

COMMENTARY

Neuronal circuits and the magnetic sense: central questions

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ABSTRACT

Magnetoreception is the ability to sense the Earth's magnetic field, which is used for orientation and navigation. Behavioural experiments have shown that it is employed by many species across all vertebrate classes; however, our understanding of how magnetic information is processed and integrated within the central nervous system is limited. In this Commentary, we review the progress in birds and rodents, highlighting the role of the vestibular and trigeminal systems as well as that of the hippocampus. We reflect on the strengths and weaknesses of the methodologies currently at our disposal, the utility of emerging technologies and identify questions that we feel are critical for the advancement of the field. We expect that magnetic circuits are likely to share anatomical motifs with other senses, which culminates in the formation of spatial maps in telencephalic areas of the brain. Specifically, we predict the existence of spatial cells that encode defined components of the Earth's magnetic field.

KEY WORDS: Navigation, Brain, Magnetic orientation, Sensory representation

Introduction

Animals navigate over geographically diverse terrain, guided in part by magnetic stimuli. The Earth's magnetic field is a dipole with three components: (1) a declination, (2) an intensity and (3) an inclination. The declination of the vector reflects the cardinal compass directions (N, S, E, W) and refers to the angle of the magnetic field lines with respect to true geographic North (Fig. 1A). The intensity of the field is reflected by the density of the field lines and varies dependent on the local geographic environment and the latitude, varying between ~30 and 60 microtesla (μT). The inclination of the magnetic field is the angle between the magnetic field vector and the surface of the planet, varying from ~90 deg at the magnetic poles to ~0 deg at the magnetic equator. Behavioural data in birds, rodents, fish and reptiles indicate that migrating animals use a combination of these parameters to determine their heading and/or location (Kishkinev et al., 2013). The mechanism by which animals detect magnetic fields is unknown, but is believed to rely on: (1) the formation of radical pairs, (2) intracellular magnetite and/or (3) electromagnetic induction. The radical pair theory hypothesises that light induces the formation of radical pairs, and that the spin state of these electrons is influenced by the local magnetic environment, which in turn influences the biochemical properties of a molecular sensor (Hore and Mouritsen,

2016). In contrast, the magnetite theory predicts the existence of an intracellular compass made of the iron oxide magnetite (Fe_3O_4), which is coupled to a mechanosensitive channel, enabling modulation of neuronal activity (Shaw et al., 2015; Winklhofer and Kirschvink, 2010). Finally, it is conceivable that magnetoreception relies on the movement of the animal through the magnetic field, which induces a small current within a conductive circuit that is detected by an electroreceptor (Viguier, 1882; Jungerman and Rosenblum, 1980). Current evidence supports the existence of both a light-dependent compass and a 'dark' sensor (Nordmann et al., 2017). For example, it has been shown that European robins possess an inclination compass that is dependent on the presence of blue-green light (Wiltschko and Wiltschko, 1972; Wiltschko and Wiltschko, 2001), whereas in pigeons, magnetically induced neuronal activation within the brain does not require the presence of light (Nimpf et al., 2019; Wu and Dickman, 2011). It is conceivable that a single species may employ more than one mechanism, enabling the detection of different components of the magnetic field depending on the available light. In many animals the utilisation of magnetic information appears to be highly plastic, whereas in others there appears to be a preference for defined magnetic conditions. This is reflected by a series of studies which have shown that some species, such as mole rats, tend to build their nests in a consistent orientation relative to the geomagnetic field (Kimchi and Terkel, 2001). Similarly, the termites *Amitermes meridionalis*, build flattened oblique mounds at a defined angle (10 deg geographic East) to the Earth's magnetic vector (Jacklyn and Munro, 2002). Astonishingly, naive Chinook salmon and loggerhead turtles alter their swimming direction in response to distinct geographically relevant magnetic stimuli (Putman et al., 2014; Lohmann et al., 2001) (Fig. 1B–D). Collectively, these studies suggest that animals possess genetically encoded neuronal circuits that process magnetic information.

