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COMMENTARY

Magnetoreception and the ruling hypothesis

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ABSTRACT

Whereas science is written by humans and cannot escape emotions intervening with scientific thought, the scientific community should be on guard against unnoticeably adopting a favorite hypothesis. When adopting a favorite hypothesis, scientists tend to review their work in favor of this hypothesis and reject contradictory data. In 1890, Thomas Chrowder Chamberlin first described this phenomenon as when 'the search for facts, and their interpretation are dominated by affection for the favored theory until it appears to its advocate to have been overwhelmingly established'. The favorite hypothesis can then quickly transition into a ruling hypothesis, leading to an unconscious bias in favor of supporting evidence and neglect of contradictory observations. This is especially problematic when a scientific field adopts a favorite hypothesis. In this Commentary, we suggest that the field of animal magnetoreception – in particular mechanisms based on radical-pair chemistry and cryptochrome proteins – may be under the reign of a ruling hypothesis. We argue that repeatedly, conclusions are unfounded or otherwise not consistent with the results presented. We use the case of magnetoreception – the only sense that remains without a clearly described receptor – to raise general awareness of the phenomenon of a ruling hypothesis in the scientific community. We emphasize the distinction between the scientist and the scientific community suffering from a hypothesis regime, and further highlight suggestions to mitigate the risk of working under a ruling hypothesis.

KEY WORDS: Favorite hypothesis, Magnetic sensing, Radical-pair mechanism

Introduction

Much of the collective achievement of science, the advancement of knowledge and the most charismatic of discoveries are a direct result of scientists being emotionally connected to, if not furiously passionate about their work. Nevertheless, the fallibility of humans also makes scientists vulnerable to misjudgments. The scientific method provides checkpoints to mitigate such gaffes. However, on occasion, the scientific community can also be susceptible. Chamberlin (1890) famously characterized one such complication, a phenomenon he called the ruling hypothesis (see Glossary). In the rest of this Commentary, we briefly describe Chamberlin's ruling hypothesis and emphasize an overlooked distinction between the individual scientist and the scientific community. We suggest, with evidence, that the field of magnetoreception may be suffering from such a condition. We conclude with remarks on how the field and the scientific community can best keep aware of a ruling hypothesis and hopefully prevent it from reigning supreme.

Passion and 'the ruling hypothesis'

In 1890, Thomas Chrowder Chamberlin first coined the term 'ruling hypothesis' (Chamberlin, 1890). Chamberlin expounded his arguments by initially defining a favorite theory (see Glossary) as when the 'search for facts, observation of phenomena and their interpretation are all dominated by affection for the favored theory until it appears to its author or advocate to have been overwhelmingly established'. The favorite theory can then quickly transition into a ruling hypothesis. What makes a ruling hypothesis truly regal is that it causes scientists to unconsciously select and magnify phenomena that fall into harmony with the ruling hypothesis and unconsciously neglect phenomena that fail to coincide (Chamberlin, 1890). The hypothesis rules the scientist's mind as it leads the scientific community to press the facts to make them fit the theory. In other words, affection for the ruling hypothesis leads to unconscious, strong biases that guide induction and interpretation. Chamberlin summarized the process of accession as 'a premature explanation passes first into a tentative theory, then into an adopted theory, and lastly into a ruling hypothesis'.

It is important to acknowledge that in Chamberlin's perspective the 'original sin' is the use of emotions in science or the vulnerability of science to emotions. Based on Chamberlin's essay, it is evident that he was deeply passionate about his scientific work. This passion is reflected in the frequency of emotional descriptors such as 'love' and 'affection' in his seminal manuscript. For example, 'Love was long since discerned to be blind and what is true in the personal realm is measurably true in the intellectual realm' (Chamberlin, 1890). As stated above, these emotions are considered the basic fault leading to the emergence of a ruling hypothesis: 'If one were to name the central psychological fault, it might be stated as the admission of intellectual affection to the place that should be dominated by impartial, intellectual rectitude alone' (Chamberlin, 1890). While ruling hypotheses can be either false or correct, they nonetheless impede the progress of science. Acknowledging that a hypothesis has a hallmark of a ruling hypothesis is often done only in retrospect and usually only when the hypothesis has turned out to be incorrect (e.g. crystallographic restriction theorem; Mackay, 1962). For two decades, it was accepted (as ground truth) that crystals are restricted to have 1-, 2-, 3-, 4- or 6-fold rotational symmetry (Mackay, 1962). However, only in the 1980s were quasicrystals (which have a 5-fold rotational symmetry) discovered (Shechtman et al., 1984). For several years the scientific community simply rejected an existing discovery as it undermined an aspect of the ruling hypothesis. This demonstrates how only in retrospect it is recognized that a false assumption is embraced by the scientific community and has been accepted as a fact. In this Commentary, we raise awareness to the ruling hypothesis phenomena in general and specifically point out that the field of magnetoreception has hallmarks of a scientific field that currently seems to be working under a ruling hypothesis.

