

# **Sensory mechanisms of animal orientation and navigation**

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Although questions such as ‘How do animals find their way, and how do they sense and process this information in the brain?’ have been asked for centuries, the field of animal orientation and navigation has seen an immense leap forward in the past few decades. Moreover, our understanding has also expanded considerably regarding the molecular and physiological mechanisms of the different compasses and cues used by animals for orientation and navigation (Åkesson et al., Chapter 9, and Svensson et al., Chapter 11). Most notable are the advances made in our understanding of how animals can sense information provided by the geomagnetic field and use this information for behavioural tasks, for example for compass orientation during migration. But despite interdisciplinary and highly integrative research over recent decades, we do not fully understand how animals perceive the Earth’s magnetic field. We know that animals use geomagnetic information for orientation tasks (see Åkesson et al., Chapter 9), but the receptor(s) remain to be identified. In this chapter, we review current knowledge in this area, outline challenges, and suggest future approaches to elucidate the sensory modalities used by animals for orientation and navigational tasks.

## **10.1 Magnetic sense**

Many hypotheses regarding how animals may sense the Earth’s magnetic field have been proposed. Three principally different mechanisms to achieve

this could theoretically be used to sense the strength of the Earth’s magnetic field, including (1) induction, (2) magnetic particles, and (3) magnetically sensitive biochemical reactions. The latter two possibilities have emerged as the most promising candidate magnetoreceptor mechanisms: A light-dependent process is thought to detect the alignment of the geomagnetic field lines in space. This provides directional information that can be used for a magnetic compass (inclination compass, see Åkesson et al., Chapter 9). The other possibility is a detection process mediated by a ferromineral that reacts to very small changes in the direction and/or intensity of the magnetic field and, thereby, can be used as a magnetic compass and/or a magnetic positioning (map or signpost) sense (for reviews see Wiltschko and Wiltschko 1995a, 2005; Lohmann and Johnson 2000; Mouritsen and Ritz 2005). Both of the latter two mechanisms are supported by behavioural and physiological data in a broad range of organisms (see also Åkesson et al., Chapter 9). In some animals, like newts and birds, the presence of both mechanisms have independently been experimentally demonstrated to be present and used by the animals for different purposes, and thus are believed to be non-exclusive (Phillips 1986, Wiltschko and Wiltschko 1995b, and see 10.1.3). Here, we present the state-of-the-art knowledge of the sensory aspects of the two magnetoreception mechanisms, and highlight recent advances and future challenges.

### 10.1.1 Magnetic sense based on ferromagnetic particles

The idea of a ferromineral-based magnetic sense originated from the findings of deposits of ferromagnetic (magnetite and/or maghemite) particles in various organisms, including several animals that use the Earth's magnetic field for behavioural tasks (Kirschvink et al. 1985, Williams and Wild 2001, Falkenberg et al. 2010, but see Treiber et al. 2012). However, we here want to stress that the mere presence of biogenic ferrominerals in any organism is the rule rather than the exception and does not automatically indicate the presence of a magnetic sense. These particles may be involved in many different roles in the physiology of an organism; for example, magnetite synthesis seems to be a general way for organisms to deposit excess iron. With the exception of magnetotactic bacteria, where magnetite crystals act like a compass needle and enable the bacteria to passively align to the geomagnetic field (Blakemore 1975), the physiological mechanisms of magnetic field reception using ferromagnetic minerals remain to be demonstrated for other organisms.

### 10.1.2 Biophysical and molecular mechanisms of ferromineral-based magnetoreception

Several conditions must be met for a magnetoreception system based on ferromagnetic minerals to work (Kirschvink and Walker 1985, Kirschvink 1989, Winklhofer and Kirschvink 2010; for details see Box 10.1): (1) the ferromagnetic material must be biochemically precipitated by the organism itself, because incorporated external material is usually too contaminated; (2) the ferromagnetic particles must fulfil a variety of magnetophysical properties and have a specific magnetization and size, i.e. be single-domain (SD) or superparamagnetic (SPM) crystals; and (3) they must be mechanically coupled to nerve fibres or sensory organelles; otherwise, they cannot transmit any magnetic information to the brain.

### 10.1.3 Behavioural and physiological evidence for ferromineral-based magnetoreception

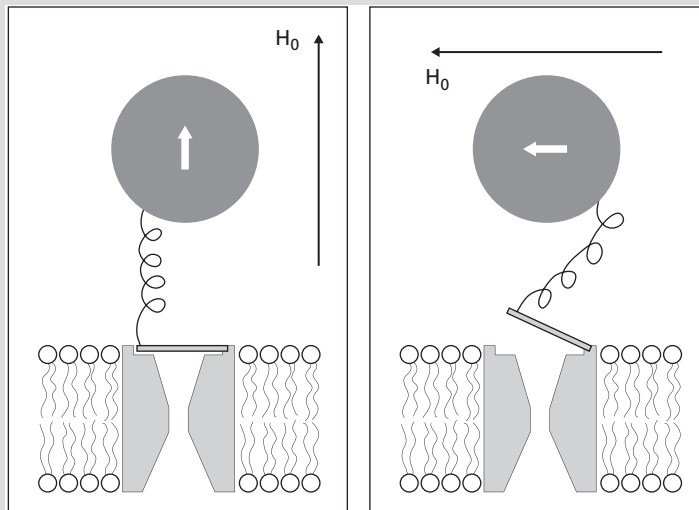
Despite numerous reports of ferromagnetic material in invertebrates, there is little direct behavioural