Central representation of sensory information

The neuronal circuitry of most sensory systems shares a common architecture. A specific set of brain nuclei is dedicated to the processing of primary stimulus properties, another set to multimodal integration and higher processing and, ultimately, a different population of neurons coordinates the motor output. If we take the avian auditory sense as an example, sound is first transduced from a mechanical stimulus to a neuronal response by sensory hair cells. This activates secondary ascending neurons in the cochlear nerve that project to the cochlear nucleus angularis and magnocellularis, which are the primary auditory processing centers in the brainstem (Carr and Code, 2000). From here, the information distributes across several brain regions, including the superior olive, lemniscal nuclei and the torus semicircularis, with each region along the auditory pathway fulfilling a specific processing task. Brainstem nuclei encode stimulus properties such as pitch or intensity and time differences between the inputs at both ears (Carr and Konishi, 1990). Midbrain areas place the stimulus into a spatial context and integrate it with other sensory modalities before higher/cortical processing areas initiate a

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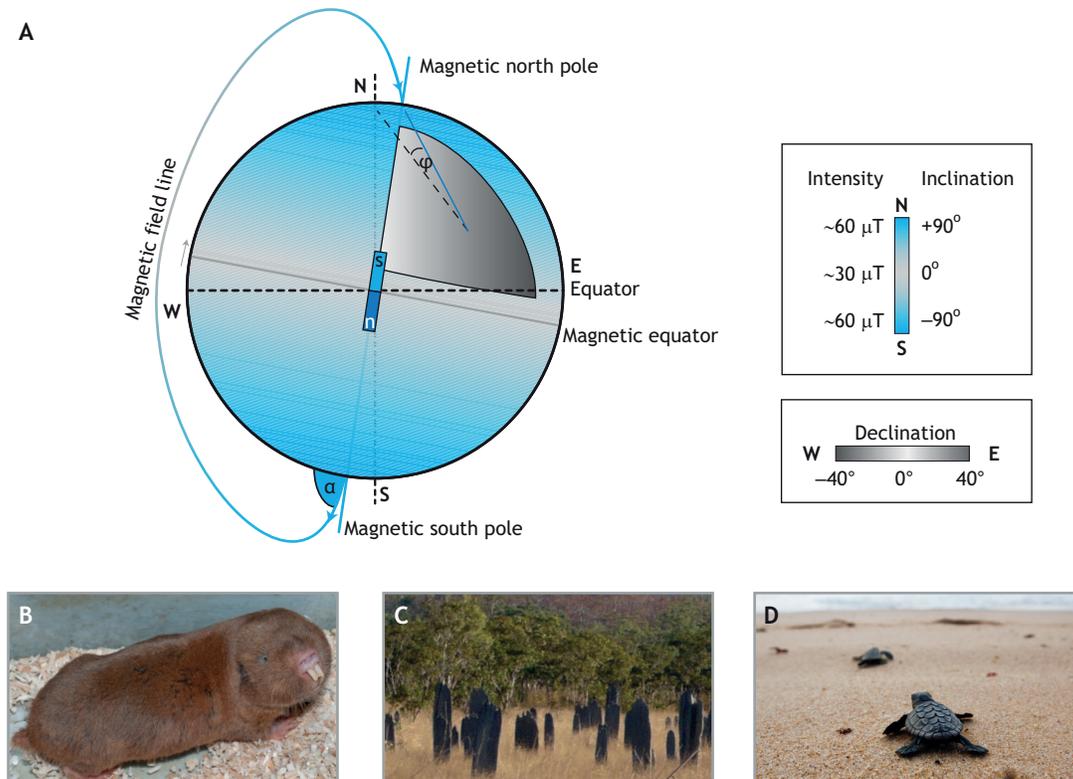


Fig. 1. Orientation using the Earth's magnetic field. (A) The components of the Earth's magnetic field that animals use for orientation include the declination, the inclination and the intensity. The declination (φ) varies with the animal's orientation with respect to the geographical north, and the inclination (α) is dependent on the latitude of the animal. The intensity of the magnetic field varies (60–30 μ T) with the latitude of the animal and with local geographic features. (B–D) Animals that show innate magnetic orientation behaviour include (B) Ansell's mole-rat (*Fukomys anselli*), (C) magnetic termites (*Amitermes meridionalis*) and (D) loggerhead turtle hatchlings (*Caretta caretta*).

corresponding motor response based on the motivational state and previous experience of the animal (Casseday et al., 2002). We expect that an analogous circuit exists for the processing of magnetic stimuli.

