

Long-distance navigation and magnetoreception in migratory animals

Henrik Mouritsen^{1,2*}

For centuries, humans have been fascinated by how migratory animals find their way over thousands of kilometres. Here, I review the mechanisms used in animal orientation and navigation with a particular focus on long-distance migrants and magnetoreception. I contend that any long-distance navigational task consists of three phases and that no single cue or mechanism will enable animals to navigate with pinpoint accuracy over thousands of kilometres. Multiscale and multisensory cue integration in the brain is needed. I conclude by raising twenty important mechanistic questions related to long-distance animal navigation that should be solved over the next twenty years.

Each year, billions of small songbirds (Fig. 1a), with ‘birdbrains’ weighing only a few grams, leave their Arctic and temperate breeding areas to overwinter in the tropics and subtropics. Most migrate at night, and young birds do so without regular contact with experienced individuals. Thus, their navigational capabilities must be innate or learned before their first departure^{1–5}. After having completed one round trip, many adult birds are able to navigate with an ultimate precision of centimetres over distances of 5,000 km or more⁶. Other impressive navigational tasks mastered by birds include bar-tailed godwits (*Limosa lapponica*, Fig. 1b) migrating from Alaska to New Zealand in a single non-stop flight lasting 7–9 days and nights⁷, arctic terns (*Sterna paradisaea*) breeding around the North Pole and wintering around the South Pole⁸, and seabirds (Fig. 1c) flying more than 100,000 km per year to return to tiny islands in the middle of vast oceans to breed^{9,10}.

Even insects with much simpler brains than birds are capable of performing impressive navigational tasks^{11–18}. In autumn, Monarch butterflies (*Danaus plexippus*, Fig. 1d) migrate from the USA and Canada to very specific overwintering trees in Mexico, up to 3,000 km away¹¹. A year later, the third-to-fifth-generation descendants of the previous year’s autumn migrants return to the exact same trees in Mexico¹¹. A similarly impressive return migration—but involving only a single generation—occurs in Southeast Australia, where millions of Bogong moths (*Agrotis infusa*, Fig. 1e) fill the night skies on their way to and from their yearly aestivation caves in the Snowy Mountains¹⁸. Recently, Chapman et al.^{17,19,20} demonstrated that directed long-distance return migrations are also widespread among high-flying insects. These movements of trillions of individual insects are critical for understanding both natural and man-made ecosystems²¹.

In the ocean, Salmonid fish (Fig. 1f) and sea turtles (Fig. 1g), for instance, return to their natal streams or beaches over thousands of kilometres^{22–25} and many dispersing coral reef fish larvae relocate their natal reefs after being at the mercy of sea currents for weeks^{26–28}.

To complete their long voyages, migratory animals have developed elaborate abilities to detect a variety of sensory cues, to integrate these signals within their nervous systems, and to use them as part of highly efficient navigational strategies^{1,3,4,10,17,29–32}. Navigation skills are also vitally important to non-migratory animals of almost any class^{1,13,14,33,34}. However, this review focuses primarily on long-distance navigation and homing. After discussion of the basic principles underlying these processes, I discuss how animals use, detect and process the main types of

navigation-relevant cue. I consider magnetic cues in more detail than other cues because the sensory mechanisms that underlie sight, olfaction and hearing are generally understood. By contrast, even though a lot of progress has been made recently, the mechanisms by which animals sense the geomagnetic field remains one of the most fundamentally important questions in sensory biology. I also highlight twenty of the most important outstanding mechanistic questions that remain to be answered (Box 1; denoted as ‘question 1’ and so on throughout the Review).

Studying navigation

Navigation and orientation

The terms ‘navigation’ and ‘orientation’ are used inconsistently in different fields. Here, ‘orientation’ means that only the direction of movement is being determined. To perform ‘true navigation’, animals need first to determine their location (map position) and then the compass direction to their goal^{3,31,35}. True navigators can correct for displacements during any phase of their journey^{3,31,35–37}. ‘Navigation’ is used for anything within the continuum between true navigation and pure compass orientation.

Maps and compasses

Map and compass information are often determined independently^{1,3,4,31}. To get a sense of direction, only a reference compass direction, such as magnetic and/or geographical North, needs to be determined, which an animal can then use to orient in any desired direction. Location can be determined in various ways. In some animals, location is defined relative to home^{1,13,14,34}, whereas many experienced migrants have developed large-scale, probably multisensory and multicoordinate maps, which can be extrapolated to correct for displacements, even at unfamiliar locations^{1,3,4,10,30,31,36–38}.

For instance, the angle of the celestial rotation centre above the horizon, geomagnetic field intensity, and geomagnetic inclination angle all gradually increase from south to north in most parts of the world^{11,3,30,38}. Thus, higher or lower values indicate displacement to the north or south, respectively. How long-distance migrants determine longitude (east–west position) is much less clear (question 19). Magnetic declination is an excellent east–west cue in some parts of the world, and experienced Eurasian reed warblers seem to use magnetic declination as part of their map³⁸. Because magnetic declination is the angular deviation between magnetic and geographical North, map and compass cues

¹Institut für Biologie und Umweltwissenschaften, Universität Oldenburg, Oldenburg, Germany. ²Research Centre for Neurosensory Sciences, University of Oldenburg, Oldenburg, Germany. e-mail: henrik.mouritsen@uol.de