evidence that these particles function as magnetoreceptors. Magnetite, maghemite, or other ferritin-like particles are found in a number of insect species, including bees, ants, and termites, but an actual magnetoreceptor has not been located or described yet (reviewed by Wajnberg et al. 2010). The most convincing data supporting a magnetite-based receptor mechanism come from fish and birds, where there is both behavioural and electrophysiological evidence in favour of a magnetite-based magnetoreception mechanism. Several behavioural studies with fish have reported alignment along magnetic fields or abilities to discriminate magnetic anomalies. For example, rainbow trout, *Oncorhynchus mykiss*, align along an external magnetic field, but become disoriented in a null magnetic field where no magnetic field is present; i.e. all dimensions of the magnetic field are cancelled out and the length of the magnetic vector is zero (Chew and Brown 1989). Trout are also able to discriminate between magnetic anomalies, but only when the conditional response allow movement and when the magnetic fields are spatially distinctive (Walker et al. 1997). Experiments with yellowfin tuna, *Thunnus albacares*, showed that these fish could sense differences in intensity of the magnetic field, but not differences in direction (Walker 1984). Neurophysiological recordings on rainbow trout supported these findings; specifically, single neurons in a side branch of the trigeminal nerve have been shown to respond to changes in intensity, but not to the direction of an imposed magnetic field (Walker et al. 1997). Single-domain magnetite particles have been reported in several locations in different fish species: near the basal lamina of the olfactory epithelium (the area innervated by the trigeminal nerve) and in the dermal bone cartilage of the skull (e.g. Walker et al. 1984, 1997). Based on the findings of iron-rich crystals in the olfactory lamellae in rainbow trout (Walker et al. 1997), Diebel et al. (2000) suggested a vertebrate magnetoreceptor in form of a multi-lobed cell, containing chains of magnetite particles located in the basal lamina of an olfactory lamella. Recently, these findings were supported by a new method developed to detect and characterize candidate vertebrate magnetoreceptor cells (Eder et al. 2012). However, despite this exciting discovery, it remains to be shown how these magnetoreceptor

### Box 10.1 Ferromineral-based magnetoreception

Magnetite ( $\text{Fe}_3\text{O}_4$ ) and maghemite ( $\text{Fe}_2\text{O}_3$ ) are the most frequently occurring of the known biogenic materials that are ferro(i)magnetic at room temperature. Ferro(i)magnets have a spontaneous magnetic moment and are composed of small regions called domains. Crystals composed of only one domain are called single-domain (SD) crystals. They are elongated particles and have a magnetic moment along the long axis directed towards one of the two ends. Magnetite particles which are sufficiently small become superparamagnetic (SP). They have no spontaneous magnetic moment, but align with an external magnetic field. The simplest magnetic compass involving magnetic material is based on SD magnetite particles that align along an external magnetic field like compass needles. The arrangement in chains as found in bacteria (Blakemore 1975) imparts the magnetite crystals an even larger magnetic moment because of additive effects. The rotation or translation of a magnetic particle can in theory translate into a sensory nerve signal in two physically different ways (Kirschvink and Walker 1985, Kirschvink 1989,

Winklhofer and Kirschvink 2010): (1) the torque may directly generate elastic resistance or pressure on mechanically coupled physiological structures, like a hair cell, a stretch receptor, or another mechanoreceptor; or (2) the torque may have indirect effects and alter magneto-chemical reactions or interact with nearby superparamagnetic particles (Fig. 10.1). Superparamagnetic ferromagnetic minerals cannot produce a torque, but can theoretically detect magnetic fields by other mechanisms: Clusters of SP magnetite particles dispersed in liquid and enclosed by a biological membrane can theoretically change the shape of these SP clusters under a magnetic field in the order of magnitude of the geomagnetic field, if connected to a mechanoreceptor. Such clusters could provide axial information about the applied field, and the magnetic-field-induced shape of the clusters could be amplified, as well as counterbalanced by osmotic pressure regulation, and thereby provide magnetic intensity information (for recent reviews see Cadiou and McNaughton 2010, Winklhofer and Kirschvink 2010).



**Figure 10.1** In the ferromagnetic transduction model, ion channels in the nerve membrane open or close depending on the magnetic torque acting at magnetite particles connected to the ion channels and thereby let  $\text{Ca}^{2+}$  ions pass through, which elicits a nerve signal. Redrawn from Kirschvink (1992) with permission.

cells function in detail, and how the information is transferred to a nerve signal.

Both birds and newts are believed to possess a dual magnetoreception mechanism, i.e. a light-dependent magnetic compass and a (putatively independent) magnetite-based magnetic map sense (Phillips 1986, Munro et al. 1997a; Åkesson et al.,

Chapter 9). Pulse remagnetization experiments and treatment with zinc sulphide of the putative receptor organ (considered as diagnostic tool to test for the involvement of magnetite-based receptor mechanism; see Box 10.2) with migratory songbirds and pigeons, *Columbia livia*, have shown that experienced adult birds, but not inexperienced juveniles, are affected

### Box 10.2 Diagnostic tools to distinguish magnetoreceptor models

Diagnostic tools used to test whether a magnetoreceptor based on ferrominerals is involved in a specific behaviour can be grouped into two categories: (1) tools that directly affect the magnetic particles, and (2) tools that affect the sensory receptor or the transduction pathways between the receptor and the brain.

(1) Pulse remagnetization is the application of a brief, strong, directional magnetic pulse (0.5 T for 4–5 ms). This procedure has been widely used to directly affect the ferromagnetic particles in a putative magnetoreceptor (e.g. Wiltschko et al. 1994, 1995B; Beason et al. 1995):

