The Extended Sensorium

Magnetoreception

Part 1 of 2

by Benjamin Deniston

The impressive migratory and homing ability of birds has long drawn attention. Detailing the wide range of impressive cases could quickly grow from papers, to books, to volumes with ease, and certainly already has. The ability to consistently navigate incredible distances (even 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 1950's, '60's, and '70's, series of tests were performed in attempts 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 the demonstrations that they will use 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 1950's, 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 bird's sensorium than even this array of abilities. For example, when homing pigeons were conditioned to a day-night light cycle shifted 6 hours ahead, this shifted their "biological clock" 6 hours, such that, when released into normal daylight, their directional sense was correspondingly shifted ~90° (6hr to 24hr 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, where the position of the sun could not be visually determined, the pigeons were able to navigate in the proper direction towards their home 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, and 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 at most) further indicated that the birds had another dimension of sensory capability. Experiments in the early 1970's 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 measur-

Image 1: compass.

able 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 traditional 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 [south] and magnetic north [south]), but 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 surface of the Earth) the magnetic vector is. 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 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 crust (referred to as magnetic "anomalies"). For example, one of the largest magnetic anomalies is found in Kursk, Russia (450km 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%).

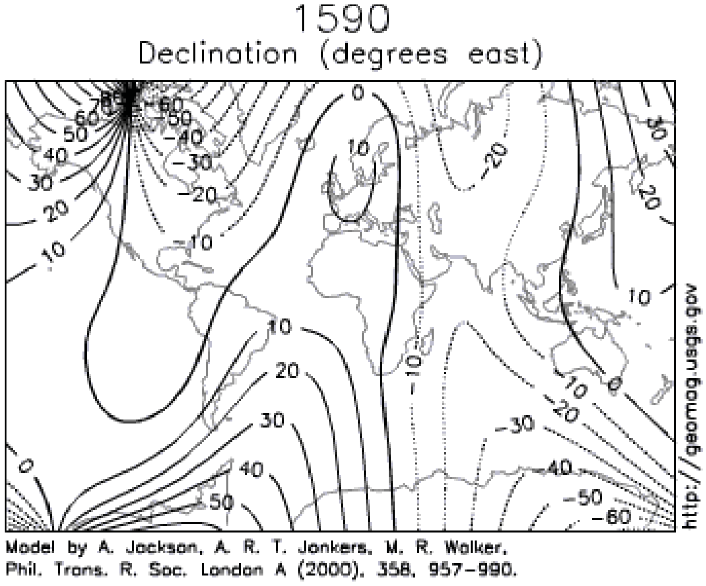
Though invisible, to us, these magnetic structures are as real and dependable as the minerals and other processes with which they are associated. Recall the geographic topology surrounding your home town. In your mind's eye, you recall those distinguishing characteristics, either its hills and valleys, 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.

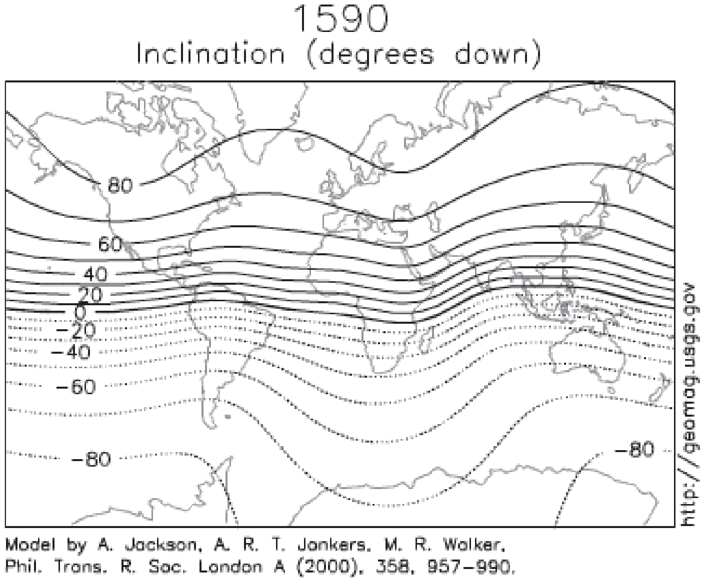
In addition to these relatively fixed structures[5] there are regular and irregular variations induced from above. The effects (gravitational and electromagnetic) of the rotational relationship of the Earth with the Sun, along with the rotational effects of the moon (gravitational) induce slight (sometimes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

So, with this know 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 most well studied, so that will be both the starting point and the bulk of this present report, with a fair number of 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 then, 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 can not 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.





Images 2 and 3: USGS animated global maps of declination and inclination over the past 400 years.