Methods for studying magnetosensitive neuronal circuits

Historically, the study of neuronal circuits has been dominated by two methodologies: (1) the assessment of immediate early gene (IEG) expression and (2) electrophysiology. IEGs are rapidly and transiently expressed in neurons in response to sensory activation, neuronal depolarization or neurotransmitter release (Hughes and Dragunow, 1995; Herrera and Robertson, 1996). They include transcriptional factors, such as c-fos, ZENK/EGR-1, Jun-D, fra-1, fos-B and jun-D, or cellular effectors, such as Rps6, Arc, pERK and Homer1a (Sauvage et al., 2019). The transcription factor c-fos is perhaps the most widely-used IEG, despite the fact that its exact function is still not well understood (Sambucetti and Curran, 1986). In general, the experimental design requires the exposure of an animal to a stimulus of interest for a period of time, followed by its sacrifice. Histological or molecular methods are then employed to quantify the levels of IEGs in specific brain areas. This approach has been used effectively to define the function and connectivity of neurons associated with vocal communication in songbirds (Jarvis et al., 2000; Liu and Nottebohm, 2005; Jarvis et al., 1995), chemosensation in rodents (Matsuoka et al., 1999; Dudley and Moss, 1999; Fernandez-Fewell and Meredith, 1994) and paternal behaviour in sticklebacks (Kent and Bell, 2018). There are two primary limitations of IEG analysis. First, not all neurons express IEGs in a stimulus-dependent manner, which can lead to false negatives (Nordmann et al., 2020). Second, most IEGs rely on transcriptional activation, and therefore provide limited temporal

resolution (Sheng and Greenberg, 1990). These issues do not arise with electrophysiology, which has long been considered the gold standard to study the properties of neurons and permits the systematic dissection of a neuronal circuit. Initially, experiments recorded signals from a single neuron; however, with the advent of microelectrode arrays (MEAs) and silicon probes, it is now possible to record from thousands of neurons simultaneously while exposing the animal to the stimulus of interest (Fiscella et al., 2012; Ulyanova et al., 2019). Studying the magnetic sense using electrophysiological methods requires great care as the stimulus itself may result in electromagnetic induction within the electrodes, compromising an investigator's ability to distinguish between a physiological response and an artefact.

Magnetoreceptive circuits in birds

To date, IEG and electrophysiological studies in birds have focused on four regions involved in the processing of magnetic stimuli: the vestibular nuclei, the trigeminal nuclei, Cluster N in the visual Wulst and the hippocampus (Fig. 2).

The vestibular nuclei

The primary vestibular nuclei include the superior (VeS), dorsal lateral (VeLd), ventral lateral (VeLv), medial (VeM), descending (VeD) and tangential nuclei (VeT) (Karten and Hodos, 1967). Afferents originating from the semicircular canals terminate in the medial parts of VeM and VeS, in contrast to neurons from the saccule, utricle and lagena, which project to lateral regions of the vestibular nuclei (Dickman and Fang, 1996). Neurons located in the vestibular nuclei project to the dorsal thalamic nuclei (DTh), which is connected to the visual Wulst and hippocampus, integrating vestibular, visual and spatial

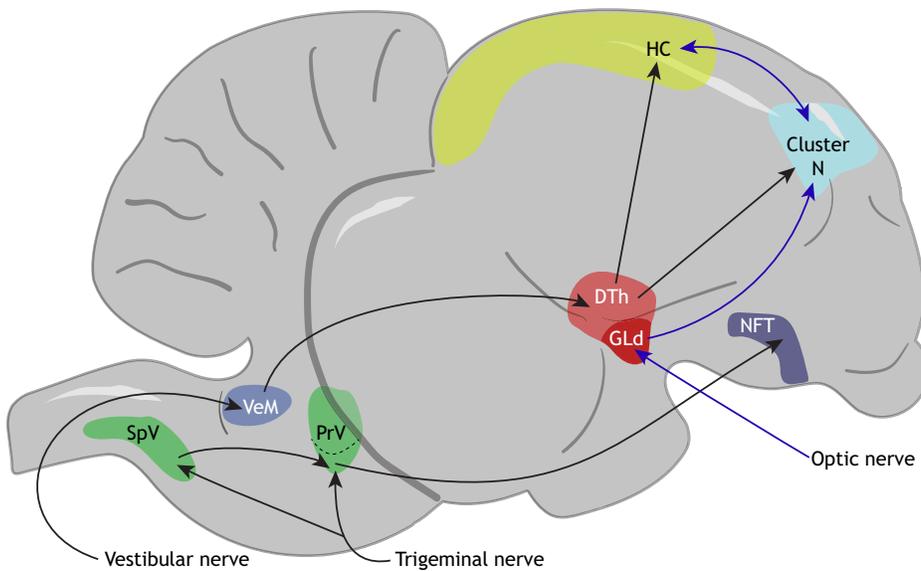


Fig. 2. Brain regions that process magnetic information in birds. In birds, magnetic stimuli have been reported to activate neurons in the medial vestibular (VeM), the principal trigeminal (PrV) and spinal trigeminal (SpV) nuclei. In the diencephalon, activation has been reported in the dorsal thalamus (DTh), the dorsal lateral geniculate nucleus (GLd) and in the telencephalon in Cluster N and the hippocampus (HC). Neurons from the PrV project to the frontal nidopallium (NFT). The arrows depict candidate circuits for a 'dark' (black arrows) and 'light' (blue arrows) magnetic sense based on known interconnections between the brain regions.

information (Vollrath and Delius, 1976; Montagnese et al., 2003; Heyers et al., 2007). Employing *c-fos* as an activity marker, the Dickman laboratory has shown that the VeM and VeD are significantly activated when awake, head-fixed pigeons are exposed to artificial rotating magnetic fields between 50 μ T and 150 μ T (Wu and Dickman, 2011). Critically, we have independently replicated this vestibular activation employing blind quantification (Nimpf et al., 2019). Consistent with the results from the Dickman lab, we found that light is not necessary for magnetically induced activation within the caudal VeM, suggesting that the primary sensors for magnetoreception reside within the inner ear and are reliant on either magnetite or electromagnetic induction. Building on their initial study, the Dickman laboratory employed electrophysiological methods, recording signals from neurons within the VeM while exposing animals to a rotating magnetic stimulus (Wu and Dickman, 2012). This resulted in the identification of neurons within the VeM that responded to distinct vectors of the magnetic field. On the basis of this work it has been proposed that the vestibular nuclei serve as a primary processing centre for magnetic information (Wu and Dickman, 2012; Nimpf et al., 2019).

The trigeminal nuclei

The trigeminal nuclei include the spinal sensory (SpV) and the principal nucleus (PrV) which has dorsal (PrVd) and ventral compartments (PrVv). The SpV and PrVd contain neurons that project to the nucleus basorostralis (NB) via the quintofrontal tract (Wild et al., 1984; Wild and Farabaugh, 1996). In Eurasian blackcaps it has recently been shown that neurons from the PrVv project to the frontal nidopallium (NFT) (Kobylkov et al., 2020). The studies implicating the trigeminal system in the processing of magnetic information have primarily relied on behavioural phenotyping and IEGs. Heyers and colleagues have reported an increased expression of ZENK in the PrV and the medial SpV in response to magnetic stimuli in European robins, which is dependent on the integrity of the ophthalmic branch (V1) of the trigeminal nerve (Heyers et al., 2010). They reported similar results when employing the pigeon and the northern wheatear as model systems, again observing an increase in the density of ZENK-positive neurons in the PrV and medial SpV when non-head-fixed birds were exposed to a changing magnetic field (Lefeldt et al., 2014; Elbers et al., 2017). The involvement of the trigeminal system

in magnetosensation is further supported by behavioural studies which have shown that an intact trigeminal nerve is required to condition pigeons to magnetic stimuli (Mora et al., 2004) and to form magnetic maps in migratory birds (Pakhomov et al., 2018).

Cluster N

Cluster N is part of the visual Wulst and is located in the medio-dorso-rostral telencephalon in birds. It was initially identified by Mouritsen and colleagues, who reported that this region exhibits increased ZENK and *c-fos* expression during night-time migration in garden warblers and European robins (Mouritsen et al., 2005). In a strikingly elegant study, they further demonstrated that chemically induced bilateral lesions to Cluster N perturbed magnetic compass-guided behaviour in European robins, but not their orientation in a planetarium, which relies on stellar cues (Zapka et al., 2009). These data suggest that Cluster N is part of a circuit processing light-dependent magnetic compass information. Neuronal tracing experiments have shown that it is connected to the retina via the thalamofugal pathway, which is one of two ascending visual projection pathways in birds (Heyers et al., 2007). The thalamofugal pathway includes retinal afferents, which terminate in the thalamic nucleus geniculatus lateralis pars dorsalis (GLd), and secondary neurons that project ipsilaterally and contralaterally to the visual Wulst (Karten and Nauta, 1968). Neurons in the visual Wulst project to a multitude of forebrain regions, such as nidopallial and striatal areas, and the avian hippocampus (Atoji and Wild, 2012).