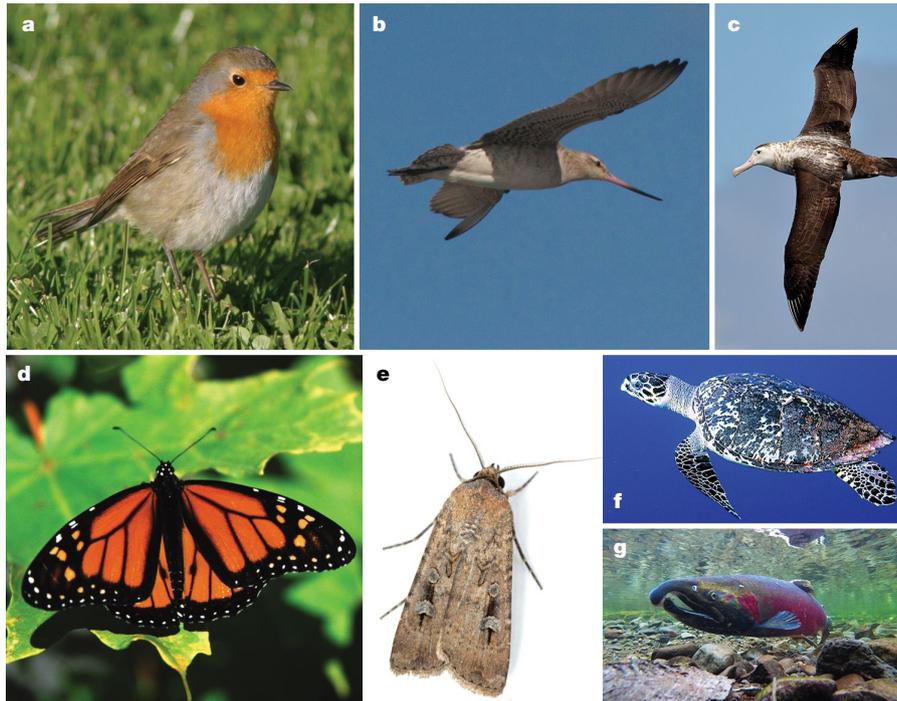


Fig. 1 | Some of the world's most famous long-distance navigators. **a**, European robin (*Erithacus rubecula*). **b**, Bar-tailed godwit (*Limosa lapponica*). **c**, Wandering albatross (*Diomedea exulans*). **d**, Monarch butterfly (*Danaus plexippus*). **e**, Bogong moth (*Agrotis infusa*). **f**, Sea turtle

(*Eretmochelys imbricata*). **g**, Salmon (*Oncorhynchus kisutch*). Photographs by H.M. (**a**, **b**, **d**); E. Dunens (**c**); A. Narendra (**e**); Adam (**f**); and the Bureau of Land Management Oregon and Washington (**g**). (**c**, **f**, **g**: <https://creativecommons.org/licenses/by/2.0/>).

might not always be as separable as previously thought. Experimental compass manipulations could also influence the map.

Experienced versus naïve animals

When studying long-distance navigation, it is important to consider whether animals are travelling for the first time. Animals such as migratory insects and coral reef fish larvae are always inexperienced migrants, as they complete only a single return journey or less^{11,18–20,39}. By contrast, most migratory birds and sea turtles make several similar journeys^{1,3,4,30,31}.

First-time migrants must use relatively simple orientation systems based on information inherited or learned before departure. Young night-migratory songbirds inherit their migratory direction and distance², but the genes underpinning this have not been identified⁴⁰ (question 16). Inexperienced migrants cannot have a detailed map of their migration route, but could have inherited simple cue values for the goal and/or a few 'signposts' and associated these with adaptive behaviours, such as the responses of hatchling sea turtles to magnetic parameters^{22,30,41}. Inexperienced bird migrants usually follow experienced companions or rely on a simple clock-and-compass strategy (vector navigation) using only an innate circannual clock and compass orientation programmes, but no map. They are therefore, except for a few emergency plans, unable to correct for geographical displacement^{3,4,31,36,38,42–45}. It remains unclear exactly which combination of sensory parameters triggers the start and stop of the first natural migration (question 17).

By contrast, many experienced migrants travelling for the second or later time have experienced cue gradients and generated a map that they can use to correct even for displacements to unknown locations. They can thus perform true navigation^{1,3,4,31,36–38,43,45–48}.

The three phases of a navigational task

Navigational cues that can be used over thousands of kilometres differ from those that are useful over a few kilometres, metres, or centimetres over time-scales of a few seconds, minutes or hours (Table 1). Furthermore, animals mostly use quite simple navigational strategies

that are good enough to solve the tasks needed for survival, but not 'perfect' mathematical solutions. Consequently, a succession of at least three different phases or stages is needed to account for the pinpoint accuracy of experienced long-distance migrants³² (Fig. 2). The three phases are: (1) a long-distance phase; (2) a narrowing-in or homing phase; and (3) a pinpointing-the-goal phase. To achieve a holistic understanding of animal navigation, all phases need to be understood, and a comparative approach is needed to evaluate whether species, groups or classes of animals use similar or different solutions.

The long-distance phase refers to navigation far away from the animal's home ranges and it usually relies on global or regionally stable cues such as celestial and/or geomagnetic information. Simple, compass-based, vector orientation relying on an inherited initial direction^{2,3,11,27,31} seems to be the only mechanism available to many inexperienced animals that travel without experienced companions^{2,3,27,31,36,39,42–44}. By contrast, experienced animals can often modify their compass headings on the basis of learned map information^{3,4,31,36–38,43,47–49}. During the narrowing-in or homing phase, in or near a familiar home range, learned local gradient maps that rely on a variety of senses and environmental cues are usually important^{1,10,32,34,39,49}. The pinpointing-the-goal phase is mostly based on remembering very specific visual landmarks and/or the odours of a specific location^{25,50,51}.

The three navigational phases seem quite universal. Night-migratory songbirds use mainly celestial and magnetic cues during the long-distance phase^{1,3,4,31,37,38}, a variety of learned, multisensory, local gradient maps during their homing phase^{1,32,49}, and visual landmarks to find their nest or sleeping perch during the pinpointing-the-goal phase³².