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Glossary

Favorite theory
The search for facts, observation of phenomena and their interpretation are all dominated by affection for the favored theory until it appears to its advocate to have been overwhelmingly established.

Ruling hypothesis
A hypothesis that is favored by scientists and causes them to unconsciously select and magnify phenomena that fall into harmony with the hypothesis and unconsciously neglect phenomena that fail to coincide.

Magnetic field inclination angle
The magnetic field inclination angle is the angle between Earth's magnetic field and the horizontal plane (i.e. Earth's surface). The inclination angle changes with latitude: at the poles, the magnetic field is perpendicular to Earth's surface (i.e. 90 deg inclination angle); at the equator, the magnetic field is parallel to Earth's surface (0 deg inclination angle).

Spin state
The configuration of electron spins within a molecule or complex.

Suggested mechanisms for magnetoreception

Radical pair mechanism
Electron spin quantum mechanics may underlie the magnetic compass sense. When radical pairs are formed in a specific molecule, the spin state dynamics are influenced by the sensor molecule's orientation (within the organism) with respect to the geomagnetic field (Hore and Mouritsen, 2016; Ritz et al., 2000).

Magnetite-based mechanism
Crystals of magnetite act as small magnets that align along Earth's magnetic field. This alignment may transduce neuroreceptors or open ion channels (Kirschvink et al., 2001).

Symbiotic magnetic sensing mechanism
Symbiotic magnetic bacteria that reside within host organisms align along Earth's magnetic field. The hosts sense these bacteria which have magnetic chains of crystals. These chains have a much larger magnetic moment than the small magnetite crystals individually (Natan and Vortman, 2017; Natan et al., 2020).

Electromagnetic induction mechanism
As organisms or their organs which are electrically conductive move through Earth's magnetic field, oppositely charged particles move to opposing sides of the organism or the organ, creating a voltage difference that is shaped by the movement relative to Earth's magnetic field (Nimpf et al., 2019).

MagR magnetic protein mechanism
The iron–sulfur clusters within the MagR protein create a protein chain with a magnetic moment. The alignment of these proteins with the magnetic field may interact with CRY molecules or serve as a sensor by itself (Qin et al., 2016).

Magnetoreception and the radical-pair hypothesis

The ability of animals, specifically birds, to navigate their way across vast continents and oceans has fascinated humans for thousands of years (e.g. 'Even the stork in the sky knows her appointed seasons, and the dove, the swift and the crane observe the time of their migration…'; Book of Jeremiah, chapter 8). As human understanding of Earth's magnetic field and its use in navigation grew, people began to wonder whether animals also possess the ability to use the geomagnetic field for navigation. Several attributes make the geomagnetic field appealing as a cue for animal navigation. First, it is an omnipresent signal – present day and night, in the air, water, land or underground, in low and high latitudes, and in all seasons. Second, the geomagnetic field is predictably variable across Earth's surface. Both the magnetic field inclination angle (see Glossary) and intensity change with latitude; thus, having the ability to detect these changes allows perception not only of north–south polarity but also of relative distance from the equator or pole (Mouritsen, 2018; Wynn and Liedvogel, 2023). Accordingly, some animals can exploit the magnetic field for directional reference (i.e. maintain headings) and some animals are apparently able to get positional information from the magnetic field (i.e. a magnetic map) (Johnsen et al., 2020; Lohmann et al., 2022). Further, the magnetic inclination also allows a vertical reference when other environmental cues, such as celestial or gravitational cues, are obstructed or unavailable (e.g. underground). However, there are many pitfalls when relying on the geomagnetic field as a navigational cue. First, it is a relatively weak (between 25 and 65 μT; Wiltschko, 2012) and noisy magnetic field, thus physically challenging to detect. Second, stochastic variation in different directions is regularly present, making the geomagnetic field a rather challenging cue for navigation (i.e. having a low signal to noise ratio) (Johnsen et al., 2020; Mouritsen, 2018). Thus, the question whether animals evolved a magnetic sense was raised, a query definitively answered by a set of pioneering experiments (see Wiltschko and Wiltschko, 1972, and references therein). For over half a century, the scientific community has unequivocally supported that a wide taxonomic range of animals are sensitive to the geomagnetic field (Nordmann et al., 2017; Wiltschko and Wiltschko, 1995). It is thus bewildering that although the scientific community in general – and sensory biology specifically – has greatly advanced since that seminal work, magnetoreception remains the only known sense without any known receptor and one of the last key frontiers in sensory biology (Johnsen, 2017). Moreover, it has even been suggested that there are two separate magnetic senses (even within the same species): one sensory pathway is related to the magnetic compass and the other to a magnetic map (Wiltschko and Wiltschko, 2019). Regardless, the scientific community agrees that no sensory receptor has been unequivocally demonstrated (Johnsen et al., 2020; Mouritsen, 2018; Nordmann et al., 2017). Both methodological challenges and scientific paradigms have likely contributed to this scientific stasis. In this Commentary, however, we would like to concentrate on the latter. Several hypotheses have been raised suggesting possible underlying mechanisms for magnetoreception: the radical-pair mechanism (Hore and Mouritsen, 2016; Ritz et al., 2000; see Glossary), the magnetite-based mechanism (Kirschvink et al., 2001; see Glossary), the symbiotic magnetic sensing mechanism (Natan and Vortman, 2017; Natan et al., 2020; see Glossary), the MagR magnetic protein mechanism (Qin et al., 2016; see Glossary) and the electromagnetic induction mechanism (Nimpf et al., 2019; see Glossary). Among these, the mechanism based on radical-pair chemistry has been the favored hypothesis for the last two decades (Ikeya and Woodward, 2021) and has been mainly (but not strictly) related to the magnetic compass sense (Wiltschko and Wiltschko, 2019). Despite the tendency to adopt the radical-pair mechanism as a leading hypothesis (Hore and Mouritsen, 2016; Wiltschko and Wiltschko, 2019), there have been many reviews which concomitantly emphasize the unknown nature of magnetoreception (Johnsen et al., 2020; Mouritsen, 2018; Nordmann et al., 2017; Putman, 2022).

In 1978, Schulten and colleagues first suggested the radical-pair hypothesis as the basis for magnetoreception (Schulten et al., 1978; Hore and Mouritsen, 2016). The radical pair-based mechanism proposes that electron spin quantum mechanics may underlie the magnetic compass sense. Following a specific wavelength excitation of a specific molecule, radical pairs are formed with either singlet or triplet spin states (see Glossary). The quantum interconversion between these states is influenced by the sensor molecule's orientation to the geomagnetic field, thus forming an interaction between the ambient magnetic field and temporary chemical processes within the organism (Mouritsen, 2018; Wiltschko and Wiltschko, 2019; see a detailed and comprehensive explanation of this mechanism by Hore and Mouritsen, 2016). Over the years, the radical-pair hypothesis has gathered popularity and continues to draw scientific attention (Gegear et al., 2010; Günther et al., 2018; Ikeya and Woodward, 2021; Mouritsen et al., 2004; Pinzon-Rodriguez et al., 2018; Ritz et al., 2000; Wynn and Liedvogel, 2023; Zoltowski et al., 2019). A primary criticism of this hypothesis has been the large gap (of several orders of magnitude) between Earth's weak magnetic field (60–65 µT at the poles and 25–30 µT at the equator; Wiltschko, 2012) and the low sensitivity of the candidate protein sensor. Nevertheless, a critical boost to the hypothesis came in 2000, when avian cryptochrome (CRY) was proposed as the putative sensor (Ritz et al., 2000) (see Fig. 1). This initiated a wave of studies examining various CRY proteins and targeting support for the radical-pair hypothesis (Hore and Mouritsen, 2016; Mouritsen et al., 2004; Ritz et al., 2004; see fig. 3 in Wynn and Liedvogel, 2023).