Hippocampus

The hippocampus is located dorsally in the avian brain and, like its mammalian homologue, is thought to play a critical role in spatial cognition and memory consolidation. In contrast to rodents, the avian hippocampus lacks a defined laminar structure with a distinct pyramidal cell layer and dentate gyrus. Its structure has been divided in a modular fashion into a ventrally located, V-shaped structure, a dorso-medial and a dorso-lateral region. Although drawing direct anatomical comparisons is problematic, the dorso-medial regions are considered to mirror the mammalian CA regions and subiculum, whereas ventral regions share some similarities with the dentate gyrus and dorso-lateral regions with the entorhinal cortex (Atoji and Wild, 2006; Atoji and Wild, 2004). These subregions of the hippocampus are connected internally via a circuit that mirrors the

tri-synaptic connectivity described in mammals (Witter et al., 2014). Projections from the hippocampus extend to the area parahippocampalis, visual Wulst, the dorsolateral nucleus in the thalamus and the locus coeruleus (Casini et al., 1986; Kahn et al., 2003). Behavioural studies have shown that hippocampal lesions impair homing ability when pigeons are released in regions close to their lofts, where they make use of familiar landmarks to return home (Bingman et al., 1988; Bingman and Mench, 1990). To date, few studies have specifically explored the role of the avian hippocampus in processing magnetic information. Dickman and colleagues have reported that rotating magnetic stimuli (50–150 μT) led to an increase in c-fos staining in the hippocampus in head-fixed birds (Wu and Dickman, 2011). This work is supported by the work of Keary and Bischof, who reported that the rostral dorsomedial hippocampus was activated in response to a rotating magnetic field (42 μT) in zebra finches (Keary and Bischof, 2012). Finally, Bingman and colleagues employed electrophysiological methods to survey the hippocampus of freely moving pigeons for magnetosensitive cells. They reported the identification of three neurons (out of 44), that responded to magnetic field changes, with each cell responding in a different manner (Vargas et al., 2006). Given the plethora of cell types that encode spatial information in vertebrate species (e.g. grid, place and head direction cells), it will be of great interest to identify and characterise magnetosensitive cells in the avian hippocampus in detail (Jeffery, 2018; Taube et al., 1990), particularly in light of the recent discovery of head direction cells in the Japanese quail (Ben-Yishay et al., 2020preprint). It is conceivable that specific cells or neuronal ensembles exist that are responsive to defined declinations, inclinations or intensity changes.

Magnetoreceptive circuits in rodents

Our understanding of the magnetic sense in mammals is limited, particularly with respect to its neuronal correlates (Begall et al., 2014). Early studies employing electrophysiology reported responses to directional changes in magnetic stimuli in the pineal gland and retina of guinea pigs, hamsters and rats (Olcese, 1990); however, these were most likely artefacts arising from currents induced by the rapid switching of the magnetic coils (Lerchl et al., 1991). The first solid and reproducible evidence for a magnetic compass sense in mammals was in African mole-rats, rodents that live in underground tunnel systems in complete darkness (Burda

et al., 1990; Oliveriusová et al., 2012). IEG analysis in mole-rats following magnetic exposure in open-field experiments have implicated the superior colliculus and the hippocampus in the processing of magnetic information (Fig. 3).

Superior colliculus

In rodents, the superior colliculus is dorsally located in the midbrain and plays an important role in multisensory integration and the control of gaze movements (King, 2004). It is a layered structure, consisting of three superficial, two intermediate and two deep layers (May, 2006). The superficial layers mainly receive retinal afferents, whereas the intermediate and deep layers are multimodal, receiving afferents from the trigeminal and auditory systems. Němec and colleagues (2001) allowed Ansell's mole-rats (*Fukomys anselli*) to explore an unfamiliar arena in the presence (field strength 46 μT) or absence (residual 0.3 μT) of a magnetic field and compared c-fos expression in the superior colliculus. They found a significant upregulation of c-fos in the presence of the magnetic field, predominantly in the medio-rostral part of the intermediate gray layer, which receives input from the brainstem principal and spinal trigeminal nuclei in other rodents (May, 2006). Periodic changes in the direction of the magnetic field led to a more widespread activation than a static field of similar intensity, which led the authors to suggest that, similar to other sensory modalities, the magnetic sense is topographically represented within the superior colliculus (Němec et al., 2001).

