THE PHYSICS AND NEUROBIOLOGY OF MAGNETORECEPTION

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Abstract | Diverse animals can detect magnetic fields but little is known about how they do so. Three main hypotheses of magnetic field perception have been proposed. Electrosensitive marine fish might detect the Earth's field through electromagnetic induction, but direct evidence that induction underlies magnetoreception in such fish has not been obtained. Studies in other animals have provided evidence that is consistent with two other mechanisms: biogenic magnetite and chemical reactions that are modulated by weak magnetic fields. Despite recent advances, however, magnetoreceptors have not been identified with certainty in any animal, and the mode of transduction for the magnetic sense remains unknown.

MAGNETORECEPTOR
A biological structure that can transduce the strength and/or orientation of the local magnetic field to an animal's nervous system.

Behavioural experiments have shown that many animals can sense the Earth's magnetic field and use it as a cue for guiding movements over both long and short distances[1]. However, relatively little is known about the neural and biophysical mechanisms that underlie this sensory ability. Whereas receptors for most other sensory systems have been characterized and studied, primary receptors involved in detecting magnetic fields have not yet been identified with certainty in any animal.

Several factors have made locating MAGNETORECEPTORS unusually difficult. One is that magnetic fields pass freely through biological tissue. So, whereas receptors for sensory modalities such as vision and olfaction must contact the external environment to detect stimuli, this restriction does not apply to magnetoreceptors, which might plausibly be located almost anywhere in an animal's body. In addition, magnetoreceptors might be tiny and dispersed throughout a large volume of tissue[2], or the transduction process might occur as a set of chemical reactions[3], so that there is not necessarily any obvious organ or structure devoted to magnetoreception. Finally, humans either lack magnetoreception[4] or are not consciously aware of it[5], so our own sensory experiences provide little intuitive insight into where magnetoreceptors might be found.

So far, most of what is known about magnetoreception has been inferred from behavioural experiments, theoretical considerations and a limited number of electrophysiological and anatomical studies. This article begins by discussing the Earth's magnetic field and the basic types of information that animals can extract from it. We then summarize the three main hypotheses of magnetoreception and critically evaluate the evidence for each. Finally, we suggest future directions for research in the field.

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Information in the Earth's field

To a first approximation, the Earth's magnetic field resembles the dipole field of a giant bar magnet (FIG. 1a). Field lines leave the southern hemisphere and curve around the globe before re-entering the planet in the northern hemisphere.

Animals can potentially extract at least two distinct types of information from the Earth's field. The simplest of these is directional or compass information, which enables an animal to maintain a consistent heading in a particular direction, such as north or south. Magnetic compasses are phylogenetically widespread and exist in several invertebrate groups, including molluscs, crustaceans and insects, as well as in all five classes of vertebrate[1].

Alone, a compass is often insufficient to guide an animal to a specific destination or to steer it reliably along a long and complex migratory route. For example, a sea turtle migrating through the ocean toward a distant target can be swept off course by currents,

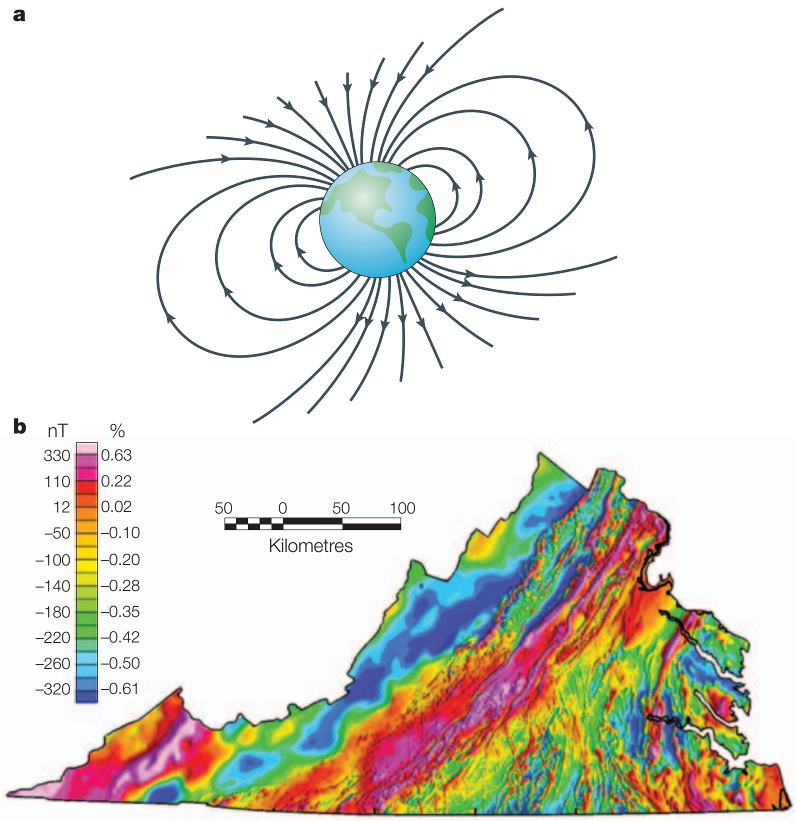

Figure 1 | **Large-scale and fine-scale structure of the Earth's magnetic field.** **a** | Diagrammatic representation of the Earth's magnetic field. The general form of the Earth's field resembles the dipole field of a giant bar magnet, with field lines emerging from the southern hemisphere, wrapping around the globe, and re-entering the Earth at the northern hemisphere. The inclination angle (that formed between the field lines and the Earth) varies with latitude. At the magnetic equator, the field lines are parallel to the Earth's surface and the inclination angle is 0°. An animal migrating north from the magnetic equator to the magnetic pole encounters progressively steeper inclination angles along its journey. At the magnetic pole in the northern hemisphere, field lines are directed straight down into the Earth and the inclination angle is 90°. This variation in the inclination angle is used by some animals to assess geographic position[11,16]. The strength or intensity of the Earth's field is weakest near the equator and strongest near the magnetic poles. Some animals can derive positional information from field intensity[12]. **b** | Merged aeromagnetic anomaly map of the state of Virginia, USA. Although some long-distance migrants evidently extract positional information from the general dipole field[10,13] shown in (**a**), fine-scale variations are more complex than the general regional patterns because concentrations of ferromagnetic minerals in the Earth's crust often generate local field anomalies. Although these variations are typically less than 1% of the total field, their gradients (that is, the variation per distance) can be significantly greater than the gradients due to the main dipole field, and can also be aligned in a different direction. The larger gradients might be easier for a short-distance migrant or homing animal to detect, but the complexity of local magnetic contours indicates that any navigational strategies that exploit magnetic topography over these smaller spatial scales are likely to be site-specific, difficult to generalize and learned rather than inherited. Colour scale shows deviations in the strength of the Earth's dipole field in Virginia (dipole field is ~52,000 nanoTesla (nT)[124]) in both nanoTesla and percent. Image reproduced from REF. 125.

GLOBAL POSITIONING SYSTEM (GPS). A network of artificial satellite transmitters that provide highly accurate position fixes for Earth-based, portable receivers.

and a migrating bird's heading can be altered by wind. Navigation can therefore be enhanced by an ability to determine position relative to a destination. For today's humans, this need is usually met through a GLOBAL POSITIONING SYSTEM (GPS), which provides users with their geographical position and continuously computes the direction to a goal. For some migratory animals, positional information inherent in the Earth's magnetic field provides a similar, although less precise, way of assessing geographical location.

Several geomagnetic parameters, such as inclination angle and field intensity, vary across the Earth's surface in ways that make them suitable for use in a position-finding sense[6,7] (FIG. 1). Some animals, including certain birds[8–10], sea turtles[11–14], salamanders[15,16] and lobsters[17], can discriminate small differences in at least some of these magnetic features. These animals exploit positional information in the Earth's field in several different ways, and at least a few are able to learn the magnetic topography of the areas in which they live and so acquire 'magnetic maps' that facilitate navigation towards specific locations (FIG. 2).

Because the parameters of the Earth's field that are useful for detecting directional and positional information differ, it is possible that some animals have two separate magnetosensory systems. Each might detect a different element of the Earth's field and each might also rely on separate receptors based on different biophysical mechanisms[18,19].

Possible mechanisms of magnetoreception

During the past three decades, a number of diverse mechanisms have been proposed that might provide the basis for detecting magnetic fields[1,20]. However, the most recent research has focused on three possibilities: ELECTROMAGNETIC INDUCTION, magnetic field-dependent chemical reactions and BIOGENIC MAGNETITE. Each mechanism is discussed below.