Monarch butterflies use a time-compensated sun compass during the long-distance phase^{12,52,53}. Monarchs do not like to cross large bodies of water (the Gulf of Mexico constrains movement towards the southeast) or to fly over high mountains (the Rocky Mountains limits them to the west). The resulting geographic funnelling effect brings the monarchs to within a couple of hundred kilometres of their wintering range³⁹. How the later parts of the narrowing-in and

Table 1 | Examples of typical cues that are relevant during the three phases of a long-distance navigational task.

| | Magnetic | Visual | Olfactory | Other |
|-------------------------------------|---|--|--|--|
| Long-distance phase | Horizontal direction; inclination angle; intensity; declination | Celestial cues related to the stars and sun; coastlines and major mountain ranges as physical constraints associated with simple response rules | Probably not useful far from familiar locations and on first time migratory journeys, probably useful at or near familiar routes | |
| Narrowing-in or homing phase | Horizontal direction; inclination and intensity down to a scale larger than 10–50 km; strong magnetic anomalies | Celestial cues; familiar leading lines (rivers, mountain ranges, coast lines, forest borders, roads, and so on); familiar beacons (specific forests, hills, lakes, buildings, and so on) | Natural olfactory gradients; olfactory 'landscapes' | Water depth; salinity; regional sound cues |
| Pinpointing-the-goal phase | Probably not useful as map cues on this scale | Very local familiar landmarks (for example, a specific tree, branch, or nest hole; a cave entrance; a small hill; a specific coral) | Local odours (for example, of home habitats or conspecifics) | Local sound cues; microclimate; waves; tidal flows |

If a long-distance navigational task is split into several legs with specific intermediate goals, the three phases could be repeated several times before reaching the final goal. For references, see main text.

pinpointing-the-goal phases work in these one-time migrants is currently unknown (question 20). The latter could be based on a combination of attraction to smells left by previous generations of conspecifics beaconing from the wintering trees and searching for the right microclimate and tree species.

Salmon might use an innate signpost 'map' coupled with adaptive compass responses similar to those of sea turtles²² to stay within a suitable oceanic range and to return as adults to the approximate location of the river mouth²³. At this point, their navigational strategy changes to one based mainly on chemical or olfactory cues, which they use to home in on the exact spawning ground where they were born^{25,54,55}. Coral reef fish larvae first seem to use an innate celestial and magnetic compass direction to relocate the vicinity of the reef^{27,28}, then olfactory²⁶ and/or auditory cues⁵⁶ to narrow in on the reef, and finally vision to locate a suitable microhabitat within the reef.

In summary, several cues are often used together during a phase, and the cues, brain-processing strategies, and behaviours involved vary substantially between phases in most cases. What determines when an animal switches from one navigational phase to the next, and how processing strategies in the nervous system transition between phases, remain exciting open questions (questions 10, 11, 18).

Owing to the three navigational phases, it is extraordinarily unlikely that a single sense or cue is used exclusively throughout a journey. One

consequence of this is that animals tested at the wrong location relative to where the relevant phase takes place in nature may not reveal their true abilities during that phase. Testing of animals during different phases or at wrong locations might explain some of the apparent contradictions in the long-distance navigation literature.

Magnetic cues and how they are sensed

The Earth's magnetic field, also called the geomagnetic field, is shaped as if a big bar magnet were placed at the centre of the Earth^{4,57}. The geomagnetic field provides omnipresent information, which can help animals to navigate. Magnetic direction (polarity) and/or inclination angle (the angle between the field lines and the Earth's surface) can be used to determine a favourable direction of movement^{1,4,57,58}. Total magnetic intensity, inclination angle, and magnetic declination can help animals to determine position^{1,4,22,30,38,41,48,57}.

Birds^{1,58,59}, sea turtles⁶⁰, fish²⁸ and amphibians⁶¹ can use magnetic polarity and/or inclination angle as a reference direction for a magnetic compass^{1,57}. Likewise, birds^{1,48,62}, sea turtles^{22,24,30,41}, fish²³ and amphibians⁴⁶ can use magnetic parameters to determine their position. By contrast, it is less clear whether long-distance migratory insects can use magnetic compass and/or map cues^{39,52,63}. As the geomagnetic field, on average, varies only by approximately 3 nT km^{-1} and $0.009^\circ \text{ km}^{-1}$ on the north–south axis and much less east–west, and owing to regular stochastic

