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REVIEW ARTICLE MAGNETORECEPTION IN FRUIT FLIES, BEES AND ANTS

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ARTICLE DETAILS	ABSTRACT
<i>Article History:</i> Received 05 January 2022 Accepted 08 March 2022 Available online 17 March 2022	Few insects have the sensory ability to sense and use the earth's magnetic field. Studies have revealed a wealth of information on the magnetic sense of some insects. However, the mechanism of sensing the earth's magnetic field, called magnetoreception, is still enigmatic in insects. Magnetoreception studies in fruit flies, bees, and ants are well-documented. Of two hypothesized types of magnetoreception mechanisms in those insects, one is ferromagnetic, and the other is light-dependent. Although experimental results appear to be consistent with the proposed hypothesized mechanisms it is possible that there is still an unknown mechanism that would explain and confirm the experimental results. Thus, theories explaining magnetoreception in insects are yet to be come out. Magnetoreception plays a role in migration, orientation, as well as navigation in insects. Several sensory cues play significant role in migration. Moreover, our understanding of magnetoreception requires information from various branches of science, such as physics, behavioural biology, zoology, and environmental biology. The article attempts to update the account of magnetoreception in the said insects as well as to identify the gaps in our knowledge thereof.
	KEYWORDS

cryptochrome, earth's magnetic field, magnetite, radical pair, sensory cues.

1. INTRODUCTION

Life on earth is believed to have originated about 3.5 billion years ago. The earth's magnetic field (EMF) has been present since that time period under which life has evolved. It does not vanish altogether during periods of geomagnetic polarity reversals. Instead, the EMF continues to provide a reference frame for orientation. Animals use the EMF to move onward, which could function amidst troubles due to fog, rain, and clouds. Biophysics aids in the understanding of magnetoreception (MR) by living beings as well as biological processes (Yan et al., 2021; Dyer et al., 2021). Spatial orientation, along with the EMF, are the basic requirements for the evolution of MR. The EMF provides directional and positional information to animals and is hence used for navigation. The direction of magnetic force differs at various locations of the earth due to the shape of the field lines. At the North and South Poles, the magnetic force is vertical; at the equator, it is horizontal; and everywhere in between, it remains at an intermediate angle to the surface. With a typical duration of a few thousand years, a global magnetic field reversal is long enough for individuals to slowly adjust to the changing conditions (Leonhardt and Fabian, 2007).

The earth's rotating iron core creates EMF. The magnet at the center of the earth shapes the EMF lines and provides a signal to organisms. Emerging from the Southern Hemisphere, such a line curve encircles the globe. In the Northern Hemisphere, the line again enters the earth. The intensity of EMF varies, being the lowest at the equator and the highest at the poles. So, animals face a sharp inclination angle while moving northward from the equator. The EMF diverts the charged particles transported by its currents and protects the biosphere from the solar wind. The response of animals to EMF, called geomagnetotaxis, is a negative-positive orientation (Mandal, 2015). Organisms adapt to and alter the environment; they exploit the environmental signals for many purposes, like navigation and orientation. The dipolar character of EMF has evolved in the last 2 billion

years (Evans, 2006). EMF serves as a source of directional information for animals (Wiltschko and Wiltschko, 2005). The horizontal component of EMF work in darkness and gives the compass reference to adjust the directional reference, and inform the organism about polarity, inclination angle, and intensity. In insects, sense organs transform stimuli into nerve impulses that reach one of the central ganglia that bring change or maintain the existing behaviour. We intend to present our present knowledge of MR, an EMF-induced behaviour, and find the gaps in our information on MR along with its adaptive significance as revealed from studies with fruit flies, bees, and ants.

2. MAGNETORECEPTION

Mesmer affirmed the impact of universal gravitation on our bodies. He introduced the idea of animal gravitation in1766 in his doctoral thesis. Later, the idea changed to animal magnetism with Mesmer's experience of magnets (vide Crabtree, 1988). Thus, the history of animal magnetism goes back more than 250 years. The concept of animal magnetism has been debunked for a variety of reasons. However, researchers found MR as the topic of interest. In the last seven decades, information on MR has become enriched as a transdisciplinary study. Insects have a magnetic sense. Karl von Frisch identified the honeybee as an animal model for neuroethological studies. The revelation of the bumblebee's dance language in 1949 impacted ethologists as well as biologists. Animals need to know their present location and the direction of travel to reach their terminus. Many animals contain and exploit the properties of magnetic particles for navigation, orientation, and migration. The big question is whether animals have such a mental magnetic map to recognize regions by their characteristic magnetic fingerprints (Dennis et al., 2007).