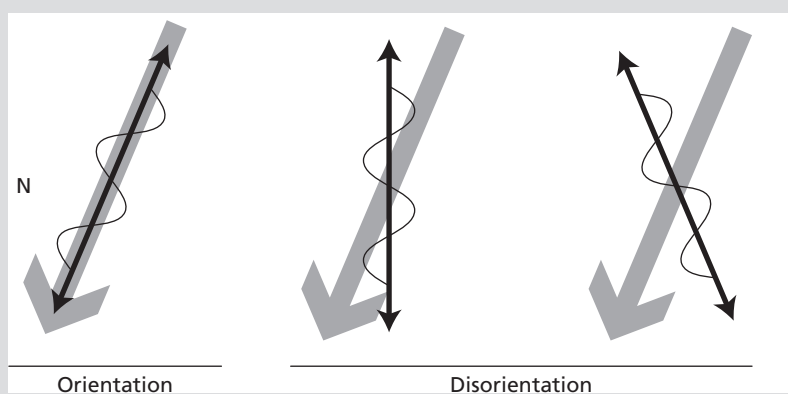
- If SD particles are involved, such a magnetic pulse will permanently remagnetize the particles in the opposite direction.
- If the pulse is applied anti-parallel to the magnetic moment and with an intensity greater than the coercivity of SD particles, i.e. greater than the intensity required to reduce the magnetization of those particles to zero, this should result in a permanent reversal or change in orientation.
- If clusters of SP magnetite are involved, such a strong magnetic pulse is expected to form agglomerations of clusters and impair the magnetoreceptor for a few days.

The downside of pulse remagnetization experiments is that it is difficult to predict the expected outcome of such a treatment as long as the exact structure and function of the receptor are not known. In addition, there is no proper

control experiment that allows distinguishing a true effect of the strong pulse on the magnetoreceptor from effects on other unrelated physiological processes.

(2) Tools in the second category aim to disrupt magnetoreceptor function, and include (i) local anaesthetics blockade or treatment with zinc sulphide of the putative receptor organ (i.e. upper beak area in birds; e.g. Holland et al. 2009), and (ii) lesion studies, where either the transmitting nerve (i.e. trigeminal nerve system in birds; cf. Mora et al. 2004) or the putative brain areas involved in the processing of the information are lesioned (via mechanical cut or chemical lesion, e.g. with ibotenic acid; Zapka et al. 2009). Note that studies using local anaesthesia should be treated with caution, as no control experiments exist that can reliably work as treatment control. Further, nothing is known about the time span of efficacy of any such treatment for most migratory animals. A further indirect indication for the involvement of a ferromineral-based mechanism is also directed orientation in total darkness, as this receptor mechanism is independent of light, but the radical-pair-based mechanism requires light to function (but it must be noted that energy for the radical-pair formation could in theory also be taken from chemical energy).

Low-intensity, oscillating radio-frequency magnetic fields (RF fields) have recently been introduced to test whether a radical-pair mechanism is involved in the primary magnetoreception process of an orientation response (Henbest et al. 2004, Ritz et al. 2004). RF fields of distinct frequencies in the lower MHz range (0.1–10 MHz;  $<1 \mu\text{T}$ ), which



**Figure 10.2** European robins, *Erithacus rubecula*, are disoriented when tested in the presence of a radio-frequency (RF) field (black double arrows with snake-line). However, the orientation of the RF field relative to the Earth's magnetic field (large, grey arrows) is crucial. The birds are only disoriented when the RF and the geomagnetic fields are aligned non-parallel (right two conditions), but not when the two fields are aligned in parallel (left condition). See Ritz et al. (2004) for details.

**Box 10.2** *Continued*

vary with the intensity of the ambient magnetic field and the magnetoreceptor molecule involved, interfere with the interconversion between the singlet and triplet excited states, and mask or alter the magnetic field effects produced by the Earth's magnetic field (Fig. 10.2). Such RF disturbances can lead to either disorientation or change in orientation, depending on the amount and type of change, and how the animals integrate the information into a migratory direc-

tion. Magnetite-based magnetoreceptors are not affected by RF fields, since the rotation of magnetite particles as proposed in animal magnetoreceptors is too slow and the ferromagnetic resonance frequency is expected to be in the GHz rather than MHz range (Ritz et al. 2000, 2004; Henbest et al. 2004). This makes the application of RF fields a unique, diagnostic tool for studying the involvement of a radical-pair mechanism in magnetoreception (Fig. 10.2).

by such a treatment (e.g. Wiltschko et al. 1994; Beason et al. 1995, 1997; Munro et al. 1997b; Holland et al. 2009). Presumably, juvenile birds exclusively use their light-dependent magnetic compass to determine their migratory direction during their first migration. Experienced adult birds likely also use their magnetic map sense, which they acquire during their first migration. Blocking the trigeminal nerve with a local anaesthetic eliminates the effects of pulse remagnetization (Beason and Semm 1996).

Where could these putative compass needles (single-domain or superparamagnetic magnetite crystals) be located in birds, and by which pathways could they transmit the magnetic information to the brain? Williams and Wild (2001) found trigeminally innervated structures in the nasal region of pigeons which they interpreted as single-domain magnetite. A few years later, Fleissner and colleagues (2003, 2007) found nerve-cell endings (branches of the trigeminal nerve) in the upper beak of pigeons. Those nerve-cell endings contained dense clusters of ferromagnetic structures at six distinct locations in the beak, which could sense the geomagnetic field and subsequently transmit this information to the brain. Depending on their alignment relative to the magnetic field, these clusters were suggested to become uniquely deformed by the Earth's magnetic field, leading to an opening of mechano-sensitive ion channels and ultimately result in a nerve signal transmitted via the trigeminal nerve to the brain. The birds would thereby be able to measure the intensity, and consequently the polarity, of a magnetic field in all three dimensions, providing them with a '3-D magnetometer'. These structures were later confirmed for several

other bird species, including migratory passerines (Falkenberg et al. 2010). The anatomical findings and theoretical assumptions were supported by behavioural experiments which demonstrated that birds are no longer able to detect magnetic stimuli when the trigeminal nerve, and thus the connection from the putative receptor to the brain, was cut (Mora et al. 2004; see also next section). Inactivation of the beak receptor in experiments (by lesioning the ophthalmic branch of the trigeminal nerve) with free-flying birds, both migratory birds and homing pigeons, supported these findings, at least with respect to experienced, adult individuals (Gagliardo et al. 2006, Holland et al. 2009).