Electromagnetic induction. A charged particle moving through a magnetic field experiences a force perpendicular to both its motion and the direction of the field. The magnitude of this LORENTZ FORCE is equal to the product of the magnetic field strength, the charge and velocity of the particles, and the sine of the angle between the motion and field vectors[21]. Therefore, if an electrically conductive bar moves through a magnetic field in any direction other than parallel to the field lines, positively and negatively charged particles migrate to opposite sides of the bar, resulting in a constant voltage that depends on the speed and direction of the bar's motion relative to the magnetic field. If the bar is immersed in a conductive medium that is stationary relative to the field, an electric circuit is formed and current flows through the medium and the bar.

This principle, known as electromagnetic induction, provides a possible explanation for how elasmobranch fish (sharks, skates and rays) detect the Earth's magnetic field[22,23]. According to this hypothesis, jelly-filled canals on the fish, known as ampullae of Lorenzini, function as the conducting bars; the surrounding sea water functions as the motionless conducting medium, and the highly resistive and sensitive electroreceptors at the inner end of the ampullae detect the voltage drop of the induced current.

However, several factors significantly complicate these simple models. First, the electroreceptors of elasmobranches cannot detect the steady fields that were originally thought to arise[24]. Second, the water surrounding marine fish is seldom motionless under

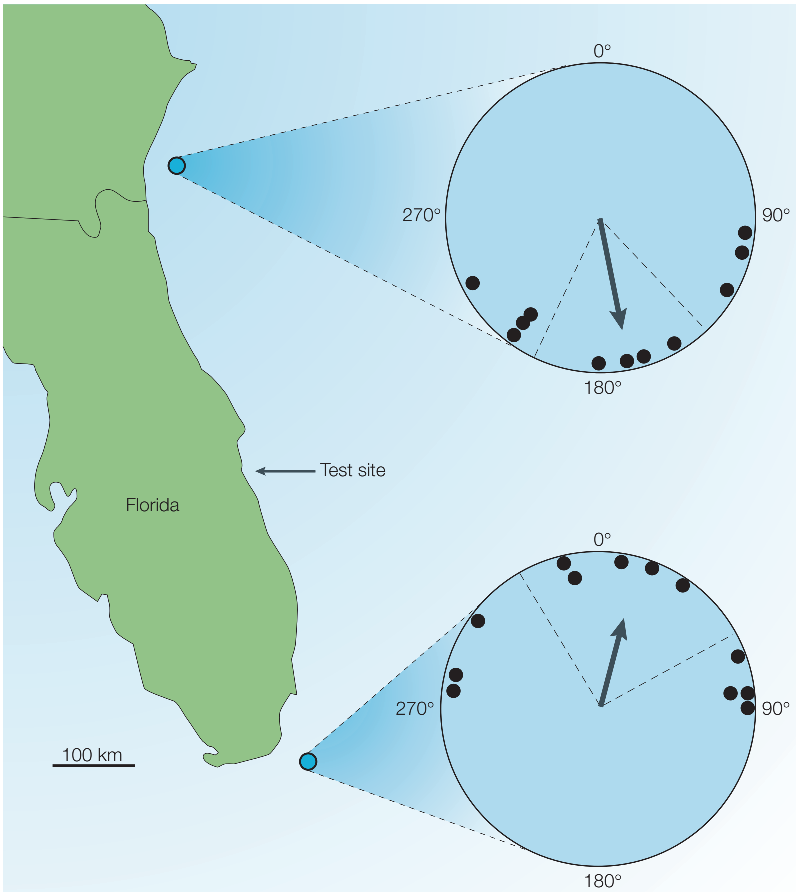

Figure 2 | **Evidence for a magnetic map in sea turtles.** Juvenile sea turtles establish feeding sites in coastal areas and home back to these sites if displaced[126,127]. To investigate how turtles navigate to specific sites, juvenile green turtles (*Chelonia mydas*) were captured in their coastal feeding areas near Melbourne Beach, Florida, USA ('test site' on map). Each turtle was tethered to an electronic tracking system and placed in a pool of water. The pool was surrounded by a magnetic coil system that could be used to replicate the magnetic fields that exist at two distant sites (marked by blue dots). In the circles, each black dot represents the mean direction of one turtle. The arrow in the centre of each circle indicates the mean angle of the group. The dotted lines indicate the 95% confidence interval for the mean angle. Turtles exposed to a magnetic field that exists ~330 km north of their feeding grounds oriented southward, whereas those tested in a field that exists an equivalent distance to the south swam north. Therefore, turtles responded to each field by swimming in the direction that would have led towards the feeding area had they actually been in the locations at which the magnetic fields exist. The results indicate that sea turtles have a type of 'magnetic map' that facilitates navigation to specific geographical areas. Modified, with permission, from REF. 14 © (2004) Macmillan Magazines Ltd.

ELECTROMAGNETIC INDUCTION
A current in a loop of conducting wire that is caused by a changing magnetic field in the circle formed by the loop.

BIOGENIC MAGNETITE
Magnetite (Fe_3O_4) synthesized by a living organism.

LORENTZ FORCE
The force exerted on a charged particle moving through a magnetic field.

natural conditions. Third, ocean currents are also conductors moving through the Earth's magnetic field, and so create electric fields of their own. Presumably, therefore, the animal must be able to determine which component of the total field that it experiences is attributable to its own motion and which is due to the motion of water[22,25]. In principle, these problems might be overcome if sharks derive magnetic field information from the oscillating electric fields that arise as the ampullae on their heads move back and forth during swimming[25]. Such fields should be distinguishable from fields caused by oceanic currents.

Although sea water is a highly conductive medium, air is not. Therefore, birds and other terrestrial animals cannot accomplish magnetoreception by induction in the same way that has been proposed for electrosensitive marine fish. Although an induction-based system using an internal current loop (a closed circuit inside an animal) is theoretically possible, such a loop would need to rotate relative to the Earth's field[21] and would probably also require a specialized internal transduction organ several millimeters in diameter[26]. The semicircular canals have some of the necessary features, but at present there is no evidence that magnetoreception occurs in the inner ear, and no likely alternative structure or site has been found in any animal[26].

Evidence for electromagnetic induction. Direct evidence that animals use electromagnetic induction to detect the Earth's magnetic field has not yet been obtained. Nevertheless, rays and sharks clearly have a highly sensitive electric sense with which they can detect the weak electric fields generated by the tissues of their prey[27]. This electrosensory system seems to be sufficiently sensitive to permit detection of the Earth's magnetic field[28].

Several studies have provided experimental or correlative evidence that is consistent with the hypothesis that elasmobranches do perceive magnetic stimuli[29–33]. In some cases, however, it was impossible to determine precisely what the animals detected. For example, in a recent experiment captive sharks learned to approach an area of the tank for a food reward when a magnetic coil surrounding the tank was turned on[33]. Although this was interpreted as a response to the imposed magnetic field, an equally plausible explanation is that the crucial stimulus might have been the transient electric field that is generated whenever the current through a coil is turned on[21]. Similarly, rays have been conditioned to move towards a specific magnetic direction in an enclosure[29], but whether the rays responded to the direction of the field *per se*, or instead to the presence of field anomalies, is debatable[1,34].

In a recent attempt to investigate the mechanism of magnetoreception in elasmobranch fish, rays were conditioned to respond to the presence or absence of magnetic field anomalies[31,32]. The conditioned response disappeared when small magnets were inserted into their nasal cavities, whereas inserting non-magnetic brass bars had no effect. These results have been interpreted as evidence against the electromagnetic induction hypothesis because induction should be unaffected by attached magnets that move in concert with the animal[32]. A crucial question is whether the movements of the magnets in the nasal cavities precisely matched movements of the electroreceptors on the flexible bodies of the fish, because if slight differences in motion occurred then a magnetoreception system based on induction might indeed have been affected. Whether elasmobranch fish rely on electromagnetic induction for magnetoreception or use an alternative mechanism remains unresolved.

Chemical magnetoreception. A second proposed mechanism of magnetoreception involves chemical reactions that are modulated by Earth-strength magnetic fields. At first glance, it seems unlikely that fields as weak as the Earth's could influence any chemical reaction, let alone those in animals. After all, such reactions involve alterations in the energies of electrons, and the energy differences between different orbitals are many orders of magnitude too large for the Earth's field to transfer electrons directly from one orbital to another. In addition, at physiological temperatures the kinetic energy of biological molecules is 2×10^{11} times greater than the energy of the Earth's field and might, therefore, be expected to overwhelm any slight magnetic effect[35].

Nevertheless, weak magnetic fields might exert an influence on biological molecules and chemical reactions under at least some circumstances. Several ingenious mechanisms have been proposed and debated[36–39], but the only hypothesis that has so far gained widespread acceptance as physically plausible is one that relies on chemical reactions involving pairs of radicals[40,41].