There are three viable hypothesis about the physical mechanism to answer the question: (i) first one is based on magnetite in mechanosensitive structures, (ii) second one is based on a radical pair mechanism, and (iii) third one is based on induction (Kirschvink and

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Gould, 1981; Brown and Ilyinsky,1978; Schulten et al.,1978; Kalmijn, 1981).The present article attempts to present the first two hypothesis which are widely accepted. The magnetite-based MR model holds the view that animals sense the EMF through magnetite that informs the animals about the magnetic map (Kirschvink et al., 2001). A CRY-based process also called chemical(radical-pair) MR depends on light and magnet sensitive photochemical reactions. In chemical MR, the animal senses the axial alignment, inclination angle of the EMF lines and thus directional magnetic information for magnetic compass orientation. Studies involving transgenic animals have so far been conducted only in insects (Gegear et al.,2010). The results point to an involvement of the cryptochrome protein in MR through the radical-pair mechanism, at least in magnetic fields ten times stronger than the natural ambient field.

Magnetite, the most common magnetic iron oxide functions in MR. Organisms perceive and transduce magnetic cues, and transfer them to the brain for interpretation and to create effective MR. The central complex called navigational heart of the insect brain mediates movement and steering. Inclination of field lines and the precise distinction between the geographic North and geomagnetic North impact route. The other affecting variables are the polarity of field lines and the strength of magnetic field (Lohmann et al., 2007). Total intensity denotes the magnitude of the local magnetic field vector at any point on Earth. Ants and honeybees are well-studied for magnetite-based MR hypotheses (Kirschvink et al., 1997; de Oliveira et al., 2010). In the presence of blue light, the retinal CRY is hypothesized to be the only magnetosensors. Nocturnal insects like bees and ants seem to use a magnetite-based magnetic sense. But, both magnetite-based and CRY-based MR could occur at the same time in an insect species (Wiltschko and Wiltschko, 1995; Johnsen and Lohmann, 2008; Nordmann et al., 2017). Spatial variation in intensity and inclination of the EMF perhaps helps to detect the map. Light can reach the magnetoreceptors located at a peripheral site of the animals.

3. ROLE OF SENSORY CUES IN INSECTS' MAGNETORECEPTION

To proceed into the process of MR, it appears to us to provide a brief account of sensory cues. Indeed, MR cannot function in the absence of sensory cues. Animals need to know the "map" step and the movement of direction (the "compass" step) for navigation. Compasses are typically arranged in hierarchies. In the absence of celestial information, magnetic cues serve as backup. For animals to calibrate celestial cues and to recalibrate between magnetic and celestial compasses are situations require, magnetic information is important. Magnetic compasses are mostly magnetic crystal based. These crystals can give the direction of the goal and distance (Heinze and Reppert, 2011). Other compasses use paramagnetic interactions between visual pigments and the short wavelength. Odours are in use as cues in some cases (Gould, 1998). Besides, the polarized skylight creates a celestial pattern that serves as a minor compass cue (Reppert et al., 2004).

During first migratory phase, insects use stars, polarization pattern and the moon's disk as compass cues. The moon reflects sun rays like a disc rather than a sphere, as it seems to the naked eye. In fact, the moon is located far away and as a result all the light rays we receive as being parallel. The expected position of the sun at any point of time relative to the butterfly's migratory direction can be atoned for with the sun's movement (Mouritsen and Frost, 2002; Froy et al., 2003). Butterfly responds to wind turbulence and require partially for crosswind drift (Chapman et al., 2010; 2015; Reynolds et al., 2010). Magnetic and celestial visual cues include stars, the sun, the moon, and celestial polarized light which in turn mostly depends on the sun, and to some extent on the moon. Using these cues as a compass insect perhaps choose a desired course (migratory phase 1). Visual landmarks together with magnetic and olfactory cues detect the location after reaching the destination (migratory phases 2 and 3) in nocturnal migration. The monarch butterfly lacks map sense. The disk of the sun plays a major role as a cue (Stalleicken et al., 2005).

Monarch butterfly can sense the EMF (Guerra et al.,2014). However, their use of EMF besides the sun's disc as a compass is yet to be ascertained (Mouritsen and Frost, 2002; Stalleicken et al., 2005; Warrant et al.,2016). The moon is a less genuine cue for a long-distance nocturnal navigator than the sun is for a non-nocturnal navigator. Birds rely on EMF as a genuine compass cue and Bogongmoths have perhaps used the same (Wiltschko and Wiltschko, 1972; Cochran et al., 2004). They measure the visual optic flow of landscape characteristics and require this drift to control the flight (Srinivasan et al., 2006). The dim pattern of polarized light around the moon, the disc of the moon, and the constellations of stars serve as nocturnal compasses in long-distance navigation. Most such cues cannot function smoothly due to changing celestial positions throughout the night. Lunar cues also vary in their duration and brightness at various times of the month. MagR (a protein) binds with iron to form a rod-shaped complex along with CRY and act as a compass needle. Associative learning helps insects detect magnetic fields (Phillips and Sayeed, 1993). Bees get cues about the direction of the food source from the waggle dance (Wajnberg et al., 2010).

Learning behaviour is also important in have reviewed the learning process in insects. Path integration, pheromone trails, and responses to stimuli are innate behaviours that ease learning for navigation (Perry et al., 2017). Insects do not undertake long journeys during a change in the surrounding environment. They travel close to the nest to get information on the key features of the environment for future use. Visual cues and wind direction also play a role in navigation. Path integration has a key role in visual learning. Ants show ability to learn faster using bimodal cues (visual and olfactory) than ants with a single cue (Steck et al., 2009; Buehlmann et al., 2020). For orientation and navigation, the insects also use multimodal information. Coordinating the interaction between the multimodal strategies and information sources directs the route to meet the needs. This shows that the small brain of an insect is dynamic in spatial cognition (Merlin et al., 2012; Buehlmann et al., 2020). Various insects take positions in water or air and comeback to a place of safety by using spatial memories. Hymenopteran life histories need spatial memories to equip their young (Collett and Collett, 2002; Buehlmann et al., 2020).

4. ROLE OF MEMORY IN NAVIGATION AND ORIENTATION

There is a functional connection between the presence of magnetite in the abdomen and MR in bees (Liang et al., 2016). Magnetic cues function in the absence of celestial cues in the learning of visual landmarks or in noting patterns (Collett and Baron, 1994). When light and chemical cues are not found, bumblebees simply follow the trained direction to the food source (Chittka et al., 1999, Wajnberg et al., 2010). A shift of 900 magnetic fields in total darkness changes the flight orientation of A. milliner. In *Schwarziana quadripunctata* the flight direction in daylight at the point of exit of underground hives is on record (Esquivel et al., 2007; Wajnberg et al., 2010). Experimental results in the presence of magnetic nanoparticles suggest that EMF serves as an orientation cue (Lucano et al., 2006). Only the reversed vertical field affects the inclination of the light trajectory. This shows that bees can perceive the EMF whether the EMF remains in a pointed down or up direction. Bees can also identify the southern and northern hemispheres (Esquivel et al., 2008).

Gravity is supposed to provide the natural basis for this reference line. Bees with non-functional gravity receptors cannot perform waggle dances, supports this idea. In case of long distances, the local geomagnetic field (LGMF) is uniform and stable. The bees inform the position of food through orientation of a vertical comb in respect to LGMF and the LGMF affects (Lambinet et al., 2014). Factors like landmarks, pheromones, gravity, the sun compass, and polarized light, and vibrations help ants to orient. Ideally, these factors should remain concealed for the sole use of a magnetic compass. The experiment by attaching the iron filings to body parts of ant Myrmica retinoids was conducted. The effect of EMF on the orientation was noted only when the iron was attached with antennae. The pedicel of the antenna was the most sensitive to EMF (Vowels, 1954; Wajnberg et al., 2010). The strongest proof for the use of a magnetic compass is the study of the re-oriented polarity of EMF. A group researchers placed a solenoid on a foraging trail of black-meadow ant (Formica pratensis) (Çamlitepe et al., 2005).

Studies with biomagnetism in several insects like leaf cutter ants (*Atta colombica*), foraging weaver ants (*Oecophyllas maragdina*), *Solenopsis substitute, Pachycondyla marginata*, and *S. invicta* are recorded. Such studies concluded the presence of a compass based on SPM particles and the involvement of nanoparticles in long-distance orientation (Riveros and Srygley, 2008). Besides, the strongest saturation of magnetic materials in antennae, use of nocturnal orientation cues, vibrational or otherwise, are recorded in ants (Riveros and Srygley, 2008; Wajnberg et al., 2004). Ants also show sensitivity to the position of the Sun, polarization of celestial light, the geometric pattern formed by the tree branches on the celestial ceiling, the landscape of the near horizon and EMF in their navigation and orientation. Involvements of neurons that respond to magnetic field stimuli have not been confirmed in insects (Weinberg et al., 2010).

5. THE MECHANISM OF MAGNETIC SENSING

The magnetite hypothesis assumes that neurons containing magnetite crystals are connected to mechanosensitive structures. In the models of the crystals tend to align with the external magnetic field and thereby generate torque (Walker et al., 2002; Kirschvink, 1992b). The torque tries to rotate the magnetic inclusion, which is mechanically linked by

cytoskeletal filament structures to mechanically gated ion channels in the plasma membrane of nerve cells. The torque causes ion-channels to open, allowing the exchange of ions through the membrane, and finally producing a signal (for example, a change in the spontaneous firing rate). The signal can be interpreted by the brain and then used for decisions in behaviour or navigation. Magnetite-based MR can be temporarily disabled with a strong magnetic pulse that is short enough to remagnetize magnetite crystals without rotating or moving them (strength 0.5T, pulse length 0.5 ms; (Walker and Bittermann, 1989; Kirschvink and Kobayashi-Kirschvink, 1999).

The radical-pair hypothesis posits certain biochemical reactions that are sensitive to weak magnetic fields, such as the EMF. A spin-correlated pair is made of two radical pairs, in which each radical contains an unpaired electron with spin being either parallel or anti-parallel with respect to the other unpaired electron in the radical pair. Since each electron-spin has its own magnetic moment, the radical pair reaction can be influenced by magnetic fields. A radical pair can be generated by short- wavelength light in the candidate molecule, the cryptochrome (CRY) (Ritz et al., 2000). CRY has been found to be expressed in great concentrations in the retinal ganglion cells of night-migratory songbirds (Mouritsen et al., 2004).

5.1 Magnetoreception in the Fruit Fly

In adult and larval fruit flies, light wavelength influences the magnetic compass and orientation. When tested in a uniform arena of short-wavelength light (450 nm), the fly becomes trained towards a light gradient under UV light. They showed orientation towards the trained magnetic direction of the light gradient. Trained flies change their orientation by 90 degrees in long wavelength light (> 450 nm). Such a change happened with respect to the learned magnetic direction (Phillips and Sayeed, 1993). It demonstrates the presence of a light-dependent magnetic compass that responds to both short and long wavelengths of light. The spectral dependencies of magnetic compass orientation in flies are compatible with a CRY-based mechanism (Phillips et al., 2010).

5.2 Magnetoreception in Relation to Light

EMF activates CRY and activates voltage-gated calcium channels (VGCCs) in the fruit fly. The VGCC hypothesis states that EMF releases calcium ions. The calcium channel blockers protect against negative effects like oxidative stress (Pall, 2013). Calcium and VGCCs play a role in neurotransmission at excitatory synapses (Atlas, 2013). Only the pathway of light-dependent activation of CRY (by EMF) in the clock neurons leads to an increased action potential. This happens due to increased calcium release at synapses. CRYs are the key photoreceptor molecules and produce magnetically sensitive radical-pair products (Mouritsen and Ritz, 2005). The CRY is used by the fruit fly to respond to and orient to the EMF. An EMF affects the Fe3O4 of magnetite and produces a transducible signal. The fly does not respond to EMF in the wavelength of light above 420 nm. Filtered light influences the action spectrum of CRY, having a size of 350 nm in plateaus and 430-450 nm in plateaus (Van Vickle-Chavez and van Gelder, 2007). When the change in CRY happens due to a missense mutation, the fly loses MR.

The free radicals are produced by a tryptophan triad (Trp triad) composed of tryptophan residues—W324, W377, and W400 of the CRY. Trp triadphotoreduces the flavin cofactor of cryptochromes by electron transportation in vitro. Cryptochrome serves as a light-independent transcription repressor or photoreceptor. EMF works on such free radicals (Gao et al., 2015). The change of tryptophan protein does not affect the MR in the fly and the fly does not respond to the weaker EMF (Gegear et al., 2010). The photolyases produce long-lasting radical-pair intermediates to alter the effects of the magnetic field in the ancestral CRYs, (Giovani et al., 2003). After getting excited by light the cryptochromes generate an intermittent radical pair. Orientation as well as the strength of the external magnetic field are known to exert an influence the reaction rate of radical pairs (Liang et al., 2016). The function of CRY in fruit flies depends in part on earth-strength magnetic fields (Gegear et al., 2008). It can transduce magnetic field information into a biochemical signal.

Drosophila contains a magnetic receptor, CG8198, or MagR, and a multimeric magneto-sensing protein complex (Qin et al., 2016). MR-related CRY forms a magneto-sensing complex that responds to ironbased and CRY-based systems and aligns with the EMF. This protein complex forms the basis of MR (Qin et al., 2016). The quantity of iron that is associated with the MagR/CRY complex would not produce a permanent dipole moment (Meister, 2016). Reactions within the CRY protein form two molecules each with a lone electron having the potential to entangle with each other. They may exist in a single state (where the spinning direction of one corresponds to the spinning direction of the other) or in a triplet state (where two electrons rotate close to in parallel). The direction of the magnetic field controls the existence of singlet or triplet states.

If it can be assumed that the singlet and triplet states of the radical pair are linked with reactions, then the products of such reactions should give cues for the direction of EMF. If these substances influence neural signalling from the bird's retina, then this mechanism explains the basis for MR (Offord, 2019). Fruit flies offer many advantages for MR study. A functional fly CRY gene as well as broadband illumination of short-wavelength (420 nm) light function are required for MR. They jointly can discriminate a magnetic field that is about ten times the intensity of the EMF (Gegear et al., 2008). Besides playing a role in the CRY-mediated effects of blue light, EMF influences the circadian rhythm (Yoshii et al., 2009). Innate preference or associative learning helps flies detect magnetic fields (Phillips and Sayeed, 1993). CRY-expressing cells perhaps represent the magneto sensory neurons as shown in the cell-specific gene knockdown of CRY. A subset of proteins interacts with CRY, binds with iron, and is expressed in the head of the fly.

The first evidence for CRY-based MR remains the training of male fruit flies to respond to a magnetic field depending on the ambient wavelength of light (Phillips and Sayeed, 1993). In the fruit fly, CRY regulates visual perception, light-dependent arousal, circadian photoentrainment, as well as UV avoidance. Perception of the EMF depends on a light-dependent magnetic sense. Electron transfer causes a conformational change in CRY that releases the C-terminal tail (CTT) of CRY and frees the binding sites for downstream partners. When CRY is not exposed to light, the CTT functions as a repressor and blocks the binding site for downstream intermediates. CRY on exposure to light interacts with the core clock protein Timeless (TIM) for proteasomal degradation. Thus, the release of CTT regulates interactions to bring about behavioural changes. In CRYmediated MR, the ROS is produced at the flavin reoxidation step on exposure of CRY to light.

Exposure of CRY1 to BL activates the protein and creates ROS and H2O2. Overexpression of the redo regulating protein catalase depletes H2O2, blocking the increase in action potential firing in the clock neurons. Lightinduced increases in neuronal excitability cause the closure of voltagegated potassium channels in the presence of HYPERKINETIC(HK), a Kv potassium channel subunit. The subunit is redo-sensitive due to an intrinsic aldo-keto-reductase domain. Thus, a photo-induced change in protein structure may perhaps enhance neuronal activity and activate the downstream signalling processes. Besides, such a change influences the cellular redox state, along with the interference in the functioning of the Kv channel. The latter mechanism appears to be intriguing as it is an HKdependent mechanism and an identical redox-modulates sleep in fruit flies (Bradlaugh et al., 2021).

5.3 Magnetoreception in Bees

Bees are highly sensitive to EMF, especially for orientation and navigation. For this reason, most such studies rely on bees. Adult honeybees have an MR sense and use EMF directional information (Ferrari, 2014). Bees learn to respond to changing local magnetic fields (Gould et al., 1980). This response requires exposure to abnormal magnetic fields (Lindauer and Martin, 1972). Magnetic material in front of the abdomen, thorax, and antenna mediates the orientation. The magnetic grain starts to develop in pupa and is also found in adults (Gould et al., 1978). The highest (2.4 to 0.15 g mg-1 tissue) iron level appears to be present in the fat body of adult workers when they start to forage. Paramagnetic substances create extra magnetism (Gould et al., 1980).

Electron-dense materials in SD and SPM magnetite are known to be found near the cuticle (Schiff, 1991). Magnetite in the abdomen exhibits sensitivity to EMF. Iron, calcium, and phosphorus granules having a diameter of 0.32 0.07-Um remain in the cytoplasm of cells of the abdominal segment (Kuterbach et al., 1982). The size and number of the granules vary according to the age of the bee. The bee extracts the iron from both the pollen and the honey. Kuterbach and Walcott suggest that iron granules play a role in orientation and iron homeostasis (Kuterbach and Walcott, 1986). Severe fