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Attracted by a magnet: Exploration behaviour of rodents in the presence of magnetic objects

Sandra Malewski[a,*], E. Pascal Malkemper[a,b], František Sedláček[c], Radim Šumbera[c], Kai R. Caspar[a], Hynek Burda[a,b], Sabine Begall[a]

[a] Department of General Zoology, Faculty of Biology, University of Duisburg-Essen, 45117 Essen, Germany
[b] Department of Game Management and Wildlife Biology, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences, Kamýcká 129, 165 21 Prague 6, Czech Republic
[c] Department of Zoology, Faculty of Science, University of South Bohemia, Branišovská 1760, 370 05 České Budějovice, Czech Republic

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ABSTRACT

Magnetosensitivity is widespread among animals with rodents being the most intensively studied mammalian group. The available behavioural assays for magnetoreception are time-consuming, which impedes screens for treatment effects that could characterize the enigmatic magnetoreceptors. Here, we present a fast and simple approach to test if an animal responds to magnetic stimuli: the magnetic object assay (MOA). The MOA focuses on investigating an animal's spontaneous exploration behaviour in the presence of a bar magnet compared to a demagnetised control. We present consistently longer exploration of the magnet in three different rodent species: Ansell's mole-rat (*Fukomys anselli*), C57BL/6J laboratory mouse, and naked mole-rat (*Heterocephalus glaber*). For the naked mole-rat this is the first report that this species reacts on magnetic stimuli. We conclude that the MOA holds the potential to screen if an animal responds to magnetic stimuli, indicating the possession of a magnetic sense.

1. Introduction

Classic sensory modalities such as vision, hearing, smell, taste and touch are known to be essential for animals to interact with other organisms and react on their environment. The relevance and function of the magnetic sense is less understood. Magnetoreception, *i.e.* the ability to perceive the geomagnetic field, has been first demonstrated in the European robin (*Erithacus rubecula*) in 1966 (Wiltschko and Merkel, 1966). Nowadays, magnetosensitivity is proven to exist throughout the animal kingdom, although most of the evidence is based on behavioural studies, while the functional and structural basis of magnetoreception remains enigmatic. Among mammals, rodents are one of the most intensively and successfully studied group (Table 1), leading to the conclusion that rodents are highly suitable subjects for studies of magnetoreception (Begall et al., 2014). However, the assays used to test the magnetic sense in rodents (Table 1) are extremely time-consuming, making it difficult to screen for the effects of treatments to characterize the magnetoreceptors. A more efficient procedure would be of high value.

Here, we present a fast approach to screen if an animal responds to magnetic stimuli, indicating the possession of a magnetic sense, creating a reliable basis to apply more complex magnetobiological assays: the magnetic object assay (MOA). Inspired by an experiment with bottlenose dolphins (*Tursiops truncatus*) (Kremers et al., 2014), the MOA focuses on comparing an animal's spontaneous behaviour in the presence of a bar magnet compared to a demagnetised control (weakly magnetic). Analogous to the novel object assay widely used in behavioural studies of laboratory mice, in the MOA an animal is introduced into an arena containing the strong and/or weak magnet in its centre. If an animal shows differences in its behavioural parameters such as the approach latency or time spent near the strong/weak magnet, the animal differentiates (actively or passively) between the two objects, and thus reacts to the magnetic stimulus.

To investigate this, we tested 1) the suitability of the MOA to demonstrate the ability to differentiate between two magnetic objects using two species for which a magnetic sense had already been established: the Ansell's mole-rat (*Fukomys anselli*) (Burda et al., 1990; Thalau et al., 2006; Němec et al., 2001) and the C57Bl/6J laboratory mouse (Muheim et al., 2006; Phillips et al., 2013), and 2) whether the naked mole-rat (*Heterocephalus glaber*), a model species in biomedical research such as aging and cancer (Miyawaki et al., 2016), responds to the presented stimuli or not. As proof-of-principle, we conducted an

* Corresponding author.
E-mail address: sandra.malewski@uni-due.de (S. Malewski).

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Table 1
List of rodent species identified as magnetosensitive to static magnetic fields of Earth strength, applied study set-ups and references.

Species	Study set-up	Reference
Ansell's mole-rat (*Fukomys anselli*)	Nest building assay	(Burda et al. 1990; Thalau et al. 2006; Marhold et al., 1997)
Bank vole (*Myodes glareolus*)	Nest building assay; Sleeping position	(Oliveriusová et al. 2014)
Blind mole rat (*Spalax ehrenbergi*)	Nest building assay; Complex labyrinth	(Kimchi and Terkel 2001; Marhold et al. 2000)
C57BL/6J mouse (laboratory mouse)	Nest building assay	(Muheim et al. 2006, Painter et al., in press)
	Magnetic water maze	(Phillips et al. 2013)
Djungarian dwarf hamster (*Phodopus sungorus*)	Nest building assay	(Deutschlander et al. 2003)
Giant mole-rat (*Fukomys mechowii*)	Nest building assay	(Oliveriusová et al. 2012)
Silvery mole-rat (*Heliophobius argenteocinereus*)	Sleeping position	(Oliveriusová et al. 2012)
Wood mouse (*Apodemus sylvaticus*)	Displacement and homeward orientation	(Mather and Baker 1981)
	Nest building assay	(Malkemper et al. 2015)

additional experiment, in which we investigated the behaviour of a second group of naïve C57BL/6J laboratory mice, when being presented the demagnetised, very weak magnet as a magnetic stimulus, and a similar sized object made of brass as a completely non-magnetic control.

2. Materials and method

2.1. Animals

We tested three rodent species (all adults): the Ansell's mole-rat (*Fukomys anselli*) ($N = 24$; 12 m, 12 f), the C57BL/6J laboratory mouse (strong versus weak magnet: $N = 24$, 5 m, 19 f; weak magnet versus non-magnetic control: $N = 24$, 10 m, 14 f), and the naked mole-rat (*Heterocephalus glaber*) (two-choice: $N = 30$, 23 f, 7 m; open field: $N = 30$, 12 m, 18 f). Ansell's mole-rats and C57BL/6J mice originated from our stock at the University of Duisburg-Essen (Germany) (permit no. 32-2-1180-71/328 Veterinary Office of the City of Essen). Naked mole-rats originated from the Zoo Osnabrück (Germany) and the University of South Bohemia (České Budějovice, Czech Republic). Testing took place between January 2015 and February 2018 in Essen, České Budějovice, and Osnabrück. Housing conditions were adjusted to the animals' needs and approved by authorities in charge. Ansell's mole-rats were held in glass terrariums (500 cm^2 floor space per animal), naked mole-rats in transparent perspex maze systems and laboratory mice in Macrolon cages (type IV, 330 cm^2 floor space per animal) filled with litter and clay pots as hiding places. Food (vegetables, food pellets, fruits), and water for the mice, were available ad libitum. Prevailing temperatures and humidity were 26 °C and 30% for mice, 24–26 °C and 30% for Ansell's mole-rats and coruros, 28 °C and 50% for naked mole-rats at the Zoo Osnabrück and up to 30 °C and 70% for naked mole-rats in České Budějovice. The light-dark cycle was 12:12 h for all species. The animals were tested during the light phase. During the 10 min tests neither food nor water was available. Temperatures and humidity during tests were similar to the housing conditions. Halogen room lamps (full spectrum) were used as light sources.

2.2. Magnetic object assay

An AlNiCo bar magnet (6 cm (L), 1.5 cm (W), 0.5 cm (H)) (EDU-7, www.supermagnete.de) served as magnetic object and an identical bar magnet of the same type as control (weak magnet). The weak magnet had been demagnetised by pole reversion: The bar magnet was placed into a coil (6 cm diagonal, 600 windings) powered by alternating current (2.5 A) producing a 50 Hz alternating magnetic field. Voltage was decreased continuously for 3 min, repeatedly. The magnetic field strengths were measured with a digital teslameter (DTM-141, Group3 Technology; Table 2). An offset to correct for the local Earth's magnetic field was used. In the additional experiment, we used the demagnetised magnet as a magnetic stimulus and a similar sized object made of brass as control. Both objects were packed odour-proof in identical plastic boxes (7 cm (L), 2 cm (W), 1.5 cm (H)).

Table 2
Magnetic field strengths of the weak (control) and strong magnet at given distances to the sensor of the teslameter (DTM-141, Group3 Technology).

Distance (cm)	Field strength weak magnet (μT)	Field strength strong magnet (μT)
< 0.1	1,410	79,252
0.5	180	30,677
1	32	15,552
1.5	15	9,222
2	5	5,922
2.3	< 1	4,815
5		1,120
10		220
15		75
20		32
30		20
40		< 1

We developed two versions of the MOA (all trials were video-recorded for 10 min):

(1) Open field MOA: Either the strong or weak magnet was placed in the centre of a square arena (60 cm (L), 60 cm (W), 21 cm (H)) made of white polystyrene (Florever Europe GmbH, Austria). The animals were tested singularly in both conditions, with 3–28 days between tests. To avoid order effects, half of the animals were tested with the strong magnet and the other half with the weak magnet first. We analysed latency (time until the animal first touched the strong/weak magnet with its head or front paws), number of contacts, and duration of stay in the direct vicinity of the strong/weak magnet (maximum distance between animal's head and object: 1.5 cm) ('object exploration time').
(2) Two-choice MOA: Two transparent cubic PVC boxes (13.5 cm edge length) connected by a tunnel (50 cm (L), 6 cm (W), 6 cm (H)) were used. The strong and weak magnets were placed randomly in the boxes. After two minutes of habituation in the middle of the tunnel, two sliding doors were opened consecutively in randomised order, enabling the animal to enter the maze. We evaluated latency to approach the strong or weak magnet (the animal's head and both front paws being in the box implying a comparable distance of ~1.5 cm from the strong/weak magnet as in the open field MOA), first choice and time spent in each box ('object exploration time').

We tested Ansell's mole-rats (Essen) and naked mole-rats (České Budějovice) in the open field MOA. A second group of naked mole-rats (Osnabrück) and both groups of laboratory mice (main and additional experiments) (Essen) were tested in the two-choice MOA. The test apparatus was placed inside a wooden (Essen) or plastic (České Budějovice, Osnabrück) box (78 cm (L), 78 cm (W), 116 cm (H)), which was uniform inside. The test animal was introduced through one of the four identical flap doors. A full spectrum halogen lamp (intensity 3.8 µmol $(s\,m^2)^{-1}$) and a camera were placed centrally above the arena. The test apparatus was cleaned after each test with water and mild detergents. During the tests, no person was inside the test room. All video analyses were performed blindly, *i.e.* the evaluator did not know the magnetic conditions. All experiments complied with the animal testing regulations of the country where they were performed.

2.3. Statistics

SPSS 24 (IBM SPSS Statistics) was used for statistical analyses. After testing for normal distribution (Shapiro-Wilk test), paired t-tests (two-tailed) or Wilcoxon signed-rank tests were performed. Latencies (two-choice MOA) were compared with a Mann-Whitney-U test. We used the Chi^2-test to test for differences in the first choices in the two-choice MOA. Bonferroni-Holm correction was applied for all *p*-values. To illustrate explorative preferences, we calculated a Magnetic exploration index (MEI) as the difference between the times spent near the strong/weak magnet divided by the total exploration time (value of 1 for absolute preference for the magnet). GraphPad Prism 7 (GraphPad Software, La Jolla, California, USA) was used to create the figures.

3. Results

In the main experiments, there were no significant differences in latency, number of contacts and first choice between the strong and weak magnet in all tested species (S1). However, all species spent significantly more time in the direct vicinity of the strong compared to the weak magnet (object exploration time, Table 3, Fig. 1, S1–S3). Similarly, in the additional experiments, no differences in latency and first choice were found, while the object exploration time of the laboratory mice was significantly longer at the weak magnetic stimulus compared to the non-magnetic control (Table 3, Fig. 1).

4. Discussion

We tested animals in two versions of the MOA. While tests in the open field MOA, similar to the experimental set-up used by Kremers et al. (2014) who showed first reactions on magnetic objects in bottlenose dolphins, were positive with Ansell's mole-rats, there were no differences in measured parameters for the naked mole-rats (first group, České Budějovice) in this set-up. We attribute this to the unfamiliar environment as naked mole-rats were kept in closed tunnel systems (contrary to the other tested species). Successful testing of a second group of naked mole-rats (Osnabrück) in the two-choice MOA supports this assumption. The two-choice MOA offers the further advantage of testing every animal only once, because the strong and weak magnet are present in one trial simultaneously, excluding effects of habituation and motivation. Therefore, we decided to employ it also for C57BL/6J mice.