The proposed mechanism is that Earth-strength magnetic fields influence correlated spin states of paired radical ions[3,37,42]. Electron spins are largely unaffected by thermal noise, and so represent one of only a few molecular features that might plausibly be influenced by the Earth's field[35].

The putative process begins with an electron transfer from a donor molecule, A, to an acceptor molecule, B. This leaves each with an unpaired electron, the spins of which are either opposite (singlet state) or parallel (triplet state). Either way, the spins precess, meaning that the axis of rotation changes slowly in much the same way that a spinning top wobbles around a vertical axis as it slows down. This analogy is not precise, however, because electron spin can have only one of two orientations (up or down). The PRECESSION of the spins is caused by interactions with the local magnetic environment, which, in turn, is determined by the combined magnetic fields that are generated by the spins and orbital motions of unpaired electrons and magnetic nuclei, and any external field.

Because the two electrons encounter slightly different magnetic forces, they precess at different rates. After a brief period of time, the electron that was transferred returns to the donor. Depending on the time that elapses before the BACKTRANSFER and the difference in precession rates between the two electrons, the original singlet or triplet state of the donor might be preserved or altered. If electron backtransfer occurs quickly, then the electron spins will have precessed little and are therefore likely to remain in their original opposite or parallel correlated state. As a result, A and B remain unchanged. However, in a longer reaction the differences in precession rates between the two electrons can alter the original spin relationship; A and B are, therefore, chemically altered, which, in turn, can influence subsequent reactions. For example, a change from a singlet to a triplet state often prevents the subsequent recombination of A and B owing to the PAULI EXCLUSION PRINCIPLE (which states that two electrons with parallel spins cannot share the same orbital)[43].

For the RADICAL PAIR mechanism to operate in magnetic fields as weak as that of the Earth's, several stringent conditions must be met[40,41]. First, the reaction time must be long enough for the small differences in precession rate to alter the spin correlation, a process that takes at least 100 ns and that cannot occur in the time course of most known radical pair reactions[3]. On the other hand, however, the reaction cannot occur too slowly, or the spin correlation might be randomized by other disruptive processes[3]. Therefore, the mechanism can presumably work only if the reaction time falls within a narrow range, although reactions of a longer than expected duration are hypothetically possible if the reactants are compartmentalized in MICELLES[44].

Several other factors impose considerable constraints on the radical pair mechanism. For example, the speed of the reaction and the strength of interactions between the spins of the electrons and nuclei in the molecules must be related in highly specific ways for the orientation and strength of the Earth's field to have a significant effect[41]. Moreover, the molecules involved must be simple and contain few hydrogen or nitrogen atoms, as otherwise internal magnetic interactions will overwhelm any effects due to the Earth's field[41]. In addition, because the influence of the Earth's field on the putative chemical processes is weak, the effect must presumably be summed over a large area. Calculations indicate that ~10^8 radical pairs over a volume of 0.4 mm^3 are required to reliably detect an anomaly with a strength of 2% of the Earth's field[42]. Finally, the initial electron transfer must not randomize the original parallel or opposite spin relationship of the two electrons. This is not true of all electron transfer processes, but is often true when the transfer is induced by photo-excitation (that is, by the absorption of light)[3,37]. Indeed, many of the best-known radical pair reactions begin with electron transfers that are induced by light absorption[3,37,43]. This consideration has led to the suggestion that chemical magnetoreceptors, if they exist, might also be photoreceptors[3].

If magnetoreception does occur in photoreceptors, then an interesting possibility is that the process involves cryptochromes, a group of photosensitive proteins that are involved in the circadian systems of plants and animals[45,46]. Cryptochromes exist in the retinae and pineal glands of many animals[47]. In addition, they show marked homology to photolyases, which are known to form radical pairs after photo-excitation[48]. Finally, neural activity during magnetic orientation behaviour co-localizes with cryptochrome expression in retinal ganglion cells in a night-active migratory bird, whereas no such co-localization occurs in non-migratory birds or during daytime[45]. However, it is not known whether this is due to a link between cryptochromes and magnetoreception or simply a link between cryptochromes and photoperiodic behaviour that is associated with migration.

PRECESSION
The relatively slow rotation of the axis of a spinning object.

BACKTRANSFER
The return of a donated electron to its donor.

PAULI EXCLUSION PRINCIPLE
Quantum mechanical principle that states, among other things, that two electrons with the same spin cannot occupy the same orbital.

RADICAL PAIR
Two charged molecules held in close proximity in solution by a cage of solvent molecules.

MICELLE
An aggregate of detergent-like molecules in solution, with hydrophilic ends facing outwards and hydrophobic ends facing inwards.

Box 1 | **Light-dependent effects: magnetoreception or motivation?**

Although evidence for magnetoreception based on a radical pair mechanism is accumulating, critics have questioned the interpretation of several key results[32]. One unresolved issue involves changes in magnetic orientation behaviour that are elicited by different wavelengths and intensities of light. These have generally been interpreted as direct effects on magnetoreceptor function, but in some cases it is difficult to rule out an alternative possibility: that light instead affects physiological processes unrelated to magnetoreception, which, in turn, affect motivation[32,112].

Light-dependent effects on magnetic orientation behaviour vary greatly among species, and some are more difficult to reconcile with motivational changes than others. For example, it is difficult to explain in terms of motivation why a newt would choose to shift its orientation by 90° when exposed to a specific type of monochromatic light[61]. However, in contrast to such clear directional shifts, many of the wavelength-dependent effects involve the disruption of orientation[60], an outcome that might arise for various reasons. An animal in the lab, for example, might decide to search for shelter instead of trying to migrate when the world around it is illuminated in a strange and perhaps alarming way.

In birds, seasonal migratory behaviour is intimately connected to light cycles and light perception. Migratory behaviour is triggered by photoperiod and, for night migrants, the motivation to begin the next leg of migration peaks at or near sunset. Given the complex interplay among light-dependent processes, biological rhythms, motivation and migration, an intriguing but largely unexplored possibility is that at least some light-dependent changes in magnetic orientation arise through effects on a circadian pacemaker system, which, in turn, influences the expression or timing of orientation behaviour.

The entrainment of circadian rhythms has recently been shown to depend at least in part on the absorption of light by the photopigment melanopsin[113]. In vertebrates, melanopsin is found in the pineal gland and in the visual system, where it has been localized to a limited number of retinal ganglion cells[114,115]. The pigment is most sensitive to blue light[116,117] and may have a blue–yellow opponency mechanism via cone inputs[118,119]. Because such opponency often results in outcomes that vary with the spectral composition of light, these findings raise the possibility that different combinations of wavelengths and intensities might affect the pacemaker system in complex and unexpected ways. Finally, the apparent lateralization of the magnetic sense, discovered in magnetic orientation experiments in which one eye of birds was covered[120], shows interesting parallels to the lateralization of the circadian pacemaker[121,122].

A first step towards investigating this possibility would be to measure melatonin levels during and after exposure to light environments that are known to affect magnetic orientation. Because melatonin peaks at night and provides a convenient assay for circadian rhythmicity, a finding that melatonin levels are unaffected by the different treatments would bolster the argument that the effects are specific to magnetoreception. If melatonin levels do change under some light regimes, then such changes could be replicated pharmacologically to investigate possible effects on orientation behaviour.

Evidence for chemical magnetoreception. At present, no chemical reactions affected by Earth-strength magnetic fields are known[43]. Some reactions that involve the radical pairs mechanism are affected by fields as weak as 1 milliTesla[49], but this field intensity is still ~20 times the strength of the Earth's field. Nevertheless, models indicate that the necessary sensitivity might be possible under at least some conditions[50,51].

Although direct evidence for chemical magnetoreception has not yet been obtained, several lines of evidence have indicated a link between magnetoreception and the visual system. Electrophysiological responses to magnetic fields have been detected in several parts of the avian brain that receive projections from the visual system[1,52]. For example, the nucleus of the basal optic root (nBOR) in pigeons receives projections from retinal ganglion cells, and some neurons in the nBOR and optic tectum respond to directional changes in the ambient magnetic field[53,54]. The amplitude of the responses in the nBOR depended on the wavelength of the light entering the eye[54] and responses to magnetic fields in both locations disappeared when the optic nerves were cut[52].

Several studies have also indicated a link between magnetoreception and the pineal gland[53,55,56]. Electrophysiological recordings from pigeon pineal cells revealed units that were responsive to gradual changes in Earth-strength magnetic fields[57]. Responses were reduced, but not abolished, when the optic nerves and other sources of input to the pineal gland were severed, which implies that one source of magnetic sensitivity is in the pineal gland itself[57]. A study with newts also revealed that the magnetic direction that newts orientated towards shifted when the pineal complex was illuminated with light of a specific wavelength, whereas no such response was elicited when the light illuminated the eyes alone[56].