Until very recently, such a '3-D magnetometer' in the upper beak of birds was almost regarded as a fact. However, the findings were recently challenged by a study demonstrating that these iron crystals were not located in nerve tissue, but rather in macrophages, and thus could not be the sensors providing the trigeminal nerve, and thereby the brain, with magnetic information (Treiber et al. 2012). Macrophages are immune cells known to contain ferritin proteins (which store iron in the cell), and their presence has been reported throughout the bird's beak and other areas of the body, but nowhere associated to nerve tissue (Treiber et al. 2012). What consequences do these results have on our understanding of how birds may perceive the Earth's magnetic field? They certainly challenge previous interpretations of behavioural experiments that concluded that the trigeminal nerve is the link that makes it possible to transfer information sensed via magnetosensors in the beak to the

brain. The new findings add no evidence to support the existence of iron-containing nerve cells at the previously reported locations along the upper beak of birds, but do not exclude the possibility that there still are magnetoreceptors at some yet-to-be-identified location in the bird's upper beak. Consequently, we need to carefully re-evaluate hypotheses and conclusions that were drawn based on behavioural studies that have previously been interpreted to support the function of a magnetite-based receptor located in the upper beak of birds. One plausible scenario could be that the real magnetoreceptors are located in the olfactory tissue, which is adjacent to the area where the supposed magnetic sense system was identified. This region is known to be connected to the nervous tissue, which was shown to transmit magnetic information to the brain in lesion experiments. This would be well supported by the finding of candidate magneto-sensitive cells in olfactory regions in trout (Walker et al. 1997; see earlier in this section).

In conclusion, the hypothesis proposing that magnetic information is perceived by a magnetoreceptor in the beak and transmitted to the brain via the trigeminal nerve might still be valid, as lesioning this link resulted in birds no longer being able to perceive magnetic stimuli. However, we do not understand the detailed function of this putative neuronal link, and we do not know which magnetosensor feeds information into the nerve. Recently, a putative third magnetoreceptor was suggested to be located in the lagena of the inner ear of pigeons and encode information on the direction and intensity of the magnetic field (Wu and Dickman 2011, 2012). However, it remains to be demonstrated whether the reported brain activities as a consequence of changes in the magnetic field originate from an actual new magnetoreceptor, or whether they are the results of the integration of vestibular and magnetic field information, which is necessary for measuring magnetic fields.

#### 10.1.4 Electrophysiological recordings and lesion experiments

The behavioural evidence for a magnetite-based map sensor is also supported by neurophysiological recordings from the ophthalmic branch of the

trigeminal nerve of the bobolink, *Dolichonyx oryzivorus*, a migratory songbird from North America. Changes in the rotation of the vertical or horizontal component of the geomagnetic field and changes in intensity of as little as 50–200 nT led to alterations in the action potentials in the trigeminal nerve (Beason and Semm 1987). Magnetic compass responses (choosing and maintaining a direction) were not affected by blocking the ophthalmic branch of the trigeminal nerve (Beason and Semm 1996). All of these findings are suggestive of the involvement of the trigeminal nerve in the processing of magnetic information from the beak to the brain.

#### 10.1.5 Conditioning experiments

Further support for an involvement of the trigeminal nerve system comes from conditioning experiments, which show that pigeons can discriminate between the presence and absence of a strong magnetic anomaly (~100,000 nT; Mora et al. 2004). This ability disappeared when the ophthalmic branch of the trigeminal nerve was cut, but remained when the olfactory nerve was lesioned instead (Mora et al. 2004). Similarly, Pekin ducks, *Anas platyrhynchos domestica*, trained to find a hidden food reward indicated by a magnetic anomaly, were not able to find the reward when the trigeminal nerve was anaesthetized by an injection of lignocaine hydrochloride, strongly indicating a role of the trigeminal nerve in the detection of magnetic anomalies (Freire et al. 2012). In addition, both pigeons (Thalau et al. 2007) and domestic chicks (Denzau et al. 2011) were able to use a small, but strong, anomaly to find a hidden food source, although none of these studies tested for the involvement of the trigeminal nerve. Still, in order for a magnetic 'map sense' to work, birds must be able to detect naturally occurring local changes in the magnetic field strengths that are about five orders of magnitude smaller (~10 nT) than the magnetic anomalies used in the operant conditioning by Mora et al. (2004). Therefore, to function as a putative biologically relevant map or signpost sense, it still remains to be demonstrated that the trigeminal magnetoreception circuit can detect biologically relevant magnetic anomalies.

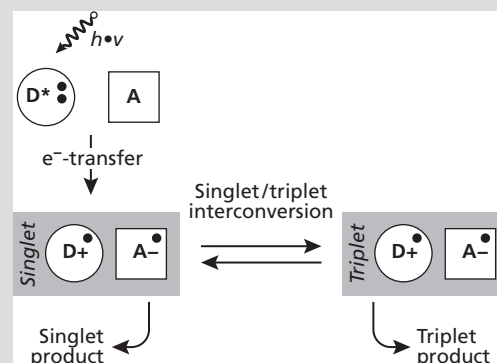
### 10.1.6 Chemical magnetoreception based on a radical pair mechanism

