Many organisms can sense the Earth’s magnetic field. They possess a kind of internal compass which enables them to perceive magnetic field lines and use them as cues for orientation. The biogeophysicist Dr. Michael Winklhofer studies the structural basis and biophysical mechanisms of the magnetic sense in animals.

They hatch in the cold mountain streams of Alaska, and their early lives are anything but idyllic. They must struggle to avoid being eaten and to withstand the powerful currents that threaten to tear them from the relative security of their nurseries. As they grow, the dark-blue stripes on their scaly skins begin to change to a brilliant silver. Now is the time to leave home. Salmon are adventurous creatures. Every Spring swarms of young salmon migrate downstream to the Pacific coast. Some populations remain in coastal waters, while others head for the high seas, venturing thousands of kilometers through the North Pacific where food is abundant. Atlantic salmon from the Eastern seaboard of North America, like their European conspecifics, make their way to the coasts of Greenland. Years later, sleek and sexually mature, they return to their native stream to spawn. And there too, worn out by the exertions of their long journey, they die.

Clearly, such trips require an efficient navigation and positioning system. Biologists assume that salmon orient themselves with respect to the sun during the day and the constellations at night. Salmon also have an acute sense of smell, which enables them to recognize the odor of their native waters — that special musty mixture of plant debris and sediments — perhaps hundreds of miles out to sea. And they can orient themselves with respect to the Earth’s magnetic field. They appear to have a sixth sense, an internal compass that allows them to perceive magnetic field lines and plot their own routes accordingly. “In the laboratory, we can influence the direction in which the fish swim using artificial magnetic fields”, says Dr. Michael Winklhofer of LMU Munich. “The question is: how exactly does this work?” The biogeophysicist wants to identify the sensory organ, the “antenna” responsible for the reception and processing of magnetic signals. It is a search that has been going on for decades.
Some migratory birds fly half-way round the world twice every year, and almost always they choose the same routes and the same stopover sites. Gray whales spend the summer in the Northern Pacific, but give birth to their young on the coasts of Mexico. They make the 15,000-kilometer round trip every year. Sea turtles travel thousands of kilometers to lay their eggs, making landfall on the same beaches each year. Just like the salmon, turtles probably exploit several different cues to find their way: keen eyesight, sharp hearing and a good sense of smell. “Here also, the Earth’s magnetic field seems to provide some of the necessary information”, says Michael Winklhofer.

For more than half a century, behavioral biologists have been trying to understand how animals might perceive and use the Earth’s magnetic field. They attached bar magnets to the necks of homing pigeons to deprive them of cues furnished by the geomagnetic field and, as a consequence of that treatment, the birds became disoriented and had difficulty finding their way home. They kept robins in darkened cages framed with Helmholtz coils. Altering the orientation of the magnetic field in the cage correspondingly shifted the direction in which the birds chose to fly upon release. Experiments in the open air have demonstrated again and again that animals make use of magnetic cues for orientation. “The difficulty with such experiments, however, is that one can never rule out the involvement of the other sensory modalities”, says Winklhofer. “This is difficult to do even under controlled conditions in the laboratory.” Here, Winklhofer speaks from experience. At the Southampton Oceanography Centre, he wanted to test how lobsters behave in the presence of a magnetic field. It is generally accepted that their relatives, the spiny lobsters, utilize magnetic field lines to orient themselves in the wild. The field to which Winklhofer subjected his lobsters, on the other hand, appeared to make little if any impression on them. “Most probably, they were more focused on the hum of the water pump in the tank.”

In any case, behavioral tests give no information about how magnetoreception actually works. Michael Winklhofer has therefore adopted a different strategy. In order to orient themselves in a magnetic field, animals must have some sort of sensory organ that responds to magnetic energy, so they must have cells that are specialized for the task. What kind of structure might such cells have? Do they function in the same way in all species? And how do they convert magnetic flux into nerve impulses? “So far, no one has been able to unambiguously identify magnetosensory cells in animals”, Winklhofer says. But he has
come up with answers to some other questions. Michael Winklhofer became interested in the biological basis of magnetoreception 15 years ago. He was working with some rather unusual bacteria at the time. These microorganisms live in oxygen-poor sediments on the seafloor or on lake bottoms − and they are magnetically sensitive. Their cells contain tiny crystals of magnetite, called magnetosomes. Magnetite (Fe3O4) is the most prevalent magnetic mineral on Earth, and occurs particularly in magmatic rocks. “The magnetite crystals form chains in the bacterial cytoplasm, which act as relatively strong magnets. The chain of magnetosomes functions like a compass needle, so that the cells are always aligned with the Earth’s magnetic field”, explains Winklhofer. Most bacteria move in random zig-zag paths, but magnetic species migrate in straight lines through their habitat.

Winklhofer’s decision to investigate the basis of magnetoreception in animals began when he was contacted by Wolfgang Wiltschko, an ornithologist at Frankfurt/Main University and a pioneer in the study of magnetic orientation. Wiltschko had discovered that it was possible to disable magnetoreception in pigeons by anesthetizing their beaks, and he had heard that the geophysicists in Munich had just set up a highly sensitive magnetometer to detect tiny amounts of magnetic material. With his mentor Professor Nikolai Petersen, Winklhofer set out to investigate the pigeon’s beak. Together they found that the upper section of the beak contained relatively high levels of magnetic material. Winklhofer’s colleague Marianne Hanzlik then examined various regions of the beak with an electron microscope. And at high magnifications, she indeed found magnetite crystals concentrated at the terminal processes of the nerves at the upper end of the beak. These crystals, only a few nanometers in size, are ten times smaller − though much more numerous − than those in the magnetic bacteria, and are not arranged into chains of magnetosomes. In his doctoral thesis, Michael Winklhofer went on to show that, in principle, these structures could function as magnetic sensors, making the nerve cells that contained them the best candidate for the long-sought magnetosensory cells in animals.

