Magnetovision: Birds' seventh sense revealed

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The navigational abilities of birds are turning out to be even more amazing than we thought

IT WAS a bunch of robins that started it. The birds were locked in cages in Frankfurt, Germany, where they were being studied by biologist Hans Fromme. When the time came when they would normally migrate to sunny Spain, Fromme noticed they were becoming restless. What's more, they always tried to flee their cages in the same direction.

This was in the late 1950s, and the thinking at the time was that migrating birds navigated using the sun, moon and stars. The cages were in a shuttered room, though, so the robins must have worked out which direction was which some other way. Magnetism was one possibility. The idea that migrating birds navigate across continents and oceans with the help of an internal compass had been suggested a century earlier by a Russian zoologist, but attempts to prove it had failed.

That changed in 1966, when zoologist Wolfgang Wiltschko showed that the direction in which the robins attempted to escape could be changed by powerful magnets. His work suggested that most birds can sense the Earth's magnetic field, although many of his peers refused to believe it.

"You don't want a stupid little bird doing something you don't do", says Roswitha Wiltschko of the University of Frankfurt, who together with her husband Wolfgang has been studying this ability for four decades. Their studies and others have proved the sceptics utterly wrong; we now know that a wide array of animals, from beetles to bats, rely on the Earth's magnetic field to help them navigate.

But how? The inner workings of this supersense have long been mysterious. Now, though, researchers think they have worked out how birds sense magnetism, and even what these master navigators perceive.

The first clues to the basis of magnetoreception came from a surprising source. In 1975, some bacteria that live in the mud on sea floors were found to contain chains of crystals of iron compounds. As these chains line up with Earth's field, they align the bacteria along with them, ensuring they swim downwards, away from oxygen-rich waters. Essentially, each bacterium is a tiny compass.

That suggested some animals might have cells containing similar crystals, whose movement would allow the animals to sense magnetic fields. Finding such cells, though, proved far from easy. Senses are typically linked to openings in the body that allow organs like eyes, ears and tongues to make contact with the outside world. Magnetic fields, however, pass freely through bone and tissue, so the receptors could be anywhere. "Basic things that you do in other senses don't make sense when it comes to magnetoreception," says Thorsten Ritz, a biophysicist at the University of California, Irvine.

Among birds, magnetic crystals were first discovered in homing pigeons and bobolinks. Nerve endings in the skin inside the upper beak contain lots of bullet-shaped structures rich in iron. It took decades to prove they really are used for magnetoreception, though.

Earlier this year, similar structures were found in robins, garden warblers and domestic chickens. These species hail from diverse lineages, so it now appears that iron-based magnetoreception is common to most, if not all, birds (*PLoS ONE*, vol 5, e9231).

A radical idea

While some researchers were hunting for magnetic crystals in animals, others took a very different approach. Klaus Schulten, a biophysicist now at the University of Illinois at Urbana-Champaign, had been studying some unusual chemical reactions that can be affected by magnetism. He realised that if similar reactions took place in living things, it might enable them to detect magnetism.

Electrons normally dance round a molecule in pairs, but light can break this happy tango by shunting an electron from one molecule to another. The result is a pair of radicals - molecules with a solo electron. Electrons have a quantum property called spin, and in a radical pair the spins of the two unpaired electrons are linked; they either spin together or in opposite directions. The angle of a magnetic field can affect the flipping of the electrons from one of these spin states to the other, and in doing so, it can affect the outcome or the speed of chemical reactions involving the radical pair.

Schulten came up with the idea that radical pairs might help to explain magnetoreception back in 1978. His first paper on it was rejected by *Science* with a note that read, "A less bold scientist might have designated this idea to the waste paper basket." Instead, Schulten published his idea in an obscure journal and kept on refining it.

He realised that because the formation of a radical pair needs light, it probably takes place in the eye. If cells in the retina contained a molecule that formed radical pairs, and each molecule was aligned the same way within the cell, the angle of these molecules - and thus their behaviour in a magnetic field - would change across the bird's hemispherical retina. If the bird could somehow detect the changing patterns across the retina as it moved, it would thus be able to sense the Earth's magnetic field.

A series of studies by the Wiltschkos in the 1980s and 1990s provided some support. They showed that the compass of several bird species requires light. It does not need much light - night-migrating birds like robins get enough - but it does need some. What's more, they found the light has to be from the blue-green end of the spectrum.

As far as anyone knew, though, no molecule capable of forming radical pairs existed in the eye. Then in 1998, Schulten heard about cryptochromes, proteins found in plants and animals that detect blue light. Their main role appears to be keeping internal clocks running on time. What struck Schulten, though, is that when light hits a cryptochrome, the protein transfers one of its electrons to a smaller molecule called FAD - potentially creating a radical pair. "When I heard about cryptochrome, I just fell off my chair," he says. "I realised this was exactly what was needed."

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In 2000, Schulten and Ritz published an updated version of the radical pair hypothesis arguing that the magnetic compass involves cryptochrome and thus depends on blue-green light (*Biophysical Journal*, vol 78, p 707). They predicted that it could be disrupted by high-frequency magnetic fields, which interfere with the flips between spin states. Sure enough, in 2004, Ritz and the Wiltschkos showed that high-frequency magnetic fields can indeed prevent robins from orientating themselves correctly (*Nature*, vol 429, p 177). The same is true of other birds, too.

Then in 2007, Miriam Liedvogel of the University of Oldenburg in Germany found a cryptochrome from the garden warbler can produce a radical pair under blue light that lasts for milliseconds, more than long enough to be affected by the Earth's magnetic field. "It's not 100 per cent proven, but people are very convinced that cryptochrome is involved in magnetoreception," Schulten says.