In 1978, the physicist Klaus Schulten proposed that magnetic sensing might have spin chemical origins (Schulten et al. 1978, Schulten 1982). In a theoretical paper, he suggested that the yield of a biochemical reaction proceeding via a radical pair might be sensitive to the orientation of an external magnetic field. Electron spins are not strongly coupled to the thermal bath and therefore represent one of only a few molecular features that might plausibly be influenced by the Earth's magnetic field. The suggested mechanism (Box 10.3) involves a light-induced electron transfer between two molecules (note: such processes can also be chemically induced). The electron transfer results in the generation of a radical-pair intermediate that will either exist in a singlet or a triplet excited state, and subsequently decay in chemically different end products. Theoretical calculations and in vitro experiments showed that the ratio between singlet and triplet products from radical-pair reactions can be modulated by an Earth-strength magnetic field during the interconversion step, i.e. when singlet radical intermediates convert to triplets and vice versa (Maeda et al. 2008, 2012). This orientation-dependent interconversion step (and subsequently resulting differences in the ratio of singlet and triplet end products) could theoretically be used to encode directional information. In a revival of this idea, Ritz et al. (2000) proposed that the retina with its almost perfect sphere would be an ideal substrate for such a mechanism. He further speculated that the radical-pair intermediate might be involved in some kind of visual reception system, exploiting the highly efficient visual transduction signalling cascade. According to this suggestion, the reaction yield anisotropy of the receptor radical pair could govern the directional response and thus form the basis of a magnetic compass (for recent reviews see Ritz et al. 2010, Mouritsen and Hore 2012).

Possible receptor candidate molecules involved in the primary magnetoreception process and mediating a light-dependent radical-pair mechanism must meet the following criteria: they need to be light-sensitive, need to be able to form radical pairs that persist long enough so that the radical-pair yields

#### Box 10.3 Radical-pair-based magnetoreception

A radical is any atom or molecule with one or more unpaired electrons. Electrons possess an angular spin momentum, and radicals are therefore paramagnetic (Fig. 10.3). The radical-pair mechanism starts with an electron transfer from a donor molecule D to an acceptor molecule A upon photo excitation (Fig. 10.3), resulting in a radical pair with both donor and acceptor molecules possessing one unpaired electron (depicted as black dots). The spins of the unpaired electrons can be either opposite (singlet state) or parallel (triplet state) and both states can interconvert. The interconversion step between singlet and triplet intermediates can be affected by an external magnetic field, and therefore modulates the ratio of singlet and triplet transient states depending on the orientation of the molecule within the field. In a final step, singlet, and triplet intermediates will react to distinct products, which may differ in their biochemical properties (modified after Ritz et al. 2000).



**Figure 10.3** Radical pairs are formed in many biochemical transformations as transient (that is: short-lived) reaction intermediates, either as singlet or triplet pairs, depending on the spin correlation of the unpaired electrons. In the singlet state, the total angular momentum of a radical pair is zero and the electron spins are oppositely directed (antiparallel) and paired ( $\uparrow\downarrow$ ). A radical pair in a singlet state can recombine. In the triplet state, electron spins are parallel ( $\uparrow\uparrow$ ) and no bonding is possible. Because each electron spin has an associated magnetic moment, the chemical characteristics of the singlet and triplet intermediate states, as well as their interconversion can be influenced by internal and external magnetic fields. Redrawn after Ritz et al. 2000 with permission from Elsevier.

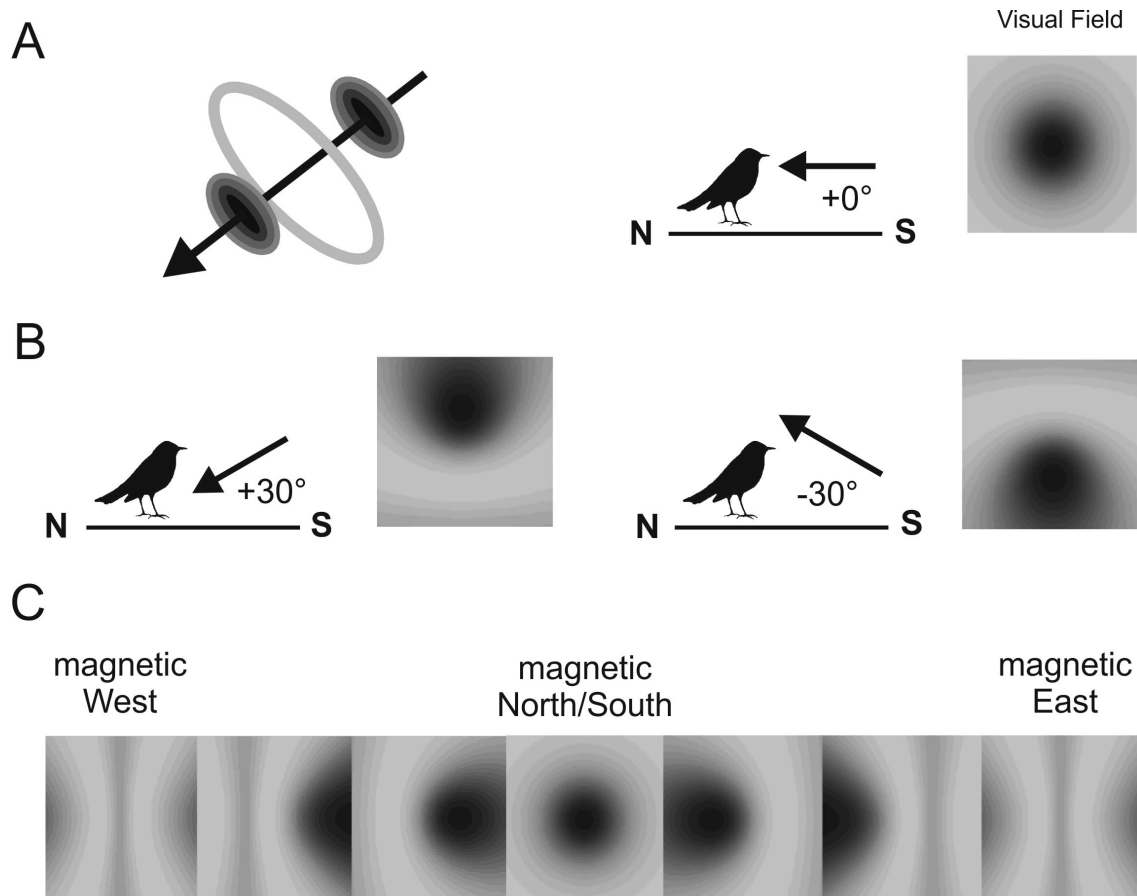
can be modified by an Earth-strength magnetic field, and should be localized in a spatially fixed relationship relative to each other criteria (reviewed by Rodgers and Hore 2009, Liedvogel and Mouritsen 2010, Phillips et al. 2010a, Mouritsen and Hore 2012). Classical photopigments like the opsins do not form radical pairs, and thus are unlikely candidates for magnetoreception. Cryptochromes, a class of blue light photoreceptor molecules, have been suggested to be the most likely molecules involved in magnetoreception. They are the only known photopigments in the vertebrate eye that have the potential to form radical pairs. Cryptochromes form a multi-gene family of blue-green light photoreceptors known to be involved in circadian rhythm regulation (for a recent review see Chaves et al. 2011). They share high sequence homology with photolyases that form radical pair intermediates persisting long enough for magnetic field effects to occur (Weber et al. 2002, Giovani et al. 2003). To date, cryptochromes from several taxa have been shown to also produce persistent, spin-correlated radical species upon photo-excitation in vitro (Liedvogel et al. 2007, Biskup et al. 2009, Schleicher et al. 2009). Cryptochromes are found in a large variety of species known to use a magnetic compass, for example, in retinas of two migratory bird species, European robins, *Erithacus rubecula*, and garden warblers, *Sylvia borin*, and two non-migratory species, chicken, *Gallus gallus*, and zebra finches, *Taeniopygia guttata* (Liedvogel and Mouritsen 2010). A detailed neuroanatomical study of cryptochrome expression in robins and chicken recently revealed that the outer segments of the avian UV/V cones are most likely the primary sites of the light-dependent magnetoreceptor (Niessner et al. 2011). Niessner and colleagues found cryptochrome expression in virtually every cone across the entire retina, which is one of the requirements for the radical-pair model to work. Still, more research is needed to unambiguously separate observations of cryptochrome expression as a result of circadian rhythmicity and magnetoreception, and to describe the full details of the reception mechanism, including the neuronal pathways mediating the sensory information to the brain.

The development of reliable magnetic compass assays in genetic model organisms, such as *Drosophila* (Phillips and Sayeed 1993, Gegear et al. 2008),

laboratory mice (Muheim et al. 2006a), and zebra finches (Voss et al. 2007), has provided access to cryptochrome knockout animals. This has opened up a new and promising avenue in magnetoreception research, allowing direct tests of the involvement of cryptochromes and other molecules possibly involved in the primary magnetoreception process. One recent study with *Drosophila* provided convincing evidence that cryptochromes indeed are involved in light-dependent magnetoreception. In this study, adult *Drosophila* were able to discriminate a magnetic field (although about 10 times stronger than the geomagnetic field) only when the cryptochrome gene was functionally intact, but not when it was genetically engineered to be dysfunctional (Gegear et al. 2008). Also, magnetic fields were shown to influence cryptochrome-mediated effects of blue light on the free-running rhythm of the circadian clock in *Drosophila* (Yoshi et al. 2009). Magnetic field sensitivity could thus be an intrinsic property of cryptochrome-based photo-signalling systems, from which light-dependent magnetoreception might have evolved (Phillips et al. 2010a, b).

From a behavioural perspective, the putative magnetoreceptor must meet the following criteria to be a likely candidate for a light-dependent magnetic compass receptor (Liedvogel and Mouritsen 2010, Phillips et al. 2010a, Ritz et al. 2010; Fig. 10.4): (1) the magnetoreceptor needs to be sensitive to light of specific spectral properties (mainly wavelength), matching the receptor molecule(s) involved in the radical-pair process (see later discussion); (2) the encoded information received by the animal needs to have axial properties and not allow to determine the polarity of the field lines, since the avian magnetic compass generally functions without using polarity, as first described by Wiltschko and Wiltschko (1972); (3) the directional information perceived by the animal must depend on the intensity of the magnetic field; thus exposure to magnetic field intensities never experienced before can lead to disorientation, followed by a slow adaptation to the 'new' intensity (Wiltschko 1968, Wiltschko et al. 2006). A light-dependent magnetic compass has been demonstrated in both invertebrates and vertebrates, including fruit flies, mealworm beetles, bullfrogs, newts, homing pigeons, and several species of migratory birds (reviewed by Wiltschko and Wiltschko 1995a, 2005; Muheim





**Figure 10.4** Illustration of the visual modulation pattern centred on the Earth's magnetic field (arrow), as suggested to be produced by magnetosensitive photoreceptors in the avian retina, enabling birds to 'see' the magnetic field (freely interpreted after Ritz et al. 2000). (A; left) Three-dimensional visual modulation pattern of the magnetic field, consisting of a dark area on each side of the magnetic field axis and a ring in the centre. (A; right) Visual modulation pattern seen by an animal (bird) looking parallel to the magnetic field at the magnetic equator, where the magnetic field is horizontal. (B) Visual modulation pattern seen by a bird looking towards magnetic south at a geographic latitude, where the magnetic field inclination is about  $30^\circ$ , (left) on the northern and (right) on the southern hemisphere. (C) Visual modulation pattern perceived by a bird looking from the west to the east (on the magnetic equator).

et al. 2002; Phillips et al. 2010a). There is also strong evidence from behavioural experiments for a light-dependent magnetic compass in C57BL/6J mice (Muheim et al. 2006a). A light-independent magnetic compass rather seems to be the exception and has only been demonstrated in a few animals, such as subterranean mole-rats (Marhold et al. 1997) and sea turtles (Lohmann and Lohmann 1993), possibly as a result of an adaptation to the non-terrestrial lifestyle of these organisms.