Hippocampus and adjacent areas

In rodents, the hippocampus is a centrally located laminar brain structure involved in learning and memory formation (Jeffery, 2018). It is part of a navigation circuit that encompasses multiple anatomical structures that contain neurons with spatial firing properties. Spatial neurons are found in large numbers in the hippocampal formation and include place cells (PC), which fire when an animal occupies a specific position in an environment, grid cells (GC), which fire at many locations that form a regular hexagonal pattern, and head direction cells (HDC), which fire when an animal is heading towards a specific direction independent of location (Moser et al., 2008; Taube, 2007). Burger and colleagues screened 18 brain regions in the Ansell's mole-rat brain for differential c-fos expression in animals that had explored an arena in the presence of a static Earth-strength, changing or shielded

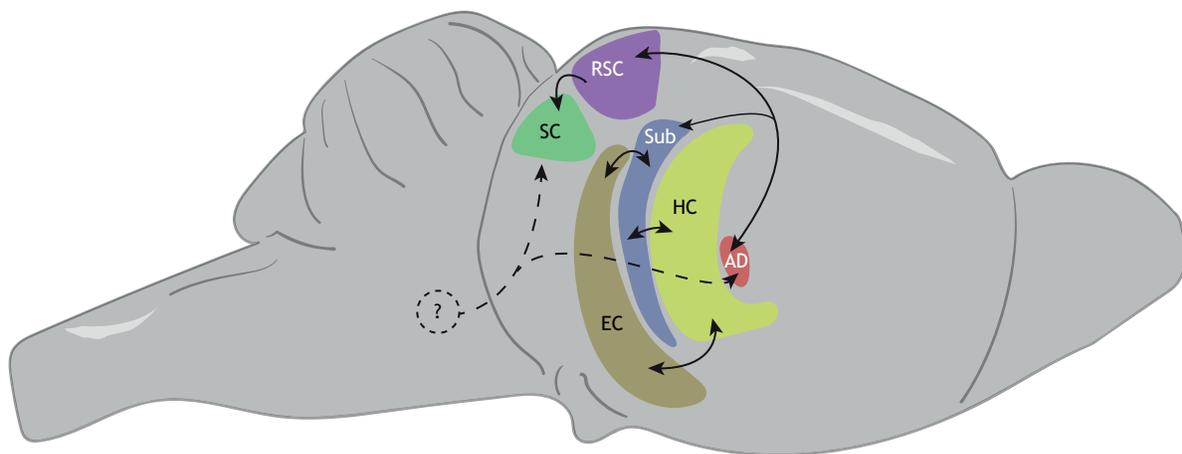


Fig. 3. Brain regions that process magnetic information in rodents. In the mole-rat *Fukomys anselli*, magnetic stimuli have been reported to activate neurons in the midbrain superior colliculus (SC) and in several brain areas that are part of the rodent navigation circuit, including the anterior dorsal thalamus (AD), the hippocampus (HC), the subiculum (Sub), the entorhinal cortex (EC) and the retrosplenial cortex (RSC). The arrows indicate known interconnections between the brain regions. Dashed lines indicate that the brainstem areas processing magnetic stimuli in rodents are unknown.

Box 1. Central questions on neuronal circuits and the magnetic sense

There is limited understanding of how magnetic information is processed and integrated within the central nervous system. In the future we believe it will be important to address the following questions:

1. What nuclei are responsible for receiving the primary sensory input?
2. Do different neuronal circuits exist for a 'dark' and 'light' magnetic sense?
3. Are there neurons that encode specific components of the magnetic field?
4. How is magnetic information integrated into spatial maps?
5. How do you genetically encode magnetic co-ordinates?

(residual 0.3 μ T) magnetic field (Burger et al., 2010). They reported that eleven brain regions were responsive to the magnetic field conditions, ten of which form part of the navigation circuit. This included the dorsal tegmental nucleus (which contains HDCs), anterodorsal and laterodorsal thalamic nuclei (HDC), postsubiculum (HDC), retrosplenial granular cortex (HDC), hippocampus dentate gyrus, CA3 and CA1 (PC) and medial and lateral entorhinal cortex (HDC, GC). In these areas, arena exploration in the ambient magnetic field induced c-fos expression, and this was significantly suppressed by magnetic field manipulations (shielding or periodic directional changes). Magnetic field effects were most significant in the hippocampus dentate gyrus, CA1, and in the postsubiculum (Burger et al., 2010). These data support the existence of spatial cells in the rodent hippocampus that encode magnetic information; however, as the author's statistical analysis did not include a correction for multiple testing, caution is advised and replication is imperative.

