The inner compass

Many animals can perceive the Earth's magnetic field. Scientists suspect that in some species this capacity is based on magnetic iron oxide particles in the animals' bodies, but they haven't yet been able to locate the corresponding sensory cells. Using sophisticated experiments and cutting-edge technology, several research groups at the University of Oldenburg are hot on the trail of this mysterious sense.

By Ute Kehse

What do desert ants, Nathusius' pipistrelle bats and rainbow trout have in common? At first glance, not much: ants crawl, bats fly, trout swim. And there are many other differences: ants are insects, weigh just a few thousandths of a gram and live in colonies. Bats are mammals, weigh several grams each and have a complex social life. Trout, a popular food fish, can each weigh several kilos and lead a solitary life in the wild.

But as different as these three species may be, they all possess an amazing yet little-understood ability: they can detect the Earth's weak magnetic field, which is imperceptible to humans. They use this sensory perception to orient themselves and, in some cases, navigate over long distances – which is why the university's scientists are studying them as experimental model organisms that can help to advance our understanding of this mysterious sense known as magnetoreception.

The magnetic sense is still considered to be one of the most mysterious phenomena in biology. "Although magnetoreception has been studied for decades, it is still a highly contentious field," explains Dr Oliver Lindecke, a Research Fellow in the University of Oldenburg's Collaborative Research Centre (CRC) "Magnetoreception and Navigation in Vertebrates" and an expert on bat navigation. One reason for the ongoing controversy, he explains, could be that "animals probably use at least two different methods to perceive the magnetic field."

There is already substantial evidence that small songbirds rely on a quantum effect known as the radical pair mechanism. These findings suggest that the mechanism is located in their eyes and is triggered by light. The Magnetoreception CRC coordinated by Oldenburg biologist Professor Henrik Mouritsen and another project funded by the European Research Council and jointly run by the Universities of Oldenburg and Oxford have been investigating this hypothesis intensively for several years. The researchers have made numerous findings that are gradually providing an overall picture of how the mechanism might function.

The second mechanism proposed for magnetoreception is based on magnetic iron oxide particles. The theory seems obvious enough given that compass needles, which are aligned northwards by the force of the Earth's magnetic field, are also made of magnetic mineral particles. However, the evidence gathered so far is confusing: although behavioural experiments indicate that various animal species use this mechanism, scientists have yet to find proof of any corresponding magnetic structures.

The researchers in Oldenburg are approaching the topic from several angles. Teams led by biologist Dr Pauline Fleischmann, Oliver Lindecke and physics Professor Michael Winklhofer study species that are sensitive to magnetic fields, including ants, bats and trout, and perform behavioural experiments to gain a detailed understanding of how their sensory perception works, while Winklhofer and his research group "Sensory Biology of Animals" are working to establish new laboratory methods and microscopy procedures.

A mysterious sense

The research in this area benefits from the fact that there are organisms called magnetotactic bacteria which are already known to use magnetic particles for orientation. These unicellular organisms synthesise chains of magnetic nanoparticles called magnetosomes, which help the microbes to move up and down along the lines of the Earth's magnetic field in bodies of water. "You can picture magnetosomes as microscopic compass needles," says Winklhofer. He and his team use the bacteria as a "positive control" group to prove that a method for detecting magnetic nanoparticles works.

Their theory is that similar chains or clumps of magnetic iron minerals could be present in the nerve cells of higher organisms. When these mini-magnets reorient they may generate a mechanical stimulus that is then converted into a signal and transmitted by the nerve cell. Winklhofer's team aims to prove the existence of these magnetic iron particles, which are probably no more than a hundred nanometres (a hundred billionths of a metre) large, and at the same time determine their exact location in the bodies of the studied species. But their endeavour is complicated by the fact that iron is ubiquitous in all living organisms and the environment, which frequently leads to contamination and false results.