Numerous experiments have indicated that the magnetic orientation behaviour of birds, newts and flies changes when the animal is exposed to specific wavelengths of light[20,58–64]. The finding that such wavelength-dependent responses also vary with the intensity of light[60,65] has greatly complicated the emerging picture because absorption of light is generally wavelength-dependent. So, if an animal is exposed to identical photon fluxes of two lights with different wavelengths, it might perceive one light to be much brighter than the other, and receptors for vision, magnetoreception, or both might absorb different amounts of light under the two conditions. For this reason, disentangling the effects of wavelength and intensity is almost impossible.

No discernable pattern has yet emerged among species, but a bewildering array of wavelength and/or intensity-dependent effects have been reported, including loss of orientation, shifts in orientation direction and shifts to axial orientation[59,60,65–68] (BOX 1). Several interesting models have been proposed to explain these complex results, most of which involve opponency between a putative dominant short-wavelength mechanism and a subordinate long-wavelength mechanism[68,69]. However, so far none of the models have been tested rigorously.

A final line of evidence that is consistent with a radical pairs mechanism of magnetoreception comes from recent studies involving radio frequency fields. Radical pair reactions can be perturbed by radio waves of approximately the same energy as that of the interaction between the spin states and the Earth's magnetic field[50,70]. This allows for a potentially diagnostic test of magnetoreceptor mechanism. Broadband radio noise (0.1–10.0 MHz) and a constant frequency signal of 7 MHz both disrupted magnetic orientation in European robins[71].

Box 2 | Magnetite: challenges in research

Attempts to locate magnetite in animals have been impeded by several factors, the first of which is that the crystals are small (50 nm diameter) and difficult to resolve microscopically. In addition, iron oxides are common environmental and histological contaminants and can be by-products of various degenerative biological processes[123]. Many fixatives that preserve membranes also dissolve magnetite[80], so it is difficult to visualize magnetite crystals and their cellular environment simultaneously. A potentially interesting approach that has not yet been attempted is the use of techniques from bioinformatics to search vertebrate genomic libraries for gene sequences involved in magnetite production, on the assumption that such sequences might have been conserved during evolution. Such an approach might be feasible, because if magnetite crystals are involved in magnetoreception, then they are probably formed through pathways that involve molecular enzymes and transporters. Moreover, these processes have now been extensively studied in magnetotactic bacteria, and the transporters and chelators involved have been sequenced[73]. Such an approach, if successful, might lead to improved methodologies for locating small clusters of magnetite crystals in animals.

Interestingly, the 7 MHz signal failed to disrupt orientation when the direction of propagation was aligned with the Earth's magnetic field, whereas experiments with known radical pair reactions have shown effects (albeit of variable strength) regardless of the alignment of the radio frequency field[70]. The results with birds were replicated using a signal of 1.315 MHz, which was calculated to have a maximally disruptive effect[72]. In both studies, the strength of the oscillating field was ~1% of the Earth's field. This and the high frequency make it unlikely that the radio signal affected a magnetite-based receptor.

This promising initial work with radio frequency fields could potentially be strengthened if future experiments reveal an action spectrum in which some, but not all, frequencies have an effect[72]. Such specificity should, in theory, exist[50,70]. Similarly, the demonstration that radio frequency fields have no discernable effects on the behaviour of animals that orient themselves using non-magnetic cues would help to eliminate the small but lingering possibility that the effects are not directly related to magnetoreception.

Magnetite. A diverse assemblage of bacteria and unicellular algae orient their movements along magnetic field lines[73]. The discovery that crystals of the magnetic minerals magnetite (Fe_3O_4) and greigite (Fe_3S_4) underlie this ability inspired searches for similar minerals in a diverse range of animals. Magnetite was subsequently detected in honeybees, birds, salmon, sea turtles and a number of other animals that are known to orient to the Earth's magnetic field[74]. Most magnetite isolated from animals has been in the form of single-domain magnetite crystals similar to those found in magnetotactic bacteria[73]. Single-domain crystals are minute (~50 nm in diameter), permanently magnetized magnets that twist into alignment with the Earth's magnetic field if allowed to rotate freely (BOX 2).

Single-domain magnetite crystals might transduce geomagnetic field information to the nervous system in several different ways[32,75,76]. One possibility is that such crystals exert torque or pressure on secondary receptors (such as stretch receptors, hair cells or mechanoreceptors) as the particles attempt to align with the geomagnetic field. Alternatively, the rotation of intracellular magnetite crystals might open ion channels directly if, for example, cytoskeletal filaments connect the crystals to the channels.

In some animals, magnetite crystals are smaller than single-domain size. These smaller crystals are said to be superparamagnetic and have different magnetic properties. Unlike single-domain crystals, they do not have a permanent magnetic moment and so cannot physically rotate into alignment with the Earth's field[77]. Instead, the magnetic axis of a superparamagnetic crystal tracks the axis of any ambient field, even though the crystal itself remains stationary.

In Earth-strength magnetic fields, superparamagnetic crystals can generate fields strong enough to attract or repel other nearby crystals. These intercrystal interactions have the potential to deform a matrix in which a cluster of these crystals are embedded[76,78]. In addition, entire clusters of superparamagnetic crystals can attract and repel each other under some conditions[79]. Mechanisms have been proposed that might, in principle, enable the nervous system to detect expansion or contraction in either a single cluster or in an array of clusters[77,79,80] (FIG. 3). This, in turn, provides a possible means of detecting the direction of the field, its intensity, or both.

Evidence for magnetite-based magnetoreception. For magnetite crystals to function as magnetoreceptors in animals, the magnetite presumably needs to contact the nervous system. Although such a link has been proposed for more than two decades, direct anatomical evidence has remained scarce. The strongest evidence has come from studies with trout[81,82] and pigeons[80,83].

In the trout, analyses of olfactory lamellae using confocal microscopy revealed cells that contain single-domain magnetite crystals[82]. The region of the trout nose that contains these cells is innervated by the ros V nerve, which is one branch of the fifth cranial nerve (the trigeminal). Electrophysiological recordings from the ros V have revealed units that respond to magnetic stimuli consisting of abrupt changes in field intensity. These findings have led to the hypothesis that magnetite-containing cells in the trout nose function as magnetoreceptors and relay information to the brain through the trigeminal nerve. Because reversals of field direction did not elicit responses from units in the ros V nerve[81], the putative magnetite-based receptors have been proposed to detect field intensity, a parameter that is potentially useful in a map sense. However, whether trout have a magnetic map sense is not yet known, and a clear link between the nervous system and the putative receptor remains to be found.

In birds, crystals of a trivalent iron compound thought to be magnetite have been detected in an area of the upper beak[80,83–85]. Ultrastructural analyses of this anatomical region in pigeons have revealed clusters of

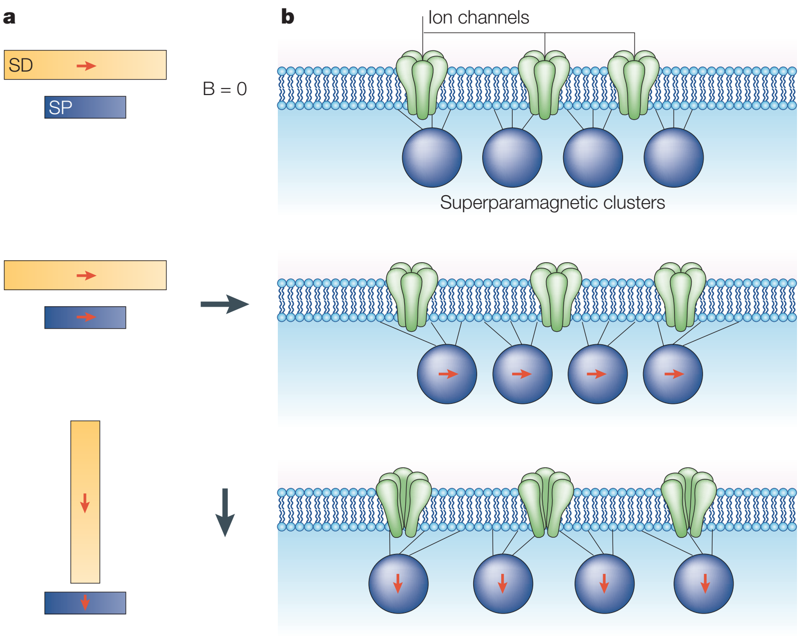

Figure 3 | **The different magnetic properties of single-domain and superparamagnetic crystals. a** | Single-domain (SD) and superparamagnetic (SP) magnetite crystals have different magnetic properties. Single-domain crystals have permanent magnetic moments (indicated by red arrows) even in the absence of an external magnetic field (B = 0). If an external field is present (black arrow) and the crystals are free to rotate, they will align with the external field. By contrast, superparamagnetic crystals have no magnetic moment in the absence of an external field. If an external field is present, however, the crystals develop a magnetic moment that tracks it, even though the crystal itself does not rotate. **b** | A hypothetical transduction mechanism based on interacting clusters of superparamagnetic crystals located in the membranes of neurons. Depending on the orientation of the external field, the clusters will either attract or repel each other, deforming the membrane and possibly opening or closing ion channels. For example, when the external field is parallel to the cell membrane, the fields in each crystal (red arrows) align in such a way that adjacent clusters attract each other like a row of bar magnets aligned end to end (middle panel). The membrane might, therefore, be slightly compressed. By contrast, a 90-degree change in the orientation of the external field (bottom panel) results in different interactions between clusters, because adjacent clusters now behave like a row of bar magnets aligned side by side. The resulting interactions might stretch the membrane and open ion channels. This model was inspired by the discovery of superparamagnetic crystals in pigeon nerve terminals[79]. Modified, with permission, from REF. 79 © (2003) Elsevier Science.