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 all 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 there of, indicating that they can sense all of these qualities.[9]

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 spring time. With no ability to see the sun, or any other landmarks, the birds are still able to consistently orient themselves in attempts to head north, suggesting that they are given indications by the natural geomagnetic field. In attempt to determine exactly 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

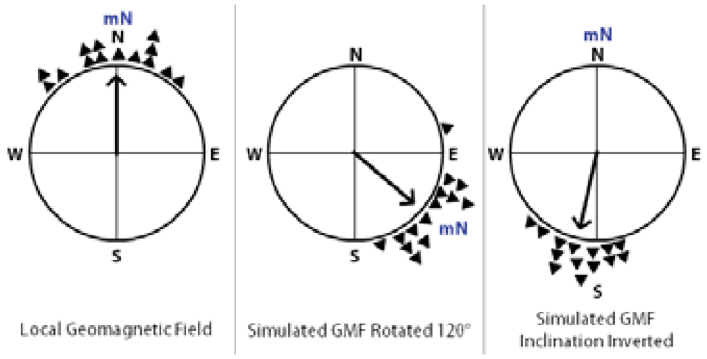


Image 4: Orientation behavior of migrating European Robins during spring time. The triangles indicate the direction of individual birds, and the large arrows indicate the averaged direction. Image adapted from "Magnetic orientation and magnetoreception in birds and other animals," Wolfgang and Roswitha Wiltschko, J Comp Physiol A (2005) 191: 675-693.

in that corresponding roughly south-east direction (as seen in the middle image below). 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 choose to go in the exact opposite direction, predominantly heading towards magnetic south (see third diagram).

This indicates that the Robins don't magnetically determine their navigational direction by the polarity (which direction is north or south), 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 downward it points depends on how close you are to magnetic north pole.

Every species of bird which has been tested for this particular "inclination compass" has shown this specific ability. Sea turtles and salamanders have also been shown to 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" (i.e. the tendency to orient based on the direction of magnetic north/south, as we would associate with using a traditional compass). Further tests were performed to determine how they were able to use this inclination compass.

For example, intensity was tested. For robins which 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 was 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 3 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 in-between, which they had not yet become accustomed to (see the diagram).

Also, in a rather interesting demonstration, it was 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 using their left eye. But when they had their 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 the ability of animals to navigate and home, it is clear that they need to know more than just a direction. Tests have long shown that 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 being able to determine direction (compass), some way for the birds to determine where they are-- 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 then kept in one location, but two groups were tested in two different magnetic environments generated to simulate the GMF at two different locations. Though they remained in the same place the entire time, 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 which would be associated with those magnetic conditions.

Some birds have demonstrated an even more sophisticated ability to use the magnetic conditions of the GMF to

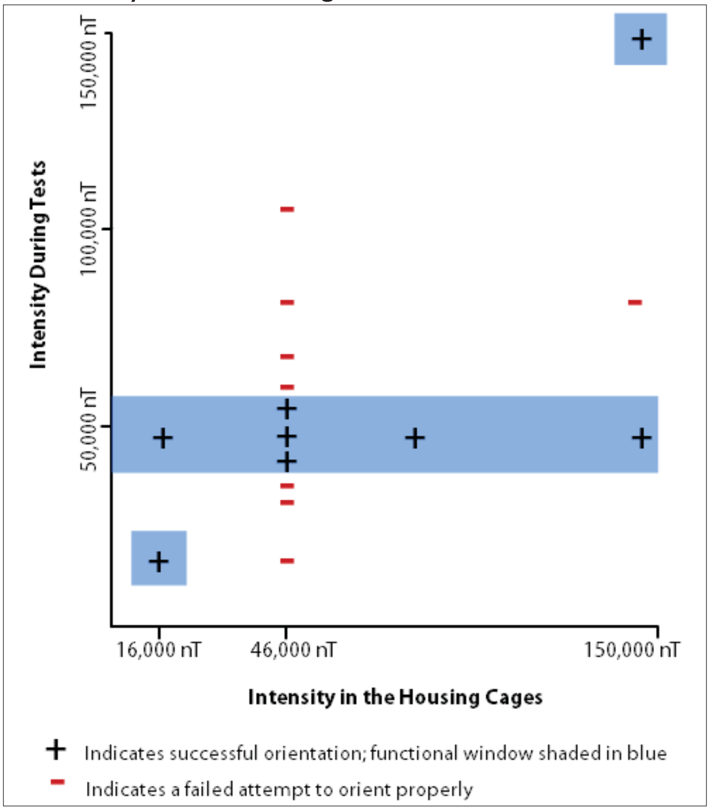


Image 5: Tests of magnetoreception abilities at different magnetic intensities. Note the difference between the intensity during the tests and the intensity of the housing cages. Image adapted from "Magnetic orientation and magnetoreception in birds and other animals," Wolfgang and Roswitha Wiltschko, J Comp Physiol A (2005) 191: 675-693.

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 fall 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 mountain range. Then, after a certain distance, they make a roughly 90° change in direction, heading southeast. The change in direction helps to avoid the Sahara Desert. Hand-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 of autumn, 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°, to southeast. There was no change in visual or other stimuli, only the magnetic conditions.

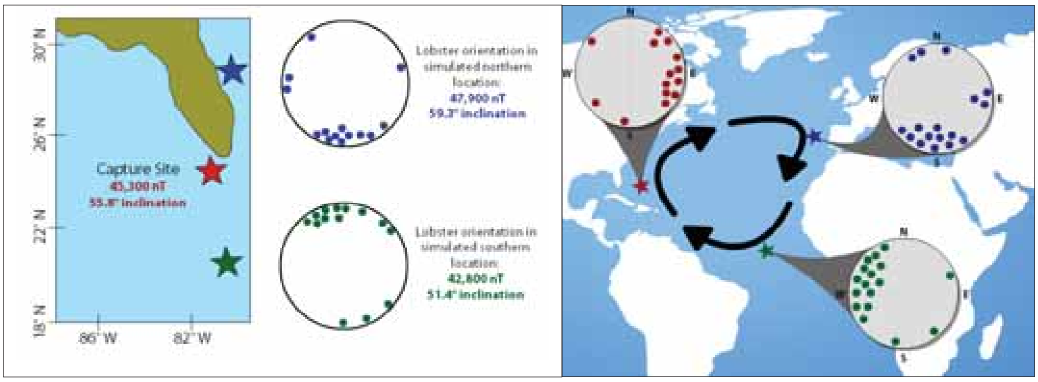


Image 6: The circles indicate the direction of individual lobsters. Image adapted from "Magnetic orientation and magnetoreception in birds and other animals," Wolfgang and Roswitha Wiltschko, J Comp Physiol A (2005) 191: 675-693.

Image 7: 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 "Magnetic orientation and magnetoreception in birds and other animals," Wolfgang and Roswitha Wiltschko, J Comp Physiol A (2005) 191: 675-693.

Note that there is nothing universal about the magnetic stimulation and the directional response of different species or different animals (i.e. there is nothing in the simulated magnetic environment in itself which indicates a particular direction for every animal). For example, if the lobsters were provided the same northern Africa 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, again, with no change in any other stimuli. Their eating habits and weight were monitored. They showed a slow, regular weight gain for 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 will put on more weight prior to crossing the desert of 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 will travel throughout 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 if this ability depended upon their magnetoreception. As in the above cases with 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 different locations on the edge of the gyre. In each of the three cases, the groups of hatchling turtles oriented in the proper direction that would keep them within the gyre, as if they had actually been at the geographic locations that the simulated magnetic conditions indicated. As hatchlings, they obviously never had experienced the extent of the Atlantic gyre, so, interestingly, in addition to even the ability to navigate by magnetic conditions, they were seemingly born with some form of magnetic map of the Atlantic Ocean.

Footnotes

1 It has also drawn man to utilize this capability. The domesticated homing pigeon has been bred to enhance this impressive navigational ability. Again, 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 to this report, *"Following the Beat of a Different Drummer."*

3 For example, if you are in a completely unfamiliar land, and you think it is 7 am, 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 pm, and see the same sun in the same location above horizon, you would be inclined to think that direction is west.

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," or "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. Also, even more interesting, the large-scale structure of the GMF changes, including "reversals" of the dipole field as a whole, where the magnetic poles actually swap their respective locations on the globe, though much of the "how" and "why" are still highly speculative.

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 their normal levels. This was by far the most extreme reduction ever witnessed, and is, still, a completely anomalous event, http://science.nasa.gov/science-news/science-at-nasa/1999/ast13dec99_1/.

7 For example, see Sky Shield's contribution to this report, *"Unheard Melodies,"* where he discusses the large-scale effects of the interaction of meteors with the Earth's ionosphere and atmosphere.

8 For a presentation of the work of Pasteur referenced here, see the LaRouche PACTV 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 his *"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 Though the experimental work leans heavily on the ability of animals to detect magnetic fields as such, often using synthetic magnetic fields generated with various man-made electromagnetic systems, we can not simply limit our understanding of animal sensation to this. It can not be assumed that the laboratory magnetic fields generated for these tests embody all of the characteristics which animals are sensitive to. What we do know is that we can simulate a limited component of the sensorium which 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, though not elaborated in this report, 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 inter-relationship have been limited to abiotic expressions). In that context, consideration must be given to the demonstrated 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, it is presumptuous to expect we can grasp the extent of the "magnetoreception" capabilities of living organisms.

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