Among the various microscopes deployed by the researchers, there is one that uses fluorescence to visualize magnetic fields and thus magnetic particles in tissue. In addition, the scientists now have access to a state-of-the-art scanning electron microscope that provides ultra-high-resolution images of even the most sensitive biological material. This device is also able to pinpoint the exact position of various elements – such as iron – within a sample. The team hopes that this high-tech combination will finally enable them to locate the iron particles within the nerve cells.

The researchers are using rainbow trout as a model organism. "Studies suggest that the trigeminal nerve may be involved in their magnetoreception," says biologist Dr Laura Ziegenbalg, a postdoctoral researcher in Winklhofer's team. In humans, this nerve transmits pain, temperature, and pressure stimuli from the facial skin and teeth to the brain. In animals, however, this nerve is known for its remarkable sensory adaptations, innervating infrared receptors in the pit organ of snakes and even electroreceptors in the snout of platypus. Mediating such a remarkable range of sensory modalities, the trigeminal nerve has been an obvious candidate for the magnetic sense, too. Indeed, an electrophysiological study on rainbow trout from the year 1997 suggested that the upper branch of this nerve carries magnetic stimuli from the snout region and nasal cavity, where magnetite particles were found too. There is still no clear anatomical evidence where exactly the elusive sensory cells are located, but the new scanning electron microscope will allow Winklhofer's team to perform the complex analyses their research involves much faster than before.

A navigation system for insects

The state-of-the-art equipment also plays an important role in the research of biologist Pauline Fleischmann, who investigates orientation in desert ants. She, too, is on the hunt for sensory cells that can detect magnetic fields. "Our working hypothesis is that the ants' magnetoreception mechanism is located in their antennae," says Fleischmann, a Research Group Fellow associated with the Oldenburg Magnetoreception CRC. The ants' delicate antennae are multifunctional organs which they use among other things to smell and touch.
Desert ants are an interesting model for magnetoreception research because they are stablished experimen-

1 Physicist Michael Winklhofer uses state-of-the-art microscopy to detect magnetic nanoparticles within cells.

2 Desert ants have an excellent sense of direction. Biologist Pauline Fleischmann is researching the insects' magnetic sense in Greece and elsewhere. In field experiments, she observes how the ants are affected by artificial magnetic fields created using Helmholtz coils.

3 The ants, which are about one centimetre long, don't bite or sting. Pauline Fleischmann brought two colonies from Greece to Oldenburg for her research.

tal models for insect navigation with excellent navigation skills and a tiny brain well-suited for neurobiological analyses "Their navigational performance is very impressive," stresses the researcher. They inhabit the barren salt pans of the North African Sahara or the pine forests of Greece. When foraging, they sometimes move hundreds of metres away from their nest, but once they have found something to eat they return to the nest in a straight line.

These ants have long been known to use a "celestial compass" system, taking the position of the sun, for example, for orientation. During her PhD project, Fleischmann and colleagues made the exciting discovery that desert ants also possess a magnetic sense. Their findings show that when the ants leave their nest for the first time and perform what is known as learning walks in preparation for foraging, they orientate themselves to the Earth's magnetic field in order to memorise the location of the nest entrance. These insects open up an interesting perspective on magnetoreception, says Fleischmann: "It is often assumed that magnetoreception is above all useful for migratory species that travel over long distances, but the desert ants are a living counterexample."

In addition to the proposed sensory organ, Fleischmann is also investigating the ants' behaviour in their natural and lab environments, as well as how their brains process magnetic stimuli. Her experiments have shown that the learning walks leave measurable traces in the insects' brains. In an article recently published in the scientific journal PNAS, the biologist and two colleagues from the University of Würzburg reported that when desert ants are exposed to an altered magnetic field the first time they leave the nest, two areas of their brain which play a key role in orientation remain noticeably smaller and less interconnected. Their findings suggest that the magnetic compass helps to calibrate the ants' visual compass and train their spatial memory. Further investigations will now aim to clarify how the lack of magnetic stimuli during the learning phase affects the ants later on when they become foragers.