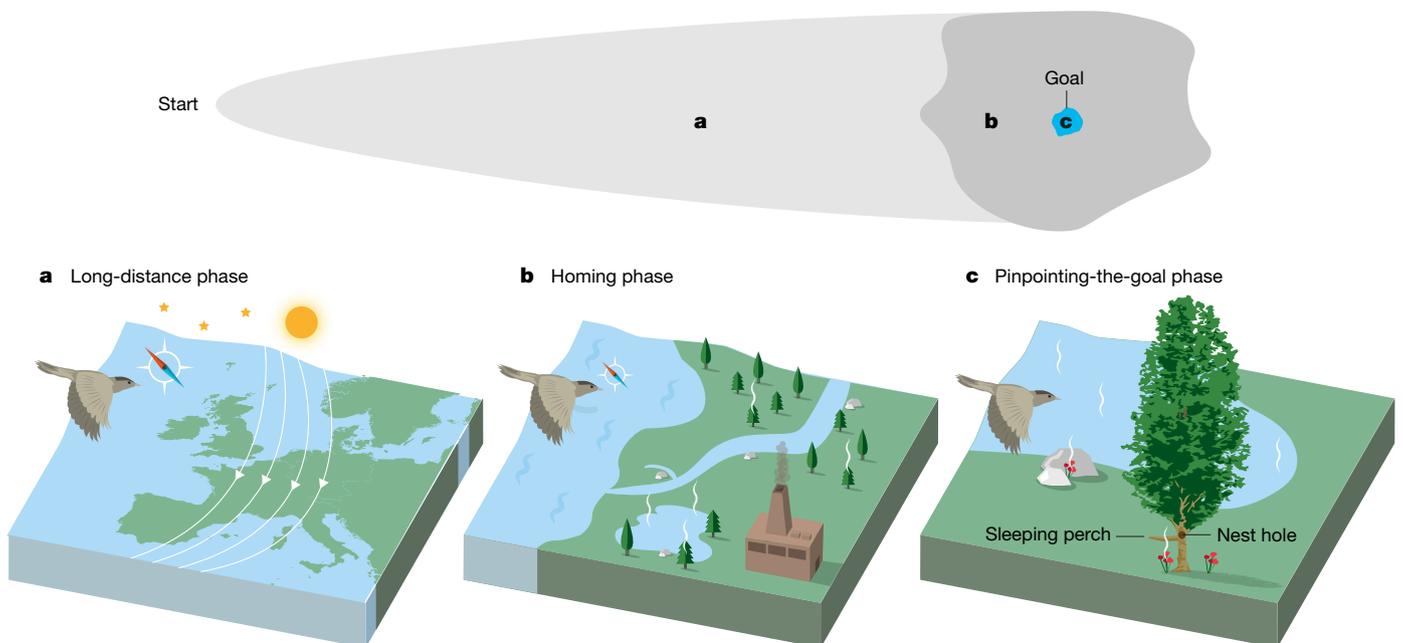


Fig. 2 | The three different phases of a long-distance navigational task and examples of the typical cues used. a, During the long-distance phase, celestial and magnetic compass and map cues are very important and landmarks such as coastlines can function as physical constraints. **b,** During the homing phase, compasses are usually still important and

regional map cues such as olfactory and visual landmarks, olfactory gradients, strong magnetic anomalies, and soundscapes become important. **c,** During the pinpointing-the-goal phase, specific within-habitat cues such as a cave entrance, a specific tree, or a smelly lake are needed to locate, for example, a nest hole or sleeping perch.

variations in the geomagnetic field of 30–100 nT in variable directions, it is hard to understand how a magnetic map could have an accuracy better than 10–30 km in fast-moving animals^{4,57,64}. Some newts and pigeons seem to be able to use a magnetic map over shorter distances^{46,62}. Unless the magnetic gradients are locally very steep and/or slowly moving animals improve resolution by averaging over many measurements, it remains to be understood how the magnetic spatial signal can be distinguished from temporal variability on a scale of less than 10–30 km (question 7). Thus, magnetic maps seem to be primarily relevant for the long-distance and/or far-distance homing phases, at least for fast-moving animals. Finally, a vast number of organisms, from magnetotactic bacteria⁶⁵ to mammals⁶⁶, align themselves with the magnetic field. Thus, many animals can detect and use the geomagnetic field for orientation and navigation, but how do they detect magnetic field parameters?

The geomagnetic field penetrates biological materials. Consequently, the primary sensors could be located anywhere inside an animal's body. Considering the anatomical constraints and known structures found within small animals, it is not obvious how biological materials can reliably detect the 25,000–65,000 nT geomagnetic field (questions 1–8) in the presence of thermal fluctuations (energy $\approx k_B T$ (Boltzmann's constant multiplied by the temperature in degrees Kelvin)) and other sources of noise^{67–72}. Only three mechanisms are currently considered to be physically viable: (1) induced electrical fields detected by highly sensitive electroreceptors; (2) magnetic-particle-based magnetoreception; and (3) radical-pair-based magnetoreception.

Electromagnetic induction

Electromagnetic induction is the production of voltage across an electrical conductor moving through a static magnetic field. A 'biological wire' occurs in elasmobranch fish (sharks, skates, and rays) in which highly conductive pores connect the electrosensitive ampullae of Lorenzini with seawater, which acts as reference potential (ground) against which induced voltages in the pores can be measured. However, it is not known whether these structures are used as magnetoreceptors⁷³. Here is a potentially exciting research area ready for someone to take a closer look at using modern methods (question 5). It is difficult to imagine how non-aquatic animals could use induction to sense the geomagnetic field. As air has low conductivity, large internal ring-shaped structures filled with conductive liquid would be needed⁷⁴, but no such structures have been reported. Thus, for terrestrial animals another mechanism must be responsible for magnetoreception^{57,67}.

Magnetic-particle-based magnetoreception

The discovery of magnetotactic bacteria, which build intracellular chains of magnetite (Fe_3O_4) particles (magnetosomes), demonstrates that organisms can synthesize magnetic crystals that could act as compass needles^{65,75}. Since the discovery of magnetotactic bacteria, magnetite and/or iron oxides have been detected in almost every animal carefully investigated^{76,77}. However, the mere presence of iron oxides, or even magnetite, does not indicate that such particles are relevant for magnetoreception^{57,71,78–81}. Iron homeostasis is important for organism function and iron oxides may just be a way for organisms to deposit excess iron^{57,78}. Only if magnetic particles are located inside cells at consistent and specific locations in many individuals of the same species and are associated with the nervous system (question 6) can the particles qualify as serious magnetosensory candidates^{57,71,78,79,81}.

Currently, the most promising magnetic-particle-based magnetoreceptor candidate structures are those described in the olfactory epithelium of fish^{80,82} (but see⁸¹). Iron-rich structures associated with the ophthalmic branch of the trigeminal nerve in birds were also thought to be magnetoreceptors⁸³. However, recent findings suggest that these structures are associated not with neurons but merely with macrophages⁷⁸. It has also been suggested that the avian lagena (a part of the bird vestibular system) plays a role in magnetoreception⁸⁴. Because mole rats, fish and sea turtles seem to use a magnetic polarity compass in complete darkness, it is most likely that they use magnetic-particle-based magnetoreception^{60,82,85,86}. If magnetic sensory particles

exist in higher animals, the magnetic signal would be expected to be transduced by opening or closing mechanosensitive ion channels^{67,76,87} (but see⁸⁸). Although the magnetite hypothesis is physically easy to explain⁷⁶, other suggested effects of magnetic fields, such as ion-gating by moving ferritin complexes^{89,90} and the MagR proposal of Qin et al.⁹¹, seem to be at odds with basic laws of physics^{69,72}. To sum up, although magnetic particles have been found in many animals, there exists no independently confirmed ultrastructural evidence for the in situ presence of bacteria-like magnetite chains in sensory structures of any insect or vertebrate^{57,78,79}.

Radical-pair-based magnetoreception

The radical-pair hypothesis suggests that the quantum mechanics of electron spins (questions 2, 3) could form the basis of a magnetic compass sense^{71,92–95}: a light-induced electron transfer reaction generates long-lived radical pairs, which can exist in singlet or triplet electronic spin-states. The coherent quantum mechanical interconversion between these two states is affected by the orientation of the sensor molecule relative to the geomagnetic field. This in turn affects the likelihood of forming a signalling state that could form the basis of a chemical magnetic compass sense that might enable birds to 'see' geomagnetic field parameters^{68,71,92,93,95,96}. Here I summarize the key points of radical-pair-based magnetoreception; for fuller details I recommend a recently published review⁷¹.

At first sight, a radical-pair compass seems implausible: the energetic interaction of the geomagnetic field (25–65 μT) with a single molecule is more than a million times smaller than the molecule's thermal energy, $k_B T$, under physiological conditions⁷¹. $k_B T$ is the energy associated with the ever-present random motions of molecules as they rotate, vibrate, and bump into one another⁷¹. Normally, a significant impact on the rate or yield of a chemical transformation is impossible unless the amount of energy supplied is at least comparable to $k_B T$. The tethering stone and fly analogy in Fig. 3 may help to explain why radical-pair reactions are different in this respect. Only when a system has previously been brought into an appropriate state far from equilibrium (the radical-pair state symbolized by the tethering stone), tiny interactions (the geomagnetic field symbolized by the fly) can have profound effects⁷¹ (for details, see legend to Fig. 3; for formal arguments, see the recent review⁷¹).

The radical-pair mechanism is unquestionably genuine. There have been hundreds of laboratory studies of radical-pair reactions on which 1–100-mT magnetic fields have an effect⁷¹, and a model compound has been shown to be sensitive to Earth-strength magnetic fields⁹⁴. However, it has not been demonstrated that this reaction scheme is responsible for animal magnetoreception⁷¹ (questions 1–3). However, a substantial amount of correlative evidence supports this idea.

The magnetic compass of birds is an inclination compass, which detects the angle between the magnetic field lines and gravity rather than the polarity of the field^{1,58,97}. The magnetic compass orientation of newts^{61,98} and birds⁹⁹ depends on the wavelengths of light that are available during behavioural tests. This wavelength-dependence suggests that the eyes and/or pineal organ are involved in the magnetic compass. In birds, the pineal organ is not needed¹⁰⁰, whereas pineal photoreceptor molecules seem to be essential for magnetic compass orientation in newts⁹⁸.

Furthermore, radiofrequency magnetic fields disrupt magnetic compass orientation in several animals^{71,101–106}. Radiofrequency fields can influence the spins of unpaired electrons in a radical pair and thus the probability of finding radical pairs in the singlet or triplet state⁷¹. To come back to the analogy shown in Fig. 3, it would be like exposing the granite block poised on its edge to a swarm of *Drosophila* hitting it from unpredictable and random directions before the bigger fly would get a chance to influence the fate of the block (Fig. 3c). By contrast, the radiofrequency fields are far too weak to break a chemical bond or physically move a magnetic particle.

A couple of cautionary notes: it has previously been predicted that time-dependent magnetic field effects should be specific to the Larmor frequency (the frequency with which electron spins precess in a plane

perpendicular to an external magnetic field if they are not influenced by any hyperfine interactions¹⁰². However, this prediction was based on several assumptions that are not true in any realistic biological molecule. A much broader band of frequencies should be disruptive to the magnetic compass^{71,107}, and indeed they are^{103,106}. Nevertheless, many studies have reported specific effects of exposing animals to Larmor-frequency fields. However, none of these studies provided measured broadband disturbance spectra. Therefore, substantial side bands and/or broadband background disturbances at other relevant frequencies might have occurred^{71,106}. Even though radical-pair theory predicts sensitivity to radiofrequency fields, it is still not understood why the bird's magnetic compass is so extraordinarily sensitive to disruptive anthropogenic electromagnetic fields^{71,107} (question 3).

What might be the identity of the light-dependent magnetic detectors (question 1)? Opsins cannot be radical-pair-based magnetoreceptors, because they use light energy to cause a conformational change and nowhere in their signalling cascade is a radical pair formed¹⁰⁸. Cryptochrome proteins are the only photoreceptor molecules known in vertebrates that use light energy to form long-lived radical pairs^{71,93,109,110}, and the radical-pair chemistry of cryptochromes have been shown to be magnetically sensitive^{71,110}. Because the radical pair in cryptochromes forms between the protein and its flavin co-factor, only cryptochromes with their flavin co-factor present can be magnetically sensitive. Four different cryptochromes have been located in the retinas of migratory birds^{71,91,111–116}, and whereas cryptochromes 1a, 1b, and 2 do not seem to bind flavin well¹¹⁷, cryptochrome 4 is a particularly attractive magnetosensory candidate because it binds flavin well^{91,116}. Furthermore, cryptochrome 4 is located in double cones, which are two cones attached to each other that look at the same location in space and thus get very similar light input^{71,116}. This should make it easier to separate magnetic field changes from light intensity and polarization changes^{71,116,118}. Behavioural evidence from genetically modified *Drosophila* also supported the involvement of cryptochromes in magnetic sensing^{119,120}, and theoretical studies of cryptochrome-like radical pairs have contributed much to our current understanding of how radical-pair-based magnetoreception could work^{68,70,71,95,96,107}.