Experiments demonstrating that radiofrequency electromagnetic noise can negatively affect the magnetic sense has been seen as critical support for the radical-pair hypothesis (Engels et al., 2014; Ritz et al., 2004; Schwarze et al., 2016). Further, the fact that the avian compass is an inclination compass rather than a polarity compass has also been considered as lending critical support for this hypothesis (Wiltschko and Wiltschko, 2019). Moreover, the field of magnetoreception in general is known for excellent, multidisciplinary, hypothesis-driven experiments and research (Bassetto et al., 2023; Engels et al., 2014; Hein et al., 2011; Kishkinev et al., 2015; Lohmann et al., 2004; Mora et al., 2004; Packmor et al., 2021; Ritz et al., 2004; Wiltschko and Wiltschko, 1972). However, despite numerous studies, the main criticism of radical pair-based magnetoreception has remained steadfast. As stated in previous reviews, 'there are hundreds of studies demonstrating that relatively modest magnetic fields (1–100 mT) can affect radical reactions' (Hore and Mouritsen, 2016; Mouritsen, 2018). This means that the evidence of an effect has, at best, been experimentally observed using magnetic fields 15 times stronger than Earth's and, at worst, 4000 times stronger. Nevertheless, experiments aiming to support the radical-pair hypothesis continuously demonstrate a chemical response only in the mT range (e.g. Hore and Mouritsen, 2016; Ikeya and Woodward, 2021; Maeda et al., 2012; Mouritsen, 2018; Xu et al., 2021; see Fig. 1). Many times, these studies recruit state-of-the-art methods (e.g. Xu et al., 2021) which clearly demonstrate that the magnetic sensitivity of CRY molecules is irrelevant to Earth's weak magnetic field (Babcock and Kattnig, 2020; Kirschvink, 2014; Kirschvink et al., 2010; Smith et al., 2024). Despite this, the results of such experiments are considered as support for the CRY-based radical-pair magnetoreception hypothesis (Hore and Mouritsen, 2016; Ikeya and Woodward, 2021; Maeda et al., 2012; Xu et al., 2021) and are further echoed in the scientific community as proof (Warrant, 2021). For a specific example of such a chain of events, we demonstrate using the recent influential and highly cited publication by Xu et al. (2021). While these authors, with meticulous scientific effort, specifically demonstrate that the sensitivity of CRY4 to magnetic fields is only in the mT range (similarly to many previous papers), instead of concluding that CRY4 is not sensitive to Earth's magnetic field they state: 'In conclusion, we have demonstrated that CRY4 from the night-migratory European robin seems to be fit for purpose as a magnetic sensor' (Xu et al., 2021). This is echoed in an editorial published alongside the paper claiming 'The protein cryptochrome *Er*CRY4, found in the eyes of migratory European robins, has the right physical properties to be the elusive magnetosensor' (Warrant, 2021). These two papers were later