The bats' journey

Some mammals can also detect the Earth's magnetic field, but as with insects, only a few studies to date have focused on their magnetic sense. "Research on mammals' orientation and navigation is at least 50 years behind that on birds," says Oliver Lindecke. The biologist specialises in bats, which he describes as good models for investigating these phenomena in mammals. "They're friendly animals that are easy to work with," he explains.

Lindecke's main objective is to find out how the magnetic compass mechanism helps bats to orient themselves. He and his colleagues are conducting experiments near the University of Latvia's Ornithological Research Centre in Pape. "Tens of thousands of bats migrate southwards along the Baltic coast in the months of August and September. It's a fantastic spectacle, unique worldwide, and truly stunning," says the researcher, who has done a lot of groundwork in recent years towards understanding the bats' behaviour and establishing appropriate experimental set-ups.

He has already achieved impressive results: first he demonstrated that when caught during migration and then released elsewhere, the bats continue their journey in the same direction. "That was the first key point to be proven in order to establish a model for mammal navigation," he explains. He then designed an ingenious experiment for determining the direction in which the bats want to fly. He uses a circular arena with a tight-fitting cover and places the bats at the centre of the plate. This means that a bat has to crawl to the edge of the plate before it can fly off. However, it cannot see the sky and can only use echolocation to a limited extent to orientate. As Lindecke demonstrated, the point at the edge of the arena from which the animals take off can be used to determine their intended direction of flight.

In addition, he discovered that Soprano pipistrelle bats calibrate their magnetic compass at sunset: they note the point at which the sun sets in order to determine their flight trajectory for later that night. In a study published at the end of 2023, Lindecke reports that during this process the bats can sense two different components of the Earth's magnetic field: the horizontal direction and the angle between the magnetic field lines and the Earth's surface, also known as the magnetic inclination .

Based on his research to date, Lindecke considers it more likely that the bats use the particle-based form of magnetoreception. The first place where he and Winklhofer now want to look for the nanoparticles is the cornea of the eye – a tissue densely innervated by the trigeminal nerve. In behavioural experiments, the researcher has already found evidence that the cornea could be involved in magnetic perception.

Lindecke is confident that the mystery surrounding particle-based magnetoreception will be solved within the next few years. He sees Oldenburg, where several research teams with wide-ranging expertise in the field of magnetoreception have congregated, well-positioned to make significant advances in this field. "If you want to be in the right place to discover where magnetoreception is located in the body, then you need to be here," he says.

Quantum effect or magnetic particles?

The two proposed mechanisms for magnetoreception are based on different principles of physics, which means that behavioural experiments can be designed to distinguish between them. The radical pair mechanism, for example, which is based on quantum mechanics, is light-dependent and therefore cannot function in absolute darkness. It is also disrupted by electrosmog, i.e. radiofrequency magnetic fields in the range of 100 kilohertz to 100 megahertz.
Magnetoreception based on magnetic particles, on the other hand, should not be affected by darkness or electromagnetic radiation, but is likely to be disrupted by a strong but brief magnetic pulse. Such pulses can reverse the direction of the magnetic field in magnetic minerals or even mix up their arrangement in magnetic sensory cells. As a result, a disturbed sensory cell can no longer reliably detect an external magnetic field until it is recalibrated or repaired.
Experiments with songbirds have shown that they need light to use their magnetic sense, and that electrosmog disturbs their orientation. These, as well as many other findings, support the theory that their magnetoreception is based on the radical pair mechanism.
By contrast, experiments with pigeons, young sea turtles and bats showed that their orientation was disrupted by magnetic pulses, which is why scientists suspect that the magnetoreception in these species is particle-based.
It cannot be ruled out that in some animal species both mechanisms are present and are used for different aspects of navigation.