these crystals inside nerve terminals and arranged along the cell membrane[80]. However, in contrast to the single-domain magnetite detected in fish[82], the magnetite crystals in the beak of the pigeon are superparamagnetic[83,85].

An interesting similarity between fish and birds is that, in both cases, the anatomical site that contains the magnetite appears to be innervated by the ophthalmic branch of the trigeminal nerve[80,81,86]. Two further findings are consistent with the hypothesis that branches of the trigeminal nerve innervate magnetoreceptors in birds. First, cutting the ophthalmic branch permanently abolished a conditioned response of pigeons that had been trained to discriminate between the presence and absence of a small magnetic anomaly[87]. Second, electrophysiological recordings in birds indicate that specific neurons in the trigeminal ganglion, to which the ophthalmic nerve projects, respond to changes in vertical field intensity as small as about 0.5% of the Earth's field[9] (FIG. 4). These cells have been proposed to function in a magnetic map sense[52].

Although direct evidence that magnetite functions in magnetoreception remains limited, additional circumstantial evidence has been provided by pulse magnetization experiments. A strong magnetic field of brief duration can be used to alter the direction of magnetization in single-domain magnetite particles[88]. Recent analyses have also indicated that such a magnetic pulse might also disrupt superparamagnetic crystals under at least some conditions[83]. Pulse magnetization might, therefore, alter magnetite-based magnetoreceptors and so change the behaviour of animals that use such receptors to derive directional or positional information from the Earth's field.

In several studies, the application of strong magnetic pulses to birds and turtles either randomized the preferred orientation direction or else deflected it slightly relative to controls[19,89–92]. These results have generally been interpreted as evidence for magnetite-based magnetoreceptors, although other explanations cannot be ruled out entirely[19], particularly given that pulsed magnetic fields generate large transient electric fields[21].

Strong magnetic pulses might hypothetically alter magnetite-based receptors that are part of a compass sense, a map sense or both. However, findings in birds indicate that the effect might be on a map sense rather than a compass sense. Pulsed fields influenced the orientation of adult birds, which are thought to rely on map information for navigation, but failed to affect young birds, which complete their first migration by flying along a consistent compass heading[93]. At the same time, pulse magnetization also significantly altered the magnetic orientation behaviour of mole rats, which have a magnetic compass but are not thought to have a map sense[94]. These results highlight the possibility that magnetite-based receptors might have different functional roles in different animals.

Compasses, maps and mechanisms

All three mechanisms that we have described seem to be capable of providing an animal with directional information that might be used in a magnetic compass sense. However, the information derived from the field is not the same in all cases. The induction model and some single-domain magnetite models are capable of detecting field polarity (that is, they can distinguish between magnetic north and south)[28,76]. By contrast, no current model based on chemical magnetoreception or superparamagnetism can do this[3,79].

Interestingly, there are two functionally different types of magnetic compass in animals. Polarity compasses, which are present in lobsters[95], salmon[96] and mole rats[94], determine north using the polarity of the horizontal field component. By contrast, the inclination compasses of birds[1,97] and sea turtles[98] evidently do not detect the polarity of the field (that is, north

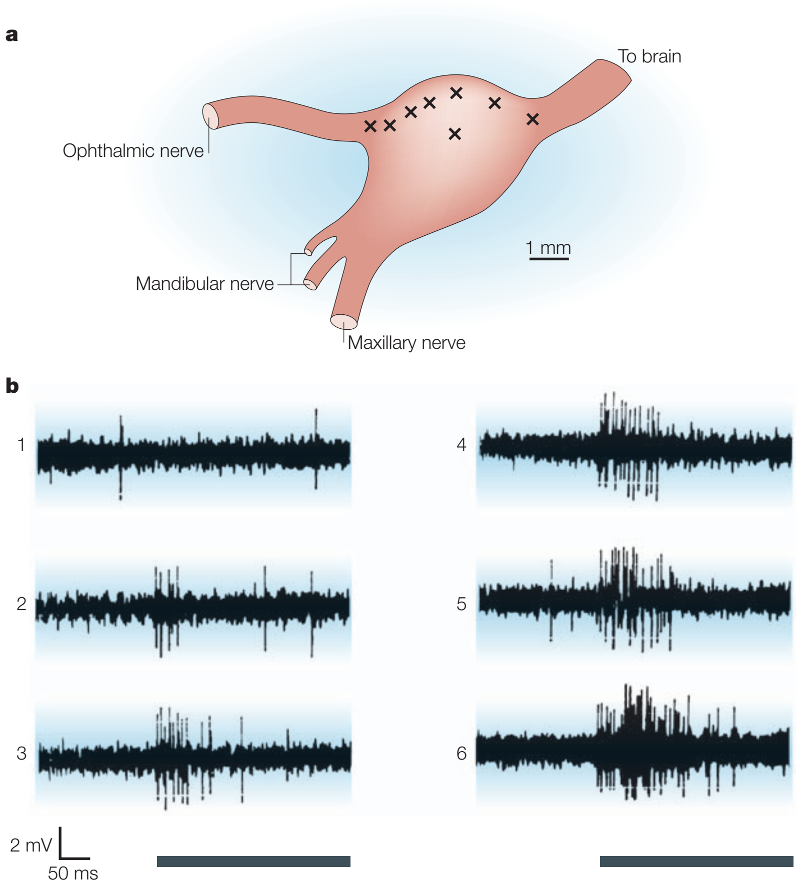

Figure 4 | **Results of electrophysiological experiments with the bobolink bird. a** | The trigeminal ganglion of the bobolink (*Dolichonyx oryzivorus*), showing the nerves and the locations of neurons (marked by crosses) that responded to changes in the ambient magnetic field with altered electrical activity. **b** | Recordings from one such ganglion cell during different changes in vertical magnetic field intensity (these changes also altered the inclination and total intensity of the field). (1) Spontaneous activity. (2) Response to 200 nanoTelsa (nT) change. (3) Response to 5,000 nT change. (4) Response to 15,000 nT change. (5) Response to 25,000 nT change. (6) Response to 100,000 nT change. The Earth's field is ~50,000 nT. Stimulus onset is indicated by the bar below each series. Modified, with permission, from REF. 9 © (2003) Elsevier Science.

versus south). Instead, they define 'poleward' as the direction along the Earth's surface in which the angle formed between the magnetic field vector and the gravity vector is smallest. Some salamanders have both types of compasses and use each in different behavioural tasks[99].

Because some of the proposed magnetoreception mechanisms can detect field polarity whereas others cannot, it is tempting to conclude that polarity and inclination compasses have different underlying mechanisms. However, this inference might be premature. For example, single-domain magnetite crystals can potentially yield receptors that are either capable or incapable of detecting field polarity[76,100]. In addition, higher-order neural processing often gives rise to behavioural outputs that do not closely mirror the properties of receptors. For now, the only safe conclusion seems to be that chemical magnetoreception and superparamagnetic magnetite cannot account for polarity compasses.

All three mechanisms seem to be capable of detecting at least some elements of the Earth's field that might be used in assessing geographical location. To detect the inclination of field lines, an animal would presumably need to integrate information from its magnetoreception system with information from a gravity-sensing system. However, no theoretical barrier seems to preclude detection of magnetic inclination by a receptor system based on any of the mechanisms.

By contrast, the different mechanisms are likely to have differing sensitivities to field intensity. Receptors based on single-domain or superparamagnetic magnetite might be able to detect very small changes in field intensity[100], whereas the chemical and induction mechanisms probably cannot[3,26]. In the chemical models, the limitation is due to the small effect of field strength on the proposed reactions[3,101]. In induction models, difficulties arise because the animal would need to precisely determine both its own velocity and the magnitude of the background (passive) electrical fields in its environment. So, given the relatively small field changes that an animal using a magnetic map would probably need to detect[102–104], a map sense based on intensity is unlikely to be mediated by a chemical or induction mechanism.