Emerging methods to address central questions on neuronal circuit processing and integration of magnetic information

To address the central questions in the field (Box 1), it will be necessary to adopt (and adapt) state-of-the-art tools in neuroscience. We think that three methodologies hold particular promise:

(1) whole-brain imaging; (2) electrophysiological recordings in freely-moving animals; and (3) *in vivo* calcium imaging coupled with virtual reality.

Whole-brain imaging

Although IEGs have proven to be a valuable tool for identifying brain regions that process magnetic cues in several vertebrates, the approach to date has primarily been hypothesis driven and limited in scope. Brains are painstakingly sectioned, stained with antibodies and positive cells counted in a particular region. Not only is this approach tedious and prone to technical artefacts, it also fails to capture a global picture of neuronal activation. The results of any given experiment are highly dependent on the brain nuclei selected for analysis. With the development of tissue-clearing methods, such as CLARITY, CUBIC and iDISCO, an unbiased global screen for neuronal activation in any vertebrate brain can now be conducted (Vigouroux et al., 2017). Whole brains can be stained for an IEG of interest, rendered transparent by various solvents and imaged with light sheet microscopy (Fig. 4). Computer algorithms count the labelled cells, map them to a standardized brain atlas and identify regions that differ in the number of activated neurons (Renier et al., 2016; Randlett et al., 2015). The connectivity of these nuclei can then be further explored using traditional tracers (e.g. wheat germ agglutinin, cholera toxin subunit B), static viral tracers (e.g. adeno-associated virus) or trans-synaptic tracers (rabies and pseudorabies viruses), again visualised in 3D by the application of this technology (Saleeba et al., 2019). We anticipate that whole-brain imaging will allow for an unbiased characterisation of the neuronal circuits involved in processing magnetic information.

Electrophysiological recordings in freely-moving animals

Within the field of magnetoreception, there has been an aversion to electrophysiological experiments, driven by the concern that the abrupt onset of an artificial magnetic stimulus might cause induction within a conductive electrode. Indeed, numerous electrophysiological experiments that have employed an on-off magnetic stimulus have been called into question for this reason (Liedvogel and Mouritsen, 2010). There are ways to address these issues, for example, by

