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Birds, brains and magnetic fields

Betony Adams and Francesco Petruccione share current theories of how birds use magnetoreception to navigate during long-distance migration

"We can only see the universe," wrote Einstein, "by the impressions of our senses reflecting indirectly the things of reality." Our senses are the interface between ourselves and our environment; they mark the boundary between our inside and our outside world. The progress of science has to some extent been the progress of artificial sense organs – the invention of telescopes and microscopes, lenses that outstrip our eyes, membranes that magnify vibrations beyond the capacity of our ears. But what if this progress identifies more than the five senses we are accustomed to: touch, sight, hearing, smell and taste?

A recent experiment revealed that, even though we may not be aware of it, humans can sense the Earth's magnetic field, known as the geomagnetic field. By having human subjects sit silently in a completely dark chamber and then flipping the direction of a simulated geomagnetic field around them, scientists demonstrated that some of the subjects experienced corresponding changes in alpha rhythms – a specific frequency of brain activity. A different experiment found that hungry men, but not women, could orient themselves in the geomagnetic field in response to cues about food. There is also some evidence that disruptions caused by magnetic storms can affect human health on both a physical and mental level.

A number of other animals possess a magnetic sense. Perhaps the most impressive usage of this sense is for migration, allowing for accurate navigation across great distances.

Turtles, sharks and birds are just some of the animals that make long journeys thought to involve magnetoreception. Turtle hatchlings have been shown to change direction according to the magnetic field they would encounter in different parts of the ocean, and it may be this that enables them to return as adults to the beaches where they hatched. Sharks also respond to magnetic fields and it has been suggested that they use special electromagnetic receptors, called ampullae of Lorenzini, to navigate, although this is still a matter of debate.

Many bird species undertake impressive feats of navigation during annual migrations. Some weird and wonderful theories about bird migration have arisen throughout history. The gathering and seasonal disappearance of particular species led some to believe that birds flew to the moon or the bottom of dams and ponds. And the fact that redstarts migrate south to Africa at the same time that robins arrive in Greece prompted Aristotle to conclude, more than 2 300 years ago, that redstarts became robins as the season changed.

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Amur falcons are small birds of prey, or raptors, which breed in south-eastern Siberia and Northern China. At the start of autumn in the northern hemisphere, they set off in large flocks to the north-eastern Indian subcontinent, where they gather in enormous numbers. After a stopover of a few weeks to feed and rest, they continue their journey, crossing the Indian Ocean to reach Africa. They then fly south to arrive in southern Africa in early summer, after a total trip of about two months. This is the longest migration of any raptor worldwide.

By now, the incredible journeys of many bird species have been mapped and studied in great detail, traditionally through bird-ringing programmes but more recently incorporating radio-, satellite- or GSM-tracking technology. While birds use a number of environmental cues to navigate, including the sun and the stars, it is generally agreed that they primarily use the geomagnetic field. There are two main theories as to how they do this. The minerals magnetite and maghemite – forms of iron oxide with magnetic properties – are found in the cells of numerous animals, including humans. Directional behaviour due to magnetic minerals has been observed in certain bacteria, which align themselves according to applied magnetic fields. It has also been suggested that animals such as fish, turtles and birds might use the action of these iron oxides to navigate and orient themselves. Magnetite in cells, responding to a magnetic field, mechanically opens ion channels, changing nerve signals and acting as a magnetic sense.

While magnetic materials such as magnetite are responsive to the poles of a magnetic field, researchers in the field of quantum biology have suggested an alternative avian compass that responds to the inclination of the geomagnetic field. Although there are still many questions to be answered, there seems to be some agreement that both mechanisms might be important. The inclination compass, which depends on how the magnetic field lines are inclined relative to the Earth, is called the radical pair mechanism, and is based on the science of spin chemistry. This is where it crosses paths with quantum theory.

Quantum theory was developed to describe how matter behaves at the atomic – extremely small – scale. Atoms are made up of a positively charged nucleus of protons and neutrons surrounded by negatively charged electrons. Protons, neutrons and electrons all have an intrinsic property called spin. Other intrinsic properties of matter are more familiar, such as mass and charge. But just as mass describes how matter will respond to a gravitational field, and charge describes how matter will respond to an electric field, spin describes how matter will respond to a magnetic field. This is the basis of the radical pair mechanism of avian magnetoreception, which depends on the paired spins of two electrons and how they respond to the Earth's magnetic field.

There is some evidence that a protein called cryptochrome, found in the eyes of birds, is the site of this radical pair compass. Cryptochrome is sensitive to light, especially blue light. Light entering a bird's eye can transfer its energy to one of a pair of electrons in cryptochrome, causing this electron to be excited and forming the spatially separated but spin-correlated electron pair that is called the radical pair. This electron pair starts out in what is called a singlet state, which means that the spins of the two electrons are arranged in a specific way with respect to each other. However, the spins can also be arranged in a different way known as a triplet state. Singlet and triplet states can interconvert under the influence of the nuclear spins of the other atoms in the surrounding protein as well as the Earth's magnetic field. Whether the paired spins are in a singlet or triplet state determines what chemical product is made, which then supplies directional information to the bird's brain.

Behavioural evidence supports the possibility of spin-dependent magnetoreception in various ways. Birds display migratory behaviour even when confined to cages, and their seasonal restlessness favours the direction in which they should be flying. By attaching carbon paper to the walls of these cages and examining the marks made by the birds as they attempt to escape, scientists can interpret the activity in specific directions under different conditions. It appears that bird migration is light-dependent and that the frequency of this light matters. It has also been demonstrated that radiofrequency electromagnetic radiation, which can influence the radical pair mechanism by modulating the singlet-triplet conversion, disrupts the accuracy of avian magnetoreception.

The scale of an electron is far beyond what we can see with our own eyes. Electrons are so small that it is difficult to measure their size accurately. Bird migration, on the other hand, happens on the scale of hundreds of kilometres. The Arctic tern flies from pole to pole and back. It is incredible to consider that the response of an electron to the geomagnetic field might shape something as impressive as a tern's journey.

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