MAGNETSENSORY CELLS IN THE NOSE

These days, Winklhofer works mainly on fish, and collaborates with colleagues at Cambridge University, Auckland University, and the California Institute of Technology in Pasadena. The group has obtained funding from the Human Frontiers Science Organisation for a detailed study of the structural basis and functional operation of magnetoreception in fish. Michael Winklhofer’s task is to characterize the magnetic characteristics of the putative sensory cells. “The magnetic dipole moment is the important parameter, because it determines how sensitive the cells are to the ambient field, and therefore the precision with which a single cell can respond to small changes in the field.” In rainbow trout, which are closely related to the migrating Pacific salmon, magnetite-containing cells are found in the nasal organ, or more specifically in the olfactory lamellae in the nasal cavity. “Surprisingly, the magnetite crystals in trout are more similar to those in magnetic bacteria than they are to the crystals found in homing pigeons.” In order to characterize these cells in greater detail,
they must first be isolated from the lamellae. To do this, Winklhofer treats the lamellae with enzymes that digest the connective tissue, places the cell suspension in a special microscope equipped with magnetic coils, and slowly rotates the artificial magnetic field. “The magnetic cells also rotate, just like the magnetic bacterial cells”, says Michael Winklhofer, “and the rate of rotation is a measure of the magnetic dipole moment.” But the fish cells are ten times as magnetic as the single-celled bacteria. “So we now know the magnetic strength of the compass needle in these cells.” As yet, he and his colleagues can only speculate on how this magnetic signal is converted into nerve impulses.

What they do know is that the Earth’s field exerts a torque on the magnetite crystals. Obviously, in the living animal, the cells themselves cannot rotate – they are integrated into the layers that form the olfactory lamellae. However, the crystals may be attached by fine protein filaments to the nerve-cell membrane. Even if the crystals are only minimally deflected by the magnetic field, the resulting torque would strain the filaments. This, in turn could open mechanosensory ion channels in the membrane, in effect converting the magnetic signal into an electrical response by inducing a so-called action potential which is then transmitted to the brain.

**“FEELING” THE MAGNETIC FIELD**

Michael Winklhofer’s collaborators in Cambridge have obtained evidence that the magnetite-containing cells can indeed produce nerve impulses in response to changes in magnetic flux. When they subjected isolated cells to an artificial magnetic field, they observed that changes in field strength were correlated with changes in the concentration of free calcium ions in the cell. “This implies that an action potential is induced.” It is also clear that, although the magnetosensory organ in trout is located in the nasal epithelium, the fish do not smell the magnetic field. “The magnetic cells are functionally linked not to the olfactory nerve, but to the trigeminal nerve, which is responsible for sensation in the face.”

This nerve also responds to changes in pressure, so that, in a sense, the fish could “feel” the magnetic field. The compass needles formed of magnetite will always tend to point in the direction of magnetic North. If the fish is facing in any other direction, the compass produces a pressure stimulus, the strength of which is proportional to the deviation from North. “Based on the orientation-dependent stimulus pattern, the fish could, in principle, determine its current heading relative to magnetic North”, says Michael Winklhofer. “This
is difficult for us to imagine, because we do not have a magnetic sense.” Perhaps the closest analogy is with our sense of balance, which sends a message to the brain whenever we alter the position of our heads.

Many aspects of magnetic sensing remain to be understood. That only serves to motivate Michael Winklhofer further: “One must always keep in mind that this is a relatively young area of research. There is still a great deal to discover, not only in terms of the biophysics of magnetic perception, but also with respect to how biomineralization of the magnetite is controlled in the magnetosensory cells of birds and fishes.” Winklhofer’s next goal is to elucidate how fish actually form the relatively large magnetite crystals present in their magnetosensory cells. For this project, he has chosen to work with zebrafish. Zebrafish behavior can be conditioned by applying magnetic fields, and the fish have magnetite-containing cells in the nasal cavity. Moreover, the zebrafish genome, in contrast to those of other fish species used for magnetosensory research, has been completely sequenced. Genetic mutants are easy to make and maintain, and large mutant collections are already available. It should therefore be possible to identify mutants for genes that regulate magnetite production in the nasal epithelium. “Chitons, which are considered to be among the most primitive molluscs, are capable of biomineralizing magnetite”, says Winklhofer, “so magnetoreception may have developed very early in the course of animal evolution.”

This could also explain why it is found in very diverse groups, including mammals. Based on an analysis of satellite images, German and Czech biologists have recently reported that grazing deer and cattle show a tendency to align themselves along the North-South magnetic axis. In the vicinity of electric power lines, however, the herds tended to orient themselves at random relative to the field lines. Bats too apparently depend on an inner magnetic compass for orientation during their nightly flights. Like songbirds that migrate only at night, the bats use the position of the setting sun to calibrate this compass. Even the naked mole rat, a hairless rodent found in East Africa that lives in colonies underground, orients its tunnel system along the North-South magnetic axis. Michael Winklhofer has already made magnetometer measurements on samples of brain and facial-nerve tissue isolated from these rodents by a colleague in Prague. They were only weakly magnetic, but did contain traces of magnetite. “That in itself doesn’t tell us much”, he says. “There may still be enough to form a simple compass.” – The search for the seat of the sixth sense goes on.

Priv.-Doz. Dr. Michael Winklhofer obtained his doctoral degree from LMU Munich in 1999. He carried out postdoctoral research at institutions in England and the USA, before returning to LMU’s Department of Earth and Environmental Sciences in 2003. In 2008 he was awarded a Heisenberg Fellowship by the German Research Foundation (DFG).

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