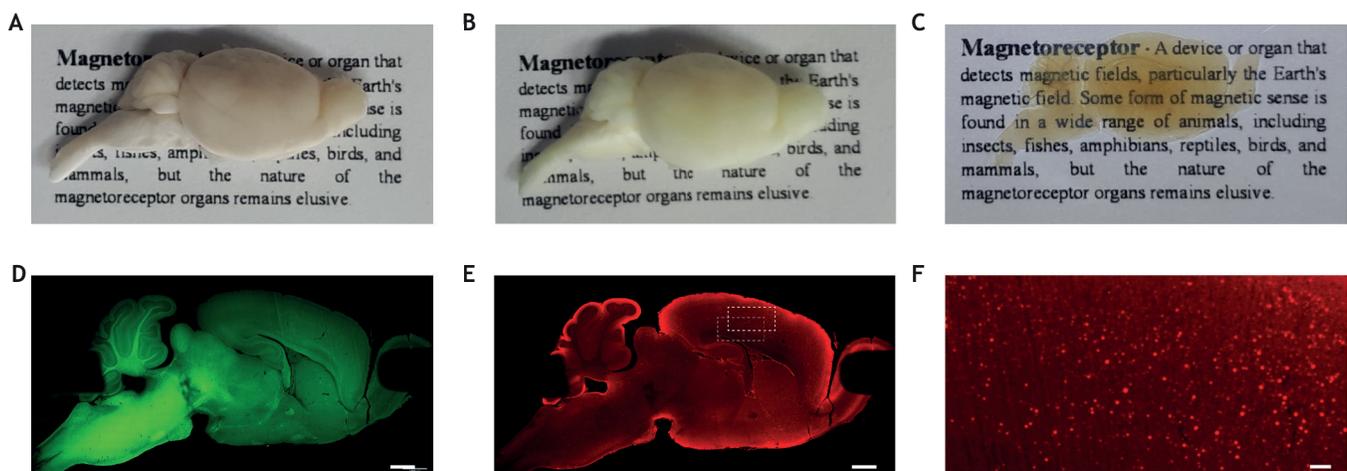


Fig. 4. Whole-brain imaging. Application of whole-brain clearing and imaging enables the identification of anatomical regions activated by a stimulus. Mole-rats (*Fukomys anselli*) are exposed to a stimulus of interest and their brains dissected (A). (B) The fixed brains are bleached, incubated with a primary antibody that binds to c-fos, followed by the application of fluorescent secondary antibody. (C) The brain is then cleared using organic solvents. The translucent brain can then be imaged using light sheet microscopy, exploiting the autofluorescence of brain structures (D, imaged at 488 nm) to register the position of c-fos-positive cells (647 nm) (E). (F) Zoom of the box in E, showing c-fos-positive nuclei in the mole-rat cortex. Scale bars: 1 mm (D,E) and 100 μ m (F). The dark areas in panels D and E result from the positioning of the sample holder.

presenting a freely moving animal with an artificial magnetic environment and undertaking electrophysiological recordings while it engages in exploratory behaviour. Analogous experiments have been performed in bats with great effect, resulting in the identification of a plethora of spatial cells that include ‘social place’, ‘goal direction’ and ‘3D head direction’ cells (Omer et al., 2018; Sarel et al., 2017; Finkelstein et al., 2015). It is conceivable that animals with a magnetic sense have spatial neurons that anchor to specific magnetic directions and/or inclinations, which could be identified by enabling them to move freely in a defined space. Importantly, and in contrast to previous electrophysiological studies, there is no need for acute magnetic field switches during the experiment. It is sufficient to change the magnetic field configuration between different recording sessions to test if a cell responds to a given magnetic cue. These experiments are now feasible in rodents and birds, as a result of technological advances in miniaturisation and telemetry.

Calcium imaging

In vivo two-photon calcium imaging is a powerful technology that permits the investigation of neuronal circuits at high temporal and spatial resolution in awake animals. This optical method relies on the visualization of intracellular calcium (Ca^{2+}) in neurons using chemical dyes (e.g. Fluo-4) or genetically encoded calcium indicators (GECIs), such as GCaMP6 (Chen et al., 2013). GECIs can be introduced into animals by genetic methods or by infecting anatomical regions with an adeno-associated virus (AAV) that drives GCaMP expression using a cell-type specific promoter. When coupled with multi-photon imaging, it is possible to visualise neuronal activity deep within the brain in a large number of neurons with a high signal-to-noise ratio (Helmchen and Denk, 2005). Indeed, technological advances that exploit 3-photon microscopy, light sculpting and temporal focusing now enable the recording of up to 12,000 neurons within a volumetric space (Weisenburger et al., 2019). Moreover, with the development of miniaturised microscopes, multi-photon imaging can now also be performed in freely-moving animals (Klioutchnikov et al., 2020). We anticipate that coupling these technologies with the presentation of artificial magnetic environments will enable investigators to explore whether there are cells within the hippocampus of rodents and birds that function as magnetic spatial cells.

Conclusion

Defining the circuits that process magnetic information is an important and interesting challenge in neuroscience. In this Commentary, we have argued that these circuits likely share anatomical motifs with other sensory systems. We expect that input from sensors located in the periphery are processed by dedicated nuclei in the brainstem, which in turn project to thalamic and midbrain areas, where magnetic information is integrated with other sensory modalities. We imagine that tertiary or quaternary neurons extend to the telencephalon, where spatial maps are formed, with individual neurons encoding different components of the magnetic field. To date, the study of IEGs has permitted the mapping of rudimentary circuits in birds and rodents, which has implicated the vestibular and trigeminal nuclei, Cluster N, the superior colliculus and hippocampus in magnetoreception. Nevertheless, the overall picture remains opaque. We expect that the application of whole-brain imaging, electrophysiological recordings in freely moving animals and *in vivo* calcium imaging will form the foundation for pellucidity.

Acknowledgements

We are thankful to three anonymous reviewers for their comments.

Competing interests

The authors declare no competing or financial interests.

Funding

D.A.K. is supported by the European Research Council (ERC, 336725, 819336) and the Austrian Science Fund (FWF, Y726). S.N. is a recipient of a DOC Fellowship of the Austrian Academy of Sciences.

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