Can light-dependent magnetoreceptors work at night (questions 1, 4)? Theoretically the answer is yes; some light is always present. Even humans can see well enough to walk on an open field on a moonless overcast night because our rod photoreceptor cells are activated by only a few photons¹⁰⁸. Light receptors responsible for light-dependent magnetoreception could also be activated by just a few photons. The key open questions are how the light-dependent magnetoreception mechanism collects sufficient reaction statistics to differentiate between magnetic directions under low light conditions, and how they separate changes in light intensity from magnetic field changes^{71,116,118} (question 4).

Finally, brain activation patterns and a lesion study in night-migratory songbirds have shown that magnetic compass information is processed in Cluster N, a specific part of the thalamofugal visual brain pathway^{121–124}. These findings strongly support the idea that light-dependent magnetoreception with primary detector molecules located in the eyes exists and that these birds perceive magnetic compass input as a visual cue^{71,121–124}. An earlier claim¹²⁵ that the magnetic compass is located only in the bird's right eye has turned out to be incorrect^{126–128}. Our knowledge about where in the brain magnetic information is processed in other animals is very sparse^{85,86} (question 8).

In summary, there is much evidence that the magnetic compasses of night-migratory songbirds (and probably other animals) rely on the spin-chemistry of radical-pair reactions. This could be fundamentally important because, if radical-pair-based magnetoreception is real, it would firmly establish the emerging field of quantum biology and thereby reduce by 6–7 orders of magnitude the threshold for sensory detection of weak stimuli in biological systems^{68,71}. To prove the existence of radical-pair-based magnetoreception, truly multidisciplinary collaborative approaches involving quantum physics, chemistry, computer simulation, and biochemistry in combination with molecular biology, neurobiology, and behavioural biology, will be needed (questions 1–4, 8).

Can animals have more than one magnetic sense?

Traditionally, many have considered the magnetoreception hypotheses described above as mutually exclusive. This must not be. In fact, I would expect the magnetic map and magnetic compass senses to have

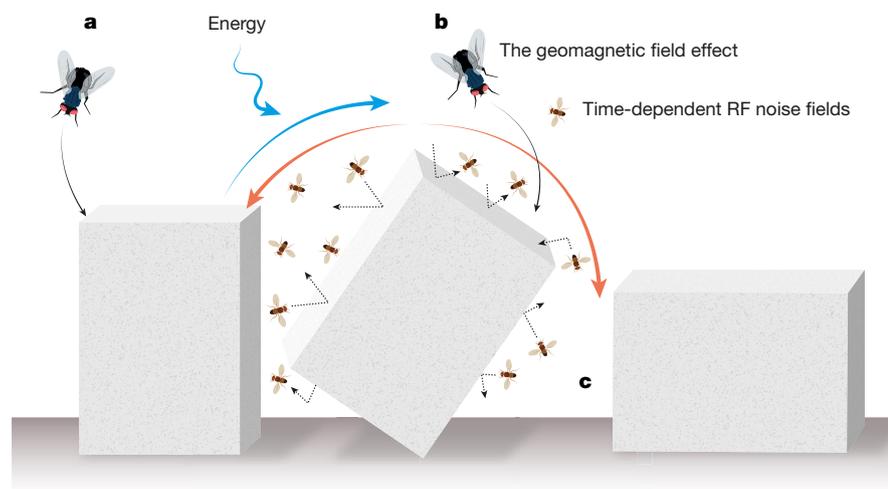


Fig. 3 | A mechanical analogy of the radical-pair mechanism. This analogy, originally designed by P. J. Hore, illustrates why a radical-pair reaction can be significantly affected by extremely small magnetic interactions. Imagine we have a heavy stone block at rest and ask whether a fly could tip it over (a). The answer, obviously, is no⁷¹. But suppose we have supplied the energy necessary to poise the stone on its sharp edge. Clearly, it would not be stable. It would very soon fall to the left or the right⁷¹. But what if a fly landed on its right-hand side while the block is teetering in this way (b)? Even though the energy imparted by the fly would be

minute, it could be enough to cause the block to fall to the right rather than the left⁷¹. Thus, tiny interactions can have profound effects, but only if a system has previously been brought into an appropriate state far from equilibrium⁷¹. In the context of radical-pair-based magnetoreception, the non-equilibrium state is the radical pair, the energy required to reach that state comes from a photon of light, and the fly is the static geomagnetic field⁷¹. Radiofrequency noise would be a bit like having a swarm of *Drosophila* (c) constantly bumping into the tethering stone block from all directions. Modified after ref. 71.

mutually distinct properties and mechanisms because a direction sensor should be insensitive to magnetic intensity and vice versa⁷¹.

Indeed, behavioural and brain activation data suggest that the magnetic compass of night-migratory songbirds is light-dependent and radical-pair-based^{93,99,101–103,106} and is processed in Cluster N^{121–124}. When Cluster N is lesioned, European robins can still use their sun compass and their star compass, but their magnetic compass no longer works¹²⁴.

By contrast, when the ophthalmic branch of the trigeminal nerve (V1) is cut bilaterally, night-migratory songbirds seem unable to compensate for displacements; that is, their map sense is disrupted^{147,48}, but their magnetic compass remains unaffected^{1,47,124}. Furthermore, magnetic field-dependent neuronal activation has been documented in hindbrain regions innervated by V1^{129,130}, and strong magnetic pulses, which should re-magnetize a magnetite-containing sensor, lead only to deflected headings in adult migratory birds that have established a map^{31,45,131}. Both types of sensor also seem to exist in amphibians^{33,61}, whereas there is evidence for a light-independent magnetoreceptor only in sea turtles and fish^{30,60}. In conclusion, radical-pair-based and magnetic-particle-based magnetoreception mechanisms seem to exist side by side in several animals and may provide animals with magnetic compass and map information, respectively.