Concluding remarks

Three physically plausible mechanisms have been proposed that might underlie magnetoreception in animals. Recent advances are consistent with the hypothesis that a magnetic compass based on chemical magnetoreception exists in birds, and candidate magnetite-based receptors, possibly functioning in a magnetic map sense, have now been reported in both birds and fish. However, these findings should be viewed as tentative. Despite recent progress, primary magnetoreceptors have not been identified with certainty in any animal, and the mode or modes of transduction for the magnetic sense therefore remain unknown.

Future progress might be expedited by two realizations. First, although magnetoreception research began with behavioural studies, such studies cannot, by themselves, elucidate transduction processes that occur at or below the cellular level. Sustained efforts to incorporate a wider range of modern neuroscience techniques into magnetoreception research are now needed — an undertaking that has perhaps just recently begun[45,46,80,105–109]. In parallel with this is the need to identify new model systems in which magnetoreception can be investigated. Migratory vertebrates, such as birds and sea turtles, have proved favourable for behavioural experiments, but they are not ideal for work in the realms of neurobiology, microscopy and genetics. The discovery that magnetic sensitivity exists in zebrafish[110], the fruitfly *Drosophila melanogaster*[62,111] and in *Tritonia diomedea*, a mollusc with a simple nervous system[107–109] might represent promising first steps in this direction.