In birds, the dependence of light of specific wavelengths for magnetic compass orientation has been studied extensively. In general, birds are well

oriented under UV to green light, and become disoriented or show shifted orientation under longer wavelengths (e.g. Wiltschko et al. 1993; Wiltschko and Wiltschko 1995b, 2001; Munro et al. 1997b; Muheim et al. 2002). European robins exposed to radio-frequency (RF) fields aligned nonparallel to the geomagnetic field vector become disoriented when tested under either a broadband RF field or distinct single frequencies of 1.375 or 7 MHz (Fig. 10.2; Ritz et al. 2004). The orientation of mole-rats, on the other hand, which is supposed to be mediated by a non-light-dependent magnetoreceptor, is not impaired by an RF field, supporting

previous indications that their magnetic compass is based on magnetite (Thalau et al. 2006).

Questions that remain to be answered include: Where in the animals' bodies are the light-dependent magnetoreceptors located, and by which neuronal pathway is the information transmitted from the receptor to the brain? As magnetic fields can transmit through all body material, the receptors could in theory be located just about anywhere. However, behavioural experiments suggest that light is necessary for light-dependent magnetic orientation to function; thus the receptors must be located at a peripheral site of the animals' body. In birds, and also mammals, the only locations where light can reach specialized photoreceptors are the eyes. Already in the 1980s, extracellular recordings provided the first evidence for the involvement of the visual centre in light-dependent magnetoreception in birds. Cells in the nucleus of the basal optic root (nBOR) and in the optic tectum showed light-dependent magnetic responsiveness to changes in the direction of a magnetic field and slow inversions of the vertical component of the magnetic field (Semm et al. 1984). Recent research on the neural basis of magnetoreception has largely substantiated these findings, and provided new insights into the neural pathways and brain areas involved in information transfer and processing in both birds and mammals (e.g. Nemec et al. 2001, Heyers et al. 2007).

In birds, a brain structure in the visual Wulst, named 'Cluster N', and connected to the retina via the thalamofugal pathway, has been identified and suggested to be involved in the processing of light-dependent magnetic information in migratory birds during the night (Mouritsen et al. 2005, Heyers et al. 2007, Zapka et al. 2009). Migratory birds with a (chemically) lesioned Cluster N are disorientated when tested for magnetic compass orientation, but their sunset or star compass remained intact and functional for orientation. These results strongly indicate that Cluster N is involved in processing magnetic compass information at low light levels (Zapka et al. 2009). However, not in all taxa is light-dependent magnetoreception necessarily limited to the retina. In animals that have special structures containing photoreceptors, like the parietal eyes of reptiles or the pineal complex of fish and some

reptiles, and the frontal organ of amphibians, light-dependent photoreception could also take place in extra-retinal photoreceptors (for review see Phillips et al. 2010a). This has been nicely demonstrated in Eastern red-spotted newts, *Nothophthalmus viridescens*, which show a 90° shifted response in magnetic compass orientation when tested under red light, compared to tests under blue or full-spectrum white light (Phillips and Borland 1992). Hence, newts trained to learn the shoreward side of a training tank with the top of their head, but not their eyes, covered with a red-light filter, showed the same 90° shifted response as control animals completely illuminated by red light (Deutschlander et al. 1999). Thus, the light-sensitive-magnetosensitive receptors mediating shoreward orientation in newts are most likely located in extraocular photoreceptors in the pineal complex or hypothalamus (Deutschlander et al. 1999). In anuran amphibians and lizards, single photoreceptors with two antagonistic photoreception mechanisms, like those proposed to underlie the light-dependent magnetic compass in newts, have been found in the pineal complex (Eldred and Nolte 1978, Solessio and Engbretson 1993).

## 10.2 Celestial compasses—sun, polarized light, and star compasses

### 10.2.1 Physiological evidence for sun and star compass orientation

While the behavioural mechanisms of sun compass orientation are well understood in many species (see Åkesson et al., Chapter 9), we know little about how the sun compass works on the physiological level, especially in higher organisms. Similarly, it remains to be shown what key features from the rotating starry sky the birds use for orientation. Are birds taking 'snapshot pictures' at certain time intervals and overlaying these to identify the centre of rotation? Or are they able to take an overexposed picture, and thus can follow the movement of the stars by seeing their paths? We can currently only speculate on how the star compass in birds functions, and how this information is mediated by the brain and which brain areas are used for processing star compass orientation.

Cleverly designed conditioning experiments could be one approach in order to get further insight into how birds are able to identify the centre of rotation as reference cue for star compass orientation. One possibility for identifying brain areas involved in processing star compass orientation would be 'behavioural molecular mapping', such as the method used to identify Cluster N as the brain area involved in magnetic compass orientation (Mouritsen et al. 2005). This requires an extremely well-designed experiment, including standardized control conditions and exclusion of any alternative variables that could putatively be used for compass orientation.

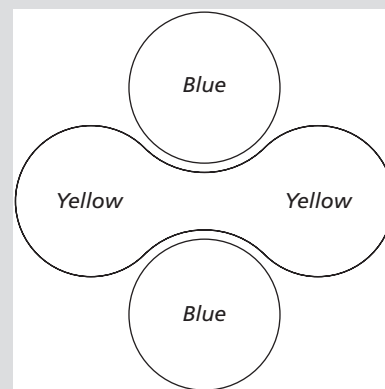
### 10.2.2 Behavioural and physiological evidence for polarized light sensitivity

The ability to perceive linearly polarized skylight and use it for orientation is common in the animal kingdom (Åkesson et al., Chapter 9). It has been extensively characterized, on both the behavioural and physiological level, first and foremost in invertebrates, such as arthropods (e.g. honeybees, crickets, ants, spiders, beetles, crabs, shrimp, crayfish, water fleas) and cephalopods (e.g. squids and cuttlefish) (for reviews see Horváth and Varjú 2004, Roberts et al. 2011). However, also vertebrates seem to use this third dimension of light in various behavioural contexts, and polarized light sensitivity has been reported in fish (e.g. Cameron and Pugh 1991, Parkyn et al. 2003), amphibians (Adler and Taylor 1973), reptiles (Adler and Phillips 1985), and birds (e.g. Able 1982, Muheim et al. 2006b, and see below). To date, no evidence for polarization sensitivity in mammals has been published, so mammals may be an exception (but see polarization vision in humans, Box 10.4).