Celestial cues and how they are sensed

Photoreceptor pigments in the eyes detect photons emitted from the sun and stars¹⁰⁸, which can be used for orientation and navigation. Virtually every animal tested can derive compass information from the sun^{12,14,27,59,132,133}. Night-migratory songbirds can also use the stars^{1,134}.

The sun compass and polarized light cues

The sun compass is learned and seems to rely only on the azimuthal direction of the sun¹³². To establish a sun compass that can be used for longer-distance orientation, young animals must observe and learn the path of the sun and must link the sun's azimuthal positions to their circadian clock^{14,15,132,135}. Animals can adapt their compass responses as the sun's movements change with the season^{27,136}.

The sun compass of many insects relies on detecting the polarized light pattern of the sky, which is generated when sunlight is scattered by molecules in the atmosphere^{14,15,135,137}. Even though monarch butterflies can detect polarized light cues¹³⁸, carefully controlled experiments found that, surprisingly, they seem to not use them for migratory orientation⁵². Whether vertebrates can detect polarized light remains unclear, with the best evidence for polarization vision coming from anchovies^{137,139}.

The visual brain pathways are known in many animals, but where celestial orientation and navigation-relevant cues are specifically processed in the brains of vertebrates is much less clear³². In insects, sun compass information in the form of polarized light is detected in the dorsal rim area of the compound eye^{14,16,53,138}. The information then passes through the medulla of the optic lobe¹⁴ on its way to the central complex in the brain, where neurons coding for the e-vector axis of polarized light have been found^{14,15,53,135}. Some central complex neurons in locusts even seem to represent matched filters to the natural polarization pattern, so that different cells respond to different orientations of the complete celestial polarization pattern across the dome of the sky¹⁵.

The star compass

The star compass of night-migratory songbirds must be learned¹³⁴. Night-migratory songbirds have no inherited knowledge of what the star patterns should look like. Instead, on the Northern Hemisphere, birds are born with the information to look for rotating light-dots in the sky and to interpret the centre of rotation as North^{134,140,141}. More than seven clear nights seem to be needed in order for birds to establish their star compass^{134,140,141}. Once this is established, birds learn the geometrical star patterns and thereafter no longer need to observe celestial rotation^{134,140,142}. One fascinating open question is how animals detect the very slow rotation of the stars (question 14). Birds can learn the concept of a rotational centre¹⁴³, but whether they actually see the slow rotation

or use a snapshot comparison mechanism remains unknown^{32,143}. It is unclear whether nocturnal arthropods have a star compass, but they can at least use night-time celestial cues as beacons¹⁴⁴.

Olfactory cues and how they are sensed

Olfactory cues are volatile chemicals in air or soluble chemicals in water that are detected by receptor proteins^{145,146}. The brain circuits responsible for olfaction in most vertebrates and many invertebrates are well understood¹⁴⁵.

Odours play a very important role in homing: for example, of fish^{25,26,54,55}, pigeons^{49,147} and experienced pelagic seabirds^{10,49,55}. Surprisingly, the ratios of several volatiles are highly stable within a 400 × 400-km² terrestrial area even across different seasons, and model pigeons could home using these ratios¹⁴⁸. Odour-based maps are probably gradient maps that provide information only about the direction of displacement⁴⁹. An inexperienced migrant cannot know how its destination thousands of kilometres away will smell. Thus, olfactory cues are likely to be most important during the homing and pinpointing-the-goal phases, but could also play a role during the long-distance phase in experienced navigators^{10,49}. Insects can also use olfactory cues for navigation, but mainly over shorter distances, for instance when locating nests¹⁴⁵ or mating partners¹⁴⁶.

Landmarks

Landmarks can in principle be detected by any sense, and animals can use visual, olfactory, magnetic, and/or auditory landmarks^{1,10,13,14,26,34,49,56,62,149}. Landmarks play an important role primarily during the last two phases of a navigational task (the homing and pinpointing-the-goal phases), but leading lines such as coastlines and mountain ranges can also be important as physical constraints during the long-distance phase^{1,10,13,14,26,34,39,49,56,149}.

Other cues

Some animals, such as charcoal beetles (*Melanophila* species), use infrared radiation (heat) detection to orient towards fires¹⁵⁰. It has also been suggested that various animals can use very long-waved 'infrasound' to home¹⁵¹. It is, however, difficult to understand how animals with head sizes much smaller than the wavelength of infrasound could extract the needed directional information.

In addition to traditional navigational cues, some aerial and aquatic migrants should also consider the speed and direction of the currents in which they are moving^{17,19,20}. Migratory insects are exquisitely adapted for choosing the most suitable days or nights and airstreams to optimize wind assistance in the preferred direction^{20,29}. By doing so, they reach migration efficiencies that match those of migratory birds, even though their flight speeds are at least three times slower²⁹. However, detection of the direction of flow by insects when they are embedded in it is not a trivial problem (question 15). Insects seem to detect micro-turbulence cues around their bodies and use these to detect flow direction¹⁵². Why can birds apparently not select favourable airflow layers as efficiently as insects^{20,29}? I suspect that, in addition to their size¹⁵², their feather coating probably prevents micro-turbulence cues from reaching the somatosensory sensors in their skin, thereby preventing detection.