There are still some loose ends. By knocking out genes, it was recently shown that the compass of fruit flies relies on cryptochromes, and the same appears true for some other insects, including butterflies. Earlier this year, though, a group studying butterflies claimed that the mechanism does not involve radical pairs. Despite this, Schulten remains confident he is right. To settle the issue, he says, we need to work out the structure of cryptochrome, and no one has yet done this.

One thing that is certain is that the compass of birds is located in their eyes. In fact, the tight connection between vision and magnetoreception suggests that birds can literally see magnetic fields.

Schulten has suggested that the fields might appear as areas of light and shade superimposed on top of what birds normally see (see mock-up). This could explain why, earlier this year, Katrin Stapput from Goethe University in Frankfurt managed to disorientate robins by covering their right eyes with frosted goggles (*Current Biology*, vol 18, p 602). Birds may use lines and edges to distinguish between what they actually see and the more fuzzy overlaid magnetic information. If the underlying image is blurred, the birds may no longer be able to distinguish between image and overlay.

Stapput covered only the right eye because the Wiltschkos have found a robin's compass is confined to its right eye, and the same appears true for many migratory birds. That may seem surprising, but since having two compasses provides no extra information, there is no reason to have one in each eye. So far, only garden warblers are known to have compasses in both eyes.

The idea that birds have a heads-up display of their compass is an evocative idea, but still a speculative one. "I'm not Doctor Doolittle," says Schulten. "I can't talk to the animals, although I would love to ask them."

Flying sly

If birds' compasses are located in their eyes, though, why do they also have iron-based magnetoreceptors in their beaks? It turns out that birds actually have two magnetic senses. By monitoring nerve activity, researchers have shown the magnetoreceptors in the beak respond to changes in the intensity of the magnetic field, rather than its direction.

How is not clear. The crystals could be attached to stretch receptors that pick up the tiny forces involved. Alternatively, the moving crystals could open or close molecular gates on the surface of nerve cells, triggering signals.

Whichever, the ability to sense the strength of a magnetic field could be even more helpful than having a compass. Field strength varies from place to place because of varying amounts of magnetic material in Earth's crust, and it is highest at the poles and lowest at the equator. As birds fly around, they could build up a mental map of these magnetic hills and valleys.

To get an idea of how useful such maps could be, imagine being dropped in mountainous terrain in thick mist, and trying to get to a specific location. A compass alone would be of little use. With an altimeter and a contour map instead, you could both pinpoint your location and work out which way to go.

The idea that birds create magnetic maps is supported by studies like those on Australian silvereyes done by the Wiltschkos in the 1990s. They exposed the birds to a strong pulse that altered the magnetism of iron crystals in their beaks but left the eye compass unaffected. In juvenile birds that had just left the nest, this made no difference - they still tried to head in the right direction.

Birds that had migrated before, however, all headed in the wrong direction after the pulse. This suggests that the juvenile birds were relying on the compass in their eyes, whereas the experienced birds were trying to navigate based on their mental magnetic map, using the intensity receptor in their beaks.

Of course in natural situations, birds use a whole range of clues for navigation, not just magnetism. They also use the sun and stars, smells, visual landmarks and perhaps even sounds like waves breaking.

An insight into how they combine these different kinds of information came from a recent study on night-migrating thrushes. When the thrushes were exposed to artificial magnetic fields at sunset, they flew in the wrong direction during the night when released. After seeing the next sunset, however, they corrected their courses. So it appears some birds calibrate their magnetic compasses against the sun each day.

While we have learned much about how birds sense and use magnetism, less is known about other animals (see "Extra sense"). The compasses of lobsters, fish and mammals like the naked mole rat definitely do not rely on the radical pair mechanism and are probably iron-based. The compass of sharks and rays, meanwhile, is thought to rely on a different mechanism entirely: electromagnetic induction. As they swim through a magnetic field, it induces electric currents in a sensory organ - but it remains unclear how sharks achieve the extraordinary sensitivity needed to detect Earth's weak field.

Resolving these mysteries will require teams that can interpret the behaviour of electrons and animals alike. "I can do the quantum mechanics, but then you have to make predictions of what an animal's going to do in a cage," says Ritz. "You have to work across disciplines and be holistic." He adds, "I think that if we look back, we'll view the next decade as the one where some of the big discoveries were made."

Extra Sense

Fish

Many fish, including salmon and trout, can detect magnetic fields, probably using iron-based magnetoreceptors in their noses. The recent discovery that the lab favourite, the zebrafish, can sense magnetism will make it much easier to work out the genetic basis.

Ants and bees

Magnetic crystals of iron compounds are found all over the bodies of ants and bees, especially in the abdomen and antennae, and are thought to act as compasses. One species of migratory ant, *Pachycondyla marginata*, probably gets these magnetic particles from the surrounding soil.

Turtles

From birth, turtles use their magnetic sense as both a compass and a map. Hatchlings can swim homewards even when they are released in a distant and unfamiliar location. Other animals known to use magnetic maps include lobsters and newts.

Bats

Bats not only "see" in the dark using echolocation, they also have a magnetic compass which they calibrate against the sun. Their compass appears to be iron-based.

Humans?

In the 1970s, it was claimed that humans have a magnetic sense, but other researchers could not replicate the results. The idea still intrigues, though. "I'd love to do a study with some indigenous people who orientate in areas with few landmarks, such as Pacific Islanders," says Thorsten Ritz, a biophysicist at the University of California, Irvine.

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