How can animals perceive polarized light? The fundamental prerequisites for a photoreceptor to be able to detect the electric vector of light are inherently polarization-sensitive pigment molecules (dichroic chromophores). Some common chromophores, like retinal, fulfil this requirement. The exceptionally high polarization sensitivity found in many insects, crustaceans, and cephalopods is enhanced by the highly organized microvilli of individual rhabdomeric photoreceptor cells

#### Box 10.4 Polarization vision in humans

Contrary to the common belief, humans possess the ability to see polarized light, at least in theory. The phenomenon is called Haidinger's Brushes, and is most likely due to an artefact, i.e. a deformation of the macula (yellow spot) in our eyes (Bone 1980). On clear days at times around sunrise and sunset, when the natural polarization of the skylight is most prominent and up to 80–90% of the incoming skylight is polarized and aligned at 90° from the sun, these images can, after some practice, be seen in the sky. The plane of polarization also becomes visible when a sheet polarizer is turned by 90° clockwise and counter-clockwise in front of a polarized light source (the natural sky or, for example, an LCD screen). When the two planes of linear polarization are arranged perpendicular to each other, no light is transmitted through the filters and a dark area is produced (Fig. 10.5; see also colour plate section). We can only speculate that humans at some point in their evolutionary history may have used this information for orientation and navigation. In theory, they could have made use of the pattern of skylight polarization as a substitute for the position of the sun when it was covered by clouds or topography, as many insects have been shown to do (see also Åkesson et al., Chapter 9).



**Figure 10.5** Polarized light as perceived by the human eye, visible as two faint blue and two faint yellow balloons (Haidinger's brushes), aligned perpendicularly, with the blue axis indicating the axis of polarization. (See Plate 3).

in an ommatidium that are often aligned at 90° to each other (Roberts et al. 2011). In insects, these polarization-sensitive photoreceptors are further concentrated in specialized regions of the eyes (in many cases in an area in the upper field of view,

so-called dorsal rim area), where they are aligned in ordered arrays to measure polarized light from different angles (Wehner 1989).

The insects' compound eyes thus seem to be better suited to perceive polarized light than the vertebrate eye, and the question is then how higher animals can perceive polarized light. When we look up in the sky, we can see the sun and blue patches of sky, but most of us cannot see the e-vector of polarized skylight, and thus the information provided by the skylight polarization pattern. This is mainly due to the fact that we have ciliary photoreceptors (unlike insects that have rhabdomeric photoreceptors). Ciliary photoreceptors do not have the necessary ultrastructure and organization for polarized light reception (Roberts et al. 2011). Thus, the receptor mechanism for perceiving polarized light via ciliary photoreceptors remains one of the big mysteries in sensory biology for most vertebrates. An exception are some fish species, like e.g. anchovies that have axially oriented cone photoreceptors enabling them to distinguish linearly polarized light from different angles, or salmonids that have double cones specialized for polarization sensitivity (Flamarique et al. 1998, Kamermans and Hawryshyn 2011).

In birds, the perception of linearly polarized skylight is still under debate. In his pioneering work, Kenneth Able first demonstrated the importance of polarized light for migratory birds (Able 1982, 1989; Able and Able 1993) by analysing the specific role of polarized light cues in migratory orientation. However, most attempts to demonstrate polarized light sensitivity in birds in indoor settings have failed, mostly due to that carefully controlled conditioning and discrimination experiments are extremely difficult to carry out. One of the problems is the differential reflection of polarized light on surfaces which can lead to light intensity artefacts (for review see Muheim 2011). Two early conditioning experiments successfully demonstrated polarized light sensitivity in homing pigeons (Kreithen and Keeton 1974, Delius et al. 1976), but other studies failed to confirm these findings. Also, discrimination experiments with Japanese quails, *Coturnix coturnix japonica*, and European starlings, *Sturnus vulgaris*, were unsuccessful in demonstrating polarized light sensitivity in birds (Greenwood et al.

2003). Still, there is strong experimental evidence that migratory birds use information from the skylight polarization pattern to determine their departure direction and calibrate their compasses (see Åkesson et al., Chapter 9). However, the (putative) reception mechanism via which birds could perceive the pattern of polarized skylight remains a mystery. There are simply no obvious anatomical structures described in their eyes that could fulfil this job. The avian double cones have been proposed as polarized light receptors, since their orientation forms a cross pattern, with two opposite double cones facing each other, and the other two pointing away from each other (Young and Martin 1984, Cameron and Pugh 1991). However, it is unclear whether they could act as polarized light receptors, and therefore, more research will be necessary to behaviourally characterize and identify the photoreceptors mediating polarized light sensitivity in birds.

### 10.3 Future perspectives

During the past decade, research on the sensory mechanisms of animal orientation and navigation has become highly integrative and interdisciplinary. The field has progressed from the observation-based study of mainly behavioural aspects of orientation and navigation, to include biophysical, neuroanatomical, and molecular tools. The introduction of new techniques from various neighbouring disciplines has led to significant advances in our understanding of the sensory and cognitive mechanisms underlying animal orientation and navigation. Still, many open questions remain to be answered. Where are the magnetoreceptors located? How is the information processed in the brain? What is the neuronal basis of star compass orientation? Which brain areas are involved in processing celestial compass information from the sun, the stars, or polarized skylight cues? How do birds (and maybe other vertebrates as well) perceive polarized light cues and use this information for compass orientation? Given recent advances in technology and enhanced collaborative effort between disciplines, many of these questions will be addressed, and hopefully answered in the years to come.

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