Multisensory input

Evolutionary advantage of multisensory input

Traditionally, many studies aimed to show that one specific cue was used exclusively for navigation, and this focus has led to many apparent controversies and contradictions. Furthermore, many kinds of calibrations from one cue to another have been demonstrated^{1,153,154}. In my opinion, there is no universally valid cue, single strategy, or fixed cue hierarchy that would enable 100% accurate navigation during all phases and in all situations. This view is strongly supported by a recent review, in which the authors attempted to route-fit single navigation mechanisms to tracking data from many free-flying migratory birds¹⁵⁴. The authors concluded that no model exists that would fit all the data¹⁵⁴. The relative cue importance seems to vary between species and phases

Box 1

Important open mechanistic questions

The questions listed below represent some of the most important open mechanistic questions for the next two decades of long-distance navigation and magnetoreception research.

1. How do the magnetic senses work on the biophysical, biochemical, and molecular levels?
2. Does quantum biology exist (that is, is magnetic sensing truly quantum in at least some animals)?
3. What are the explanation for and ecological consequences of the extraordinary sensitivity of the bird's magnetic compass to disruptive anthropogenic electromagnetic fields?
4. How does the light-dependent magnetoreception mechanism distinguish between changes in light intensity and magnetic direction, and how does it collect enough reaction statistics to detect magnetic directions under low light conditions?
5. Do some animals use electromagnetic induction to detect the geomagnetic field?
6. Do magnetic particles exist inside cells at consistent and specific locations in many individuals of any migratory animal, and are the particles associated with the nervous system?
7. How, if at all, can slow-moving animals distinguish the spatial magnetic signal from temporal geomagnetic field variation to allow for a magnetic map with a resolution below 10–30 km?
8. Where and how is magnetic information sensed and processed?
9. Where in the brain, and how, is multisensory navigational information integrated and weighted?
10. How do processing strategies in the nervous system transition between the different phases?
11. How does the brain deal with conflicting and/or incomplete information, and does this depend on the ecological conditions and/or the navigational phase?
12. Do place and grid cell equivalents exist as neural correlates of the map over scales of kilometres or even thousands of kilometres, and, if yes, which cues contribute to their establishment?
13. Do equivalents of head direction cells exist that code for celestial and/or magnetic compass direction on a regional or global scale?
14. How is the very slow rotation of the stars detected?
15. How do small animals moving in air or water detect the direction of flow even though they are embedded in the flowing medium themselves?
16. Which genes trigger migration behaviour and/or code for migratory direction and distance?
17. Exactly what cues signal to an animal that it should start migrating or that it has reached its destination and should terminate migration?
18. What determines when an animal switches from one navigational phase to the next?
19. How is longitude (east–west) position determined on a regional or even global scale?
20. How does the pinpointing-the-goal phase work in a monarch butterfly or Bogong moth, which can pinpoint their very specific wintering locations even though they have never been there before?

and with ecological context^{1,59,153–155} (question 11). This is not very surprising, as animals that can use several navigation strategies and integrate information from all potentially relevant cues will be more versatile and therefore have a long-term evolutionary advantage over animals that use only a single strategy and cue. Understanding multisensory integration in the animals' brain will thus be key to understanding animal navigation.

Multisensory cue integration in the brain

In birds, the hippocampus and the caudolateral nidopallium (NCL), which receive input from all sensory modalities, could be involved in multisensory integration, in the weighting of navigational cues, and/or in deciding to fly in a particular direction at any given moment in time³². In insects, the integration of multisensory navigational cues and decision-making is most likely to happen in the central complex¹⁶.

Once the integrative centres in the brain have been identified (question 9), we can investigate how animals estimate the reliability of each navigational cue, how animals use these estimates, and whether animals take an estimated-reliability-weighted average or use a winner-takes-all strategy (question 9). Maybe cues that are estimated to be less reliable than a certain threshold will be ignored completely. Consequently, unclear or unnatural stimuli provided during a scientific experiment might be ignored, even if an animal could in principle sense them. For instance¹⁰⁷, if anthropogenic radiofrequency fields, a source of noise not present until about 100 years ago, add noise to the perception of magnetic fields, magnetic cues could be ignored even though the noise is not strong enough to entirely mask the static geomagnetic signal (question 13).

Neural representations of map and compass

The rodent hippocampus contains place cells, which define a specific location within a small arena, and head direction cells, which represent the animal's current heading⁵⁰. Furthermore, the entorhinal cortex contains grid cells, which fire at node-points in a repetitive triangular array covering the entire available surface¹⁵⁶. Grid cells might define distances^{50,156}. These fascinating cell types are highly likely to be neural representations of location and direction during the pinpointing-the-goal phase, as these cell types are established relative to prominent local landmarks^{50,156}. In contrast to the extensive knowledge about short-distance navigation in rats, mice, and fruit bats, very little is known about long-distance navigation mechanisms in mammals. Do similar cell types exist that define direction (compass information) and location (map information) during the homing and long-distance phases of a navigational task (question 12)? If so, their responses would need to be established relative to global cues such as celestial bodies or the geomagnetic field (question 13), because long-distance migrants and homing animals can determine direction and location in unfamiliar places. Furthermore, during the pinpointing-the-goal phase, the spatial coding cells of many animals will need to define three-dimensional space. Recently, place, grid, head, and goal direction cells defined in three-dimensional space were found in flying Egyptian fruit bats^{50,51}. Compass neurons also exist in the central complex of migratory insects (see above). Map concepts—let alone map neurons—are very controversial among insect researchers^{13,14,157}.

Key open questions for the next two decades

Despite substantial advances in our understanding of long-distance animal navigation and magnetoreception over the last two decades, many fascinating questions remain unanswered. The twenty questions in Box 1 are a summary of the most important mechanistic questions that arose from preparing this review (their order does not indicate relative importance). To answer many of them, a long-term collaborative effort combining new multidisciplinary approaches from quantum mechanics and biophysics, via molecular biology, biochemistry, neurobiology, and genetics all the way to perception and behaviour of the intact animal will be required. These will be exciting times in the field.

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