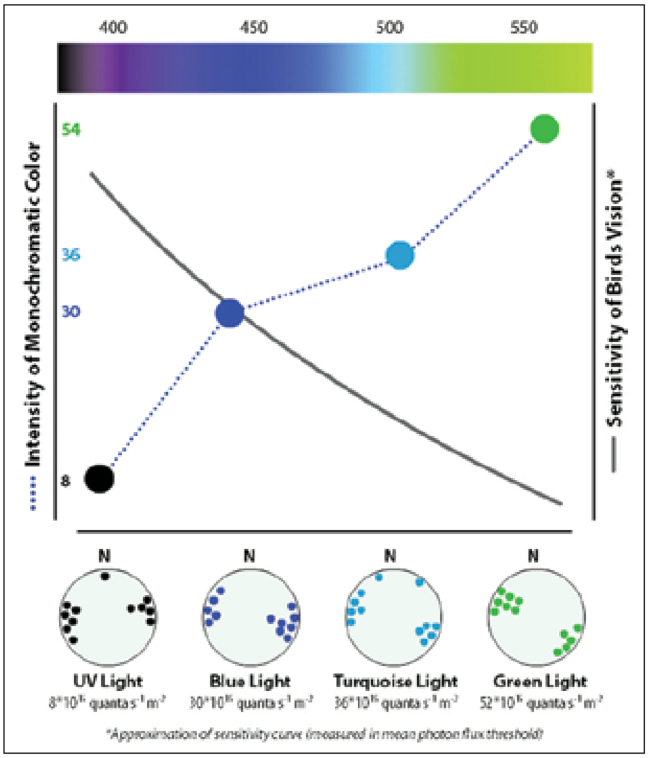


Direction of birds at successively higher levels of intensity of green light. Image adapted from Roswitha Wiltschko et al. (2010), op. cit.

tified as an "axial preference" (**Figure 8**).

Because the intensity was still far below that of noon on a normal day (where the birds have no trouble orienting), 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 chose 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 obtain 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 (**Figure 9**).

FIGURE 9



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 Roswitha Wiltschko et al. (2010), op. cit.

It is worth noting that this relationship of the intensity and color roughly corresponds to the sensitivity of the different light cones of the birds' eyes. 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.

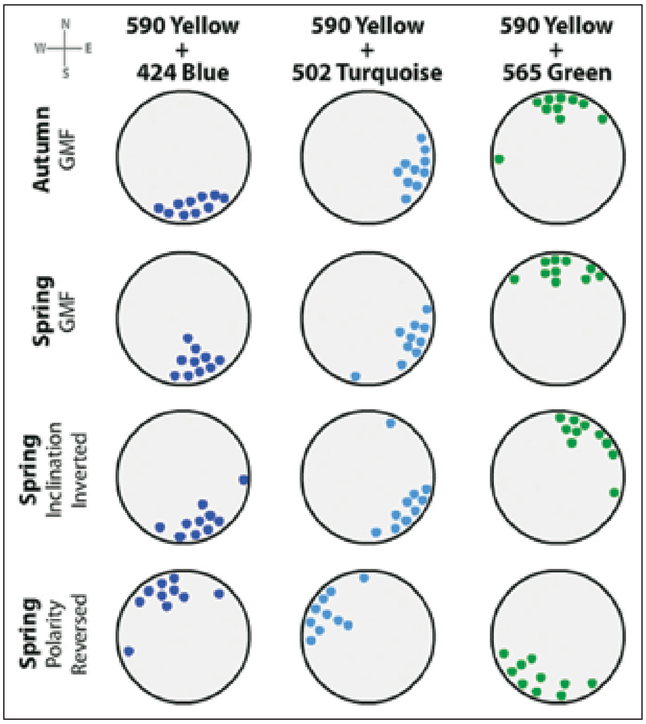
What we have seen is that under low-level monochromatic light from the UV to green range, the light-dependent magnetic response of birds functions; but it does not function under yellow-red light, under which the birds orient randomly. Now, in a new set of tests, when low-level turquoise light is added 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 southeast direction, in both the Spring and Autumn, whereas under normal light conditions, they orient 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."

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. How-

FIGURE 10



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 Roswitha Wiltschko et al. (2010), op. cit.

ever, the following set of tests demonstrates that it shows characteristics *opposite* to 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 was shown to be the same when the inclination was inverted, but reversed when the polarity was reversed. That is, showing the opposite characteristics of the normal light-dependent response (**Figure 10**).

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 are still consistently 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 birds' normal light-dependent magnetic sense. 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 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

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 its visual system. Recall two indications of this.

First, in tests with various intensities of light, certain fixed axis responses were induced, whereby the birds consistently chose to go in a specific direction, even though it was different than their expected migration. 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 bird's 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 Figure 10, 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.

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 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 led to believe.

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