1. Wiltschko, R. & Wiltschko, W. *Magnetic Orientation in Animals* (Springer, Berlin, Germany, 1995).
Provides a comprehensive review of magnetoreception research and its history up to 1995.
2. Kirschvink, J. L. Birds, bees and magnetism: a new look at the old problem of magnetoreception. *Trends Neurosci*. **5**, 160–167 (1982).
3. Ritz, T. *et al.* A model for vision-based magnetoreception in birds. *Biophys. J.* **78**, 707–718 (2000).
Develops the radical pair model as a possible mechanism for magnetoreception and speculates on its connection with visual perception.
4. Gould, J. L. & Able, K. P. Human homing – an elusive phenomenon. *Science* **212**, 1061–1063 (1981).
5. Baker R. R. *Human Navigation and Magnetoreception* (Manchester University Press, UK, 1989).
6. Skiles, D. D. in *Magnetite Biomineralization and Magnetoreception in Organisms* (eds Kirschvink, J. L., Jones, D. S. & MacFadden, B. J.) 43–102 (Plenum, New York, USA, 1985).
7. Lohmann, K. J. *et al.* Long-distance navigation in sea turtles. *Ethol. Ecol. Evol.* **11**, 1–23 (1999).
8. Beck, W. & Wiltschko, W. in *Acta XIX Congressus Internationalis Ornithologica.* (ed. Ouellet, H.) 1955–1962 (University of Ottawa Press, Ottowa, Canada, 1988).
9. Semm, P. & Beason, R. C. Responses to small magnetic variations by the trigeminal system of the bobolink. *Brain Res. Bull.* **25**, 735–740 (1990).
Provides electrophysiological evidence for a link between magnetoreception and the trigeminal system in birds.
10. Fransson, T. *et al.* Bird migration: magnetic cues trigger extensive refueling. *Nature* **414**, 35–36 (2001).
11. Lohmann, K. J. & Lohmann, C. M. F. Detection of magnetic field inclination by sea turtles: a possible mechanism for determining latitude. *J. Exp. Biol*. **194**, 23–32 (1994).
12. Lohmann, K. J. & Lohmann, C. M. F. Detection of magnetic field intensity by sea turtles. *Nature* **380**, 59–61 (1996).
13. Lohmann, K. J. *et al.* Regional magnetic fields as navigational markers for sea turtles. *Science* **294**, 364–366 (2001).
14. Lohmann, K. J. *et al.* Geomagnetic map used in sea-turtle navigation. *Nature* **428**, 909–910 (2004).
15. Fischer, J. H. *et al.* Evidence for the use of magnetic map information by an amphibian. *Anim. Behav.* **62**, 1–10 (2001).
16. Phillips, J. B. *et al.* Behavioral titration of a magnetic map coordinate. *J. Comp. Physiol. A* **188**, 157–160 (2002).
17. Boles, L. C. & Lohmann, K. J. True navigation and magnetic maps in spiny lobsters. *Nature* **421**, 60–63 (2003).
Shows that lobsters can navigate over relatively small distances, apparently using magnetic cues. The distances involved imply that their magnetic sensitivity must be quite high.
18. Beason, R. C. & Semm, P. Magnetic responses of the trigeminal nerve system of the bobolink (*Dolichonyx oryzivorus*). *Neurosci. Lett*. **80**, 229–234 (1987).
19. Wiltschko, W. & Wiltschko, R. Migratory orientation of European robins is affected by the wavelength of light as well as by a magnetic pulse. *J. Comp. Physiol. A* **177**, 363–369 (1995).
20. Lohmann, K. J. & Johnsen, S. The neurobiology of magnetoreception in vertebrate animals. *Trends Neurosci.* **23**, 153–159 (2000).
21. Purcell, E. M. *Electricity and Magnetism: Berkeley Physics Course* Vol. 2 (McGraw-Hill, New York, USA, 1985).
22. Kalmijn, A. J. in *Handbook of Sensory Physiology* Vol III/3 (ed. Fessard, A.) 147–200 (Springer, Berlin, Germany, 1974).
23. Kalmijn, A. J. in *International Conference on Comparative Physiology*, *'Comparative Physiology of Sensory Systems'*, *Crans-sur-Sierre*, *Switzerland*, *14–18 Jun 1982* (eds Bolis, L., Keynes, R. D. & Maddrel, S. H. P.) 525–560 (1984).
24. Montgomery, J. C. Dogfish horizontal canal system: responses of primary afferent, vestibular and cerebellar neurons to rotational stimulation. *Neuroscience* **5**, 1761–1769 (1980).
25. Paulin, M. G. Electroreception and the compass sense of sharks. *J. Theor. Biol.* **174**, 325–339 (1995).
26. Rosenblum, B. *et al.* in *Magnetite Biomineralization and Magnetoreception in Organisms* (eds Kirschvink, J. L., Jones, D. S. & MacFadden, B. J.) 365–384 (Plenum, New York, USA, 1985).
27. Kalmijn, A. J. The electric sense of sharks and rays. *J. Exp. Biol.* **55**, 371–383 (1971).
28. Kalmijn, A. J. in *Sensory Biology of Aquatic Animals* (eds Atema, J., Fay, R. R., Popper, A. N. & Tavolga, W. N.) 151–186 (Springer, Berlin, Germany, 1988).
29. Kalmijn, A. J. in *Animal Migration*, *Navigation*, *and Homing* (eds Schmidt-Koenig, K. & Keeton, W. T.) 347–353 (Springer, Berlin, Germany, 1978).
Demonstrates that an electrosensitive elasmobranch can respond to magnetic fields and develops the hypothesis that this sensitivity is due to electromagnetic induction.
30. Klimley, A. P. Highly directional swimming by scalloped hammerhead sharks, *Sphyrna lewini*, and subsurface irradiance, temperature, bathymetry, and geomagnetic field. *Mar. Biol.* **117**, 1–22 (1993).
31. Walker, M. M., Diebel, C. E. & Kirschvink, J. L. in *Sensory Processing in Aquatic Environments* (eds Collin, S. P. & Marshall, N. J.) 53–74 (Springer, New York, USA, 2003).
32. Kirschvink, J. L., Walker, M. M. & Diebel, C. E. Magnetite-based magnetoreception *Curr. Opin. Neurobiol.* **11**, 462–467 (2001).
33. Meyer, C. G., Holland, K. N. & Papastamatiou Y. P. Sharks can detect changes in the geomagnetic field. *J. R. Soc. Interface* **2**, 129–130 (2005).
34. Kirschvink, J. L. Magnetite biomineralization and geomagnetic sensitivity in animals: an update and recommendations for future study. *Bioelectromagnetics* **10**, 239–259 (1989).
35. Edmonds, D. *Electricity and Magnetism in Biological Systems* (Oxford Univ. Press, Oxford, 2001).
36. Leask, M. J. M. A physicochemical mechanism for magnetic field detection by migratory birds and homing pigeons. *Nature* **267**, 144–145 (1977).
37. Schulten, K. in *Festkörperprobleme* (*Advances in Solid State Physics* Vol. 22) (ed. Treusch, J.) 61–83 (Vieweg, Braunschweig, Germany, 1982).
38. Lednev, V. V. Possible mechanism for the influence of weak magnetic fields on biological systems. *Bioelectromagnetics* **12**, 71–75 (1991).
39. Liboff, A. R. Electric-field ion cyclotron resonance. *Bioelectromagnetics* **18**, 85–87 (1997).
40. Grissom, C. B. Magnetic field effects in biology: a survey of possible mechanisms with emphasis on radical pair recombination. *Chem. Rev.* **95**, 3–24 (1995).
A critical review of the potential mechanisms by which weak static and alternating magnetic fields might influence biological processes.
41. Adair, R. K. Static and low-frequency magnetic field effects: health risks and therapies. *Rep. Prog. Phys.* **63**, 415–454 (2000).
42. Weaver, J. C., Vaughan, T. E. & Astumian, R. D. Biological sensing of small field differences by magnetically sensitive chemical reactions. *Nature* **405**, 707–709 (2000).
43. Timmel, C. R. & Henbest, K. B. A study of spin chemistry in weak magnetic fields. *Phil. Trans. R. Soc. Lond. A* **362**, 2573–2589 (2004).
Provides an in-depth review of the field of spin chemistry, with particular emphasis on the effects that weak magnetic fields exert on radical pair reactions.
44. Eveson, R. W. *et al.* The effects of weak magnetic fields on radical recombination reactions in micelles. *Int. J. Rad. Biol.* **76**, 1509–1522 (2000).
45. Mouritsen, H. *et al.* Cryptochromes and neuronal-activity markers colocalize in the retina of migratory birds during magnetic orientation. *Proc. Natl Acad. Sci. USA* **101**, 14294–14299 (2004).
Gives molecular and neurobiological evidence that cryptochromes are expressed in the retinae of birds immediately before migratory behavior.
46. Möller, A. *et al.* Retinal cryptochrome in a migratory passerine bird: a possible transducer for the avian magnetic compass. *Naturwissenschaften* **91**, 585–588 (2004).
47. Cashmore, A. R. *et al.* Cryptochromes: blue light receptors for plants and animals. *Science* **284**, 760–765 (1999).
48. Giovani, B. *et al.* Light-induced electron transfer in a cryptochrome blue-light photoreceptor. *Nature Struct. Biol.* **10**, 489–490 (2003).
49. Taraban, M. B. *et al.* Magnetic field dependence of electron transfer and the role of electron spin in heme enzymes: horseradish peroxidase. *J. Am. Chem. Soc.* **119**, 5768–5769 (1997).
50. Canfield, J. M., Belford, R. L. & Debrunner P. G. Calculations of Earth-strength steady and oscillating magnetic field effects in coenzyme B12 radical pair systems. *Mol. Phys.* **89**, 889–930 (1996).
51. Cintolesi, F. *et al.* Anisotropic recombination of an immobilized photoinduced radical pair in a 50-μT magnetic field: a model avian photomagnetoreceptor. *Chem. Phys.* **294**, 385–399 (2003).
52. Beason, R. C. & Semm, P. in *Biological Effects of Electric and Magnetic Fields* Vol. 1 (ed. Carpenter, D. O.) 241–260 (Academic, New York, USA, 1994).
53. Semm, P. *et al.* Neural basis of the magnetic compass: interactions of visual, magnetic and vestibular inputs in the pigeon's brain. *J. Comp. Physiol. A* **155**, 283–288 (1984).
54. Semm, P. & Demaine, C. Neurophysiological properties of magnetic cells in the pigeon's visual system. *J. Comp. Physiol. A* **159**, 619–625 (1986).
55. Semm, P. *et al.* in *Avian Navigation* (eds Papi, F. & Walraff, H. G.) 329–337 (Springer, New York, USA, 1982).
56. Deutschlander, M. E. *et al.* Extraocular magnetic compass in newts. *Nature* **400**, 324–325 (1999).
57. Demaine, C. & Semm, P. The avian pineal gland as an independent magnetic sensor. *Neurosci. Lett.* **62**, 119–122 (1985).
58. Wiltschko, W. *et al.* Red light disrupts magnetic orientation in migratory birds. *Nature* **364**, 525–527 (1993).
59. Wiltschko, W. & Wiltschko, R. The effect of yellow and blue light on magnetic compass orientation in European robins, *Erithacus rubecula*. *J. Comp. Physiol. A.* **184**, 295–299 (1999).
60. Muheim, R., Backman, J. & Akesson, S. Magnetic compass orientation in European robins is dependent on both wavelength and intensity of light. *J. Exp. Biol.* **205**, 3845–3856 (2002).
Reports on tests of magnetic orientation under diverse lighting environments and reviews light-dependent effects up to 2001.
61. Phillips, J. B. & Borland, S. C. Behavioural evidence for use of a light-dependent magnetoreception mechanism by a vertebrate. *Nature* **359**, 142–144 (1992).
This paper was the first to demonstrate that the wavelength of light can affect magnetic orientation behaviour. It also develops an opponency model that involves two systems responsive to different wavelengths.
62. Phillips, J. B. & Sayeed, O. Wavelength-dependent effects of light on magnetic compass orientation in *Drosophila melanogaster. J. Comp. Physiol. A* **172**, 303–308 (1993).
63. Wiltschko, W. & Wiltschko, R. Magnetic compass orientation in birds and its physiological basis. *Naturwissenschaften* **89**, 445–452 (2002).
64. Vacha, M. & Soukopova, H. Magnetic orientation in the mealworm beetle *Tenebrio* and the effect of light. *J. Exp. Biol.* **207**, 1241–1248 (2004).
65. Wiltschko, W. *et al.* Magnetic orientation in birds: non-compass responses under monochromatic light of increased intensity. *Proc. R. Soc. Lond. B* **270**, 2133–2140 (2003).
66. Wiltschko, W. & Wiltschko, R. Light-dependent magnetoreception in birds: the behaviour of European robins, *Erithacus rubecula*, under monochromatic light of various wavelengths and intensities. *J. Exp. Biol.* **204**, 3295–3302 (2001).
67. Wiltschko, W. *et al.* Light-dependent magnetoreception in birds: analysis of the behaviour under red light after pre-exposure to red light. *J. Exp. Biol.* **207**, 1193–1202 (2004).
68. Wiltschko, W. *et al.* Light-dependent magnetoreception in birds: interaction of at least two different receptors. *Naturwissenschaften* **91**, 130–134 (2004).
69. Ritz, T., Dommer, D. H. & Phillips, J. B. Shedding light on vertebrate magnetoreception. *Neuron* **34**, 503–506 (2002).
70. Henbest, K. B. *et al.* Radio frequency magnetic field effects on a radical recombination reaction: a diagnostic test for the radical pair mechanism. *J. Am. Chem. Soc.* **126**, 8102–8103 (2004).
71. Ritz, T. *et al.* Resonance effects indicate a radical-pair mechanism for avian magnetic compass. *Nature* **429**, 177–180 (2004).
72. Thalau, P. *et al.* Magnetic compass orientation of migratory birds in the presence of a 1.315 MHz oscillating field. *Naturwissenschaften* **92**, 86–90 (2005).
References 71 and 72 were the first to show that radio frequency fields can disrupt magnetic orientation, a key prediction of the chemical magnetoreception model.
73. Bazylinski, D. A. & Frankel, R. B. Magnetosome formation in prokaryotes. *Nature Rev. Microbiol.* **2**, 217–230 (2004).
A comprehensive review of the molecular underpinnings of magnetosome formation.
74. Kirschvink, J. L. *et al. Magnetite Biomineralization and Magnetoreception in Organisms* (Plenum, New York, USA, 1985).
75. Presti, D. & Pettigrew, J. D. Ferromagnetic coupling to muscle receptors as a basis for geomagnetic field sensitivity in animals. *Nature* **285**, 99–101 (1980).
76. Kirschvink, J. L. & Gould, J. L. Biogenic magnetite as a basis for magnetic field detection in animals. *Biosystems* **13**, 181–201 (1981).
77. Shcherbakov, V. P. & Winklhofer, M. The osmotic magnetometer: a new model for magnetite-based magnetoreceptors in animals *Eur. Biophys. J.* **28**, 380–392 (1999).