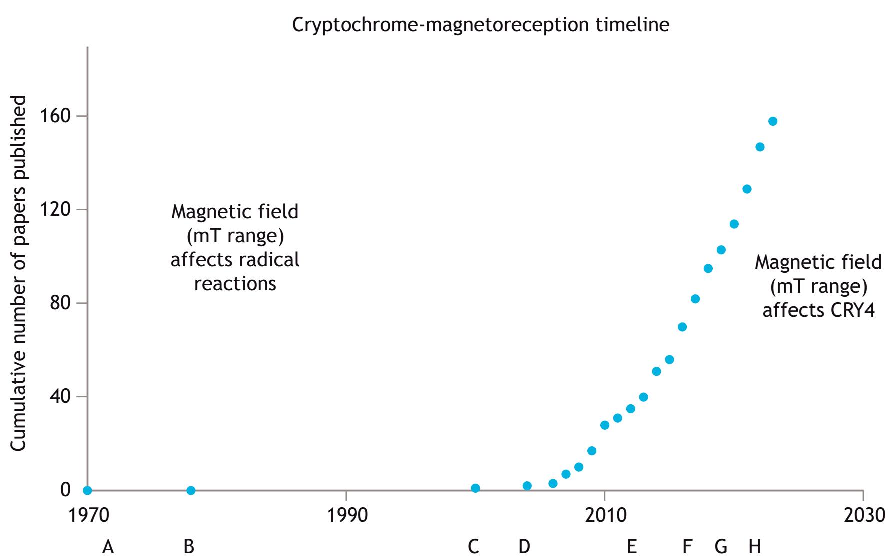

Fig. 1. A timeline of publications on radical-pair magnetoreception. The *y*-axis shows the number of accumulated published papers which have both magnetoreception and cryptochrome in their title or abstract. The data were obtained by querying the PubMed database on 15 September 2023. (A) Birds shown to have the ability to sense the magnetic field inclination angle (Wiltschko and Wiltschko, 1972); magnetic field effects observed to influence radical-pair reactions (Ritz et al., 2000). (B) Radical-pair mechanism suggested as the mechanism behind magnetic sensing (Schulten et al., 1978). (C) A detailed theoretical review of radical pair-based magnetoreception and suggestion for cryptochrome molecules as the possible agent (Ritz et al., 2000).
(D) Experiments supporting CRY1 involvement (Mouritsen et al., 2004); resonance effect indicates a radical-pair mechanism (Ritz et al., 2004). (E) Magnetic field in the mT range shown to affect AtCRY (*Arabidopsis thaliana* CRY) (Maeda et al., 2012); experiments on chickens support CRY4 involvement in magnetoreception (Watari et al., 2012). (F) A review claiming a radical-pair mechanism is the leading hypothesis (Hore and Mouritsen, 2016).
(G) Experiments supporting CRY4 involvement in magnetoreception (Günther et al., 2018; Pinzon-Rodriguez et al., 2018). (H) Magnetic field in the mT range shown to affect ErCRY4 (Xu et al., 2021) and Hela cells (Ikeya and Woodward, 2021).

echoed to the general public in a best-selling book (Yong, 2022). While the book aims to fairly describe the complexities of the field and the various hypotheses that exist, it nevertheless states ‘Even if the radical-pair hypothesis is the only correct one, it leaves many unanswered questions’. Whereas the author did his best to interview leading experts in the field, this is the impression he was left with. Despite that, by definition, the radical-pair hypothesis could not be relevant to many magnetic sensing organisms; for example, organisms living underground, where light is absent (Kimchi et al., 2004).

While science being echoed imprecisely is a separate issue, the lack of ability to refute the main criticism prompts the question why scientific, peer reviewed, publications have declared the CRY-based radical-pair hypothesis as the ‘leading hypothesis’ (Hore and Mouritsen, 2016) and even the ‘favorite hypothesis’ (Ikeya and Woodward, 2021). We argue that these declarations might exhibit the hallmark patterns of a scientific field working under Chamberlin’s definition of a ruling hypothesis (Chamberlin, 1890) – a hypothesis having risen to power despite contradicting results which are unconsciously neglected. As a result, and despite years of laborious scientific investigation, the field of magnetoreception is stuck at a continuous, unsuccessful attempt to demonstrate that a particular molecule (or molecules) can react to Earth’s magnetic field with an ever increasing number of publications (Fig. 1; see also fig. 3 in Wynn and Liedvogel, 2023). The increasing number of studies (Fig. 1) focusing on the radical-pair hypothesis may indicate that the CRY-based radical-pair magnetoreception hypothesis is on the way to being unequivocally demonstrated, as evidence is accumulating at an increasing pace (Fig. 1). Alternatively, it may indicate that a ruling hypothesis has usurped the research community. The fact that the fundamental criticism (i.e. the lack of sensitivity to Earth’s weak magnetic field) has held and that unfounded conclusions have been presented in numerous published articles supports the latter, but only time will unravel this puzzle.

From the perspective of the last two decades, and following the abovementioned research (Gegear et al., 2010; Günther et al., 2018; Ikeya and Woodward, 2021; Pinzon-Rodriguez et al., 2018; Ritz et al., 2004; Xu et al., 2021; Zoltowski et al., 2019), inferring to the best explanation (i.e. abductive reasoning; Harman, 1965) would actually lead to the adoption of an alternative hypothesis. Assuming that an alternative hypothesis may be equally plausible, hyperbolic headlines in scientific journals (Warrant, 2021) will entrap the scientific community in the pretense of established theory and prevent the scientific community from conducting a paradigm shift that might be needed. After decades of research, perhaps it is time to encourage, rather than discourage, intellectual space for examining alternative hypotheses (Falkenberg et al., 2010; Kirschvink et al., 2001; Natan and Vortman, 2017; Natan et al., 2020; Nimpf et al., 2019; Qin et al., 2016) that may finally lead to finding the missing, or otherwise enigmatic, magnetic sensor.