The only parameter of the MOA differences were found for was the object exploration time. Latency, number of contacts and first choice

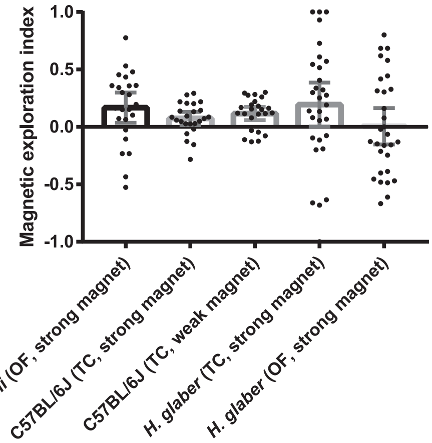

Fig. 1. Magnetic exploration indices (MEI; meaning the difference between the times spent near the strong/weak magnet divided by the total exploration time; a value of 1 represents absolute preference for the stronger magnet) for three rodent species tested in the MOA (OF = open field, TC = two-choice), demonstrating a consistent preference for the stronger magnet. Error bars: 95% confidence interval.

were not different between the two objects in any of the tested species. In this respect, our results are not consistent with the results of Kremers et al. (2014), where latency was the only parameter that differed – the dolphins approached the magnet significantly faster than the demagnetised control. However, the differences between the exploration time near the strong/weak magnet indicate the animal's ability to respond to and differentiate (actively or passively) the two objects and thus might indicate magnetosensitivity in the three rodent species. The MOA's replicability was confirmed by the results of our additional experiment – by offering a weak magnetic object (demagnetised magnet) and a completely non-magnetic control (brass bar), laboratory mice showed a clear preference for the magnetic stimulus by spending significantly more time in its direct vicinity.

Given that magnetoreception in the Ansell's mole-rat and C57BL/6J mice has been previously demonstrated by means of other assays (Table 1), our findings indicate the suitability of the MOA to test for reactions on magnetic stimuli. We used it to show, for the first time, that the naked mole-rat responds to magnetic stimuli and therefore would be worth to be tested in more complex assays, investigating magnetoreception. This finding is important as the naked mole-rat genome is known (Kim et al., 2011), and in addition to C57BL/6J mice, it represents an interesting candidate species to study the molecular basis of the mammalian magnetic sense.

We can only speculate about the reasons and meaning of the animals' preference for the stronger magnetic stimulus: The generally explorative rodents could have been attracted to a new, unknown source of sensory stimulation (Klein, 2000; Corbetta and Shulman, 2002). Furthermore, assuming the animals might be magnetosensitive, they could use the stronger magnetic stimulus as a magnetic landmark, where they start exploring and developing a cognitive map of their environment based on magnetic cues to better orientate and navigate

Table 3
Means and 95% confidence intervals of object exploration time of the MOA. P-values (Bonferroni-Holm corrected) refer to either Wilcoxon-test (*Z* value) or *t*-test (*T* value).

	Ansell's mole-rat	C57BL/6J mouse	C57BL/6J mouse (additional experiments)	Naked mole-rat	Naked mole-rat
	Open field MOA (N = 24)	Two-choice MOA (N = 24)	Two-choice MOA (N = 24)	Two-choice MOA (N = 30)	Open field MOA (N = 30)
Object exploration time at the weak/strong magnet (sec)	Weak magnet: 55 (43–66) Strong magnet: 78 (63–94) $P = 0.027$ $T_{23} = 2.846$	Weak magnet: 120 (109–131) Strong magnet: 139 (126–153) $P = 0.033$ $Z = 2.543$	Weak magnet: 183 (162–205) Non-magnetic object: 149 (126–172) $P = 0.006$ $T_{23} = 3.491$	Weak magnet: 88 (63–113) Strong magnet: 152 (112–193) $P = 0.042$ $Z = 2.468$	Weak magnet: 28 (22–33) Strong magnet: 30 (22–37) $P = 1.0$ $Z = 0.097$

during long and short-term orientation and navigation (Wiltschko and Wiltschko, 1992; Kimchi and Terkel, 2001; Kimchi et al., 2004; Kishkinev et al., 2015) as it was already proposed for diverse magnetosensitive animals (Ernst and Lohmann, 2018; Lohmann et al., 2007). Starting explorations from the point of highest magnetic intensity seems to be intuitively reasonable as the animal can follow the gradient back to its source. The principle of using specific points as 'landmarks' during exploration has already been described for laboratory mice (C57BL/6J), disregarding magnetoreception (Dvorkin et al., 2010), although this sensory ability might theoretically play a role. After observing that mice returned conspicuously often to specific knots during exploration in an open field, the authors concluded that this behaviour might 'function as a way to obtain an overview of the entire environment, allowing recalibration of the mouse's locale map and compass directions' (Dvorkin et al., 2010, p. 1). In general, animals are assumed to combine idiothetic with allothetic information to further stabilise their orientation abilities (Kimchi et al., 2004; Mittelstaedt and Mittelstaedt, 1980). The Earth's magnetic field as an external source offers allothetic cues, which might be used by animals during orientation and navigation.

In contrast to our findings, a recent study showed that spiny lobsters (*Panulirus argus*), tested in a comparable two-choice assay, preferred a non-magnetic control to a bar magnet (Ernst and Lohmann, 2018). However, it must be noted that the magnet used by Ernst and Lohmann (2018) (703 mT) was much stronger than ours (79 mT), what might explain the lobster's avoidance.

The fact that all species tested here showed consistent responses makes it likely that the underlying mechanism is the same. In the main experiments, the animals were exposed to relatively strong magnetic field gradients, which might have caused magnetic induction. Although we achieved similar results in the additional experiment, in which a very weak (demagnetised) magnet was used (Earth-strength range around 1 cm distance), the question may arise if the observed behavioural differences can be explained by induced currents rather than direct perception of the magnetic fields. Two scenarios seem plausible: First, magnetic stimulation might have unspecifically activated neurons similarly to the principle of clinical transcranial magnetic stimulation (TMS). In humans, magnetic field strengths of 1.5–2 Tesla activate cortical neurons at a depth of 1.5–2.1 cm beneath the scalp (Epstein et al., 1990; Rudiak and Marg, 1994). These strengths are 20 times higher than the intensities to which the animals were exposed in the MOA (max. 0.08 T). Furthermore, the efficiency of TMS is lower in small rodent brains (Weissman et al., 1992), making it highly unlikely that unspecific induction accounts for our findings. In the second scenario, specialized electroreceptors would be excited by induced currents. Electrosensitivity has been reported for (semi-)aquatic mammals such as the platypus (*Ornithorhynchus anatinus*) and the Guiana dolphin (*Sotalia guianensis*) (Czech-Damal et al., 2012), but no evidence exists in rodents. Though electromagnetic induction as a mechanism for magnetoreception seems unlikely for terrestrial animals, because of low conductivity in air, the semicircular canals have been suggested to provide a suitable circuit (Jungerman and Rosenblum, 1980). The basis of the mammalian magnetic sense is unknown so far (Begall et al., 2014). We do not attempt to speculate about the underlying mechanisms here, but highlight that the MOA provides a platform that can produce critical data concerning an animal's ability to react on magnetic stimuli and thus potentially concerning magnetosensitivity in a reasonable timeframe, with little effort and a small amount of resources. As a next step for future experiments to investigate an animal's magnetosensitivity our approach could be modified as follows: A double wrapped coil systems could be used (Kirschvink, 1992; Kirschvink and Kirschvink, 1991) instead of the magnet, functioning as the magnetic stimulus (parallel current flow implying the possibility to increase magnetic field intensity), and the other as control (antiparallel current flow meaning no change of the magnetic field). By using this approach, the maximum intensities of the magnetic stimulus could be decreased down to a comparable strength as the Earth's magnetic field exhibits, to adjust the experimental conditions closer to natural ones, investigating magnetosensitivity directly.

To conclude, the MOA provides a simple, low-cost and fast method, which seems to be well suited to check if an animal responds to magnetic stimuli. It holds the potential to be modified to provide insights into underlying receptor mechanisms e.g. by testing the influence of radiofrequencies or diverse light regimes (Wiltschko et al., 2010; Malkemper et al., 2015).

Author contributions

SB and SM conceived the experiments, SM and KRC performed these. FS and RŠ contributed to the experimental phase. EPM, SB and SM analyzed the data. EPM prepared the figures. SM drafted the manuscript with significant input from SB, HB, and EPM. All authors approved the final version of the manuscript.

Data accessibility

The datasets supporting this article is accessible as part of the supplementary information (S4).

Competing interests

No competing interests declared.

Ethical statement

All experiments complied with the animal testing regulations of the country were they were performed. No ethical permissions were necessary.

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