78. Bacri, J. C. *et al.* Flattening of ferro-vesicle undulations under a magnetic field. *Europhys. Lett.* **33**, 235–240 (1996).
79. Davila, A. F. *et al.* A new model for a magnetoreceptor in homing pigeons based on interacting clusters of superparamagnetic magnetite. *Phys. Chem. Earth* **28**, 647–652 (2003).
80. Fleissner, G. E. *et al.* Ultrastructural analysis of a putative magnetoreceptor in the beak of homing pigeons. *J. Comp. Neurol.* **458**, 350–360 (2003).
Provides detailed ultrastructure of deposits of superparamagnetic magnetite crystals in the beak of a bird.
81. Walker, M. M. *et al.* Structure and function of the vertebrate magnetic sense. *Nature* **390**, 371–376 (1997).
82. Diebel, C. E. *et al.* Magnetite defines a vertebrate magnetoreceptor. *Nature* **406**, 299–302 (2000).
References 81 and 82 provide the best morphological evidence to date for a magnetoreceptor based on single-domain magnetite.
83. Winklhofer, M. E. *et al.* Clusters of superparamagnetic magnetite particles in the upper-beak tissue of homing pigeons: evidence of a magnetoreceptor. *Eur. J. Mineral.* **13**, 659–669 (2001).
84. Beason, R. C. & Brennan, W. J. Natural and induced magnetization in the bobolink, *Dolichonyx oryzivorus* (Aves: Icteridae). *J. Exp. Biol.* **125**, 49–56 (1986).
85. Hanzlik, M. *et al.* Superparamagnetic magnetite in the upper beak tissue of homing pigeons. *Biometals* **13**, 325–331 (2000).
86. Dubbeldam, J. L. in *The Central Nervous System of Vertebrates* Vol. 3 (eds Nieuwenhuys, R., ten Donkelaar, H. J. & Nicholson, C.) 1525–1636 (Springer, Berlin, Germany, 1998).
87. Mora, C. V. *et al.* Magnetoreception and its trigeminal mediation in the homing pigeon. *Nature* **432**, 508–511 (2004).
88. Kalmijn, A. J. & Blakemore, R. P. in *Animal Migration*, *Navigation*, *and Homing* (eds Schmidt-Koenig, K. & Keeton, W. T.) 354–355 (Springer, Berlin, Germany, 1978).
89. Wiltschko, W. *et al.* A magnetic pulse leads to a temporary deflection in orientation of migratory birds. *Experientia* **50**, 697–700 (1994).
90. Beason, R. C. *et al.* Behavioural evidence for the use of magnetic material in magnetoreception by a migratory bird. *J. Exp. Biol.* **198**, 141–146 (1995).
91. Beason, R. C. *et al.* Pigeon homing: effects of magnetic pulses on initial orientation. *Auk* **114**, 405–415 (1997).
92. Irwin, W. P. & Lohmann, K. J. Disruption of magnetic orientation in hatchling loggerhead sea turtles by pulsed magnetic fields. *J. Comp. Physiol. A* **191**, 475–480 (2005).
93. Munro, U. *et al.* Evidence for a magnetite-based navigational 'map' in birds. *Naturwissenschaften* **84**, 26–28 (1997).
94. Marhold, S. *et al.* A magnetic polarity compass for direction finding in a subterranean mammal. *Naturwissenschaften* **84**, 421–423 (1997).
95. Lohmann, K. J. *et al.* Magnetic orientation of spiny lobsters in the ocean: experiments with undersea coil systems. *J. Exp. Biol.* **198**, 2041–2048 (1995).
96. Quinn, T. P. *et al.* Magnetic field detection in sockeye salmon. *J. Exp. Zool.* **217**, 137–142 (1981).
97. Wiltschko, W. & Wiltschko, R. Magnetic compass of European robins. *Science* **176**, 62–64 (1972).
98. Light, P. *et al.* Geomagnetic orientation of loggerhead sea turtles: evidence for an inclination compass. *J. Exp. Biol.* **182**, 1–10 (1993).
99. Phillips, J. B. Two magnetoreception pathways in a migratory salamander. *Science* **233**, 765–767 (1986).
100. Yorke, E. D. in *Magnetite Biomineralization and Magnetoreception in Organisms* (eds Kirschvink, J. L., Jones, D. S. & MacFadden, B. J.) 233–242 (Plenum, New York, USA, 1985).
101. Schulten, K. & Windemuth, A. in *Biophysical Effects of Steady Magnetic Fields* (eds Maret, G., Boccara, N. & Kiepenheuer, J.) 99–106 (Springer, Berlin, USA, 1986).
102. Moore, B. R. Is the homing pigeon's map geomagnetic? *Nature* **285**, 69–70 (1980).
103. Gould, J. L. The map sense of pigeons. *Nature* **296**, 205–211 (1982).
104. Gould, J. L. Sensory bases of navigation. *Curr. Biol.* **8**, R731–R738 (1998).
105. Nemec, P. *et al.* Neuroanatomy of magnetoreception: the superior colliculus involved in magnetic orientation in a mammal. *Science* **294**, 366–368 (2001).
106. Nemec, P., Burda, H. & Oelschlager, H. H. A. Towards the neural basis of magnetoreception: a neuroanatomical approach. *Naturwissenschaften* **92**, 151–157 (2005).
107. Wang, J. H., Cain, S. D. & Lohmann, K. J. Identification of magnetically responsive neurons in the marine mollusc *Tritonia diomedea*. *J. Exp. Biol.* **206**, 381–388 (2003).
108. Wang, J. H., Cain, S. D. & Lohmann, K. J. Identifiable neurons inhibited by Earth-strength magnetic stimuli in the mollusc *Tritonia diomedea*. *J. Exp. Biol.* **207**, 1043–1049 (2004).
109. Cain, S. D. *et al.* Magnetic orientation and navigation in marine turtles, lobsters, and molluscs: concepts and conundrums. *Integr. Comp. Biol.* **45**, 539–546 (2005).
110. Shcherbakov, D. *et al.* Magnetosensation in zebrafish. *Curr. Biol.* **15**, R161–R162 (2005).
111. Wehner, R. & Labhart, T. Perception of the geomagnetic field in the fly, *Drosophila melanogaster*. *Experientia* **26**, 967–968 (1970).
112. Deutschlander, M. E. *et al.* The case for light-dependent magnetic orientation in animals. *J. Exp. Biol*. **202**, 891–908 (1999).
113. Brown, R. L. & Robinson, P. R. Melanopsin — shedding light on the elusive circadian photopigment. *Chronobiol. Int.* **21**, 189–204 (2004).
114. Hattar, S. *et al.* Melanopsin-containing retinal ganglion cells: architecture, projections, and intrinsic photosensitivity. *Science* **295**, 1065–1070 (2002).
115. Chaurasia, S. S. *et al.* Molecular cloning, localization and circadian expression of chicken melanopsin (*Opn4*): differential regulation of expression in pineal and retinal cell types. *J. Neurochem.* **92**, 158–170 (2005).
116. Brainard, G. C. *et al.* Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. *J. Neurosci.* **21**, 6405–6412 (2001).
117. Lockley, S. W., Brainard, G. C. & Czeisler, C. A. High sensitivity of the human circadian melatonin rhythm to resetting by short wavelength light. *J. Clin. Endocrin. Metab.* **88**, 4502–4505 (2005).
118. Figueiro, M. G. *et al.* Preliminary evidence for spectral opponency in the suppression of melatonin by light in humans. *Neuroreport* **15**, 313–316 (2004).
119. Dacey, D. M. *et al.* Melanopsin-expressing ganglion cells in primate retina signal colour and irradiance and project to the LGN. *Nature* **433**, 749–754 (2005).
120. Wiltschko, W. *et al.* Lateralization of magnetic compass orientation in a migratory bird. *Nature* **419**, 467–470 (2002).
121. Iglesia, H. O., Meyer, J. & Schwartz, W. J. Lateralization of circadian pacemaker output: Activation of left- and right-sided luteinizing hormone-releasing hormone neurons involves a neural rather than a humoral pathway. *J. Neurosci.* **23**, 7412–7414 (2003).
122. Iglesia, H. O. *et al.* Antiphase oscillation of the left and right suprachiasmatic nuclei. *Science* **290**, 799–801 (2000).
123. Dobson, J. Magnetic iron compounds in neurological disorders. *Ann. NY Acad. Sci.* **1012**, 183–192 (2004).
124. Sweeney, R. E. IGRFGRID — a program for creation of a total magnetic field (International Geomagnetic Reference Field) grid representing the Earth's main magnetic field. *U.S. Geological Survey Open-File Report 90–45a* 37 (1990).
125. U.S. Geological Survey Open File Report 2005–1052 [online] <http://pubs.usgs.gov/of/2005/1052/> (2005).
126. Avens, L. & Lohmann, K. J. Navigation and seasonal migratory orientation in juvenile sea turtles. *J. Exp. Biol.* **207**, 1771–1778 (2004).
127. Ireland, L. C. in *A Handbook for Biotelemetry and Radio Tracking* (eds Amlaner, J. & MacDonald, D. S.) 761–764 (Pergamon, Oxford, 1980).

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Competing interests statement

The authors declare no competing financial interests.