The scientist or the scientific community – Chamberlin’s overlooked distinction

Looking forward, how can the scientific community avoid working under a favorite hypothesis? In his seminal manuscript, Chamberlin did not distinguish between the individual researcher and the scientific community (Chamberlin, 1890). Chamberlin suggested that individual researchers should best work, or operate, under multiple hypotheses. Being aware that the ‘original sin’ is affection for a single hypothesis, Chamberlin suggested that working under multiple hypotheses distributes the effort and divides the affection. This approach is emotionally naive (recognized as such by Chamberlin himself), and it came during an era when mixing affection with science was considered false practice (e.g. Grinnell, 1931). However, in contemporary science, it is a positive attribute, and arguably important, for a scientist to be passionate about their work. Researchers are human, not machines, and we prefer them as such. Moreover, the approach of working under multiple hypotheses is perhaps impossible for sometimes practical reasons (see also Johnson, 1990). This is particularly true for sensory biology, which is a multidisciplinary and methodologically complicated field. The naive thought that a research group will invest equal efforts to examine various alternative hypothesis is unrealistic (Johnson, 1990). Thus, at the level of the individual researcher or research group, the risks are inherent and prominent; good science, candor and awareness are the main tools left at the individual level (see ‘Conclusions and future directions’, below). But the fact that an individual researcher has a leading hypothesis will cause little harm as long as the scientific method is appropriately used, and that hypotheses are not mistaken for facts. The eminent danger arises when the larger scientific community adopts or enables a ruling hypothesis. When the scientific community becomes beguiled with the favored hypothesis, the same unconscious selection to magnify phenomena that fall into harmony whilst neglecting phenomena that fail to coincide could be devastating. This may lead to publication biases (Fig. 1; fig. 3 in Wynn and Liedvogel, 2023) and/or distorted, exaggerated headlines in scientific journals (Warrant, 2021), which in turn create a false impression in the community that the favored hypothesis is correct and established. At this stage, a chain reaction may ensue, as reviewers of research grants and manuscripts will reduce the probability that other hypotheses will be raised or properly examined. At this stage, unless by chance the ruling hypothesis is indeed the true hypothesis, there is little room for any alternative hypotheses to be considered. Moreover, even if the ruling hypothesis is indeed correct, open mindedness should remain, as other, alternative hypotheses may still prevail. In other words, interactions among the scientific community are not always subject to the scientific method, peer reviewed, or done with best scientific practices.

Conclusions and future directions

Being passionate about one’s science is a necessity, as people choose the long and challenging endeavor of science because they are passionate about it. The wonders of nature increase our passion more and more through the years, and in many ways, this is the scientist’s major reward. So how should the scientific community avoid operating under the influence of a ruling hypothesis? One step is to bring the term ruling hypothesis and the insights raised by Chamberlin more than a century ago to the forefront. Further, here we suggest key points and key positions that should increase their awareness. A general action for reducing the probability of working under a ruling hypothesis which relates to all positions, from the student through the PI and to the reviewers and editors, would increase awareness of the ruling hypothesis term and the phenomenon. Students and PIs should discuss and examine the working hypothesis (or multiple working hypotheses) in light of the term ‘ruling hypothesis’, acknowledge the risks of having a leading hypothesis and identify and discuss the risks with an emphasis on the relationship between the results and conclusions. Reviewers should assume all hypotheses are equally valid and avoid judgment against the non-favored hypothesis and be equally critical regardless of the level of support for the popular hypothesis. They should avoid any criticism that is raised to an alternative hypothesis by assuming the leading hypothesis is correct. Editors should recognize the leading hypothesis in each field and examine each, considering the term ‘ruling hypothesis’. They should avoid magnifying supportive results and neglecting contradictory results with respect to the leading hypothesis. They should introduce the concept and make the reviewers aware of the favorite hypothesis if it exists in a field. Special attention should be given to editorials and news and views which are later the basis of press releases.

The process of establishing a ruling hypothesis entails favoring and adapting a provisional theory, thus permitting emotions to unconsciously magnify supporting results and neglect opposing results. This is especially harmful when a community is largely captured by a ruling hypothesis. While a ruling hypothesis may indeed be correct, it blocks the healthy development and progress of science. We suggest that the field of animal magnetoreception has the hallmarks of a ruling hypothesis. We hope the insights highlighted here will raise awareness of the phenomena in general and in magnetoreception more specifically, and allow for the required criticism, from authors, reviewers and editors. This, in turn, can aid in the avoidance of unfounded conclusions and encourage open-minded and critical thinking within our scientific disciplines. As a community, we are passionate about our science, we simply need to be aware that this passion possesses some risks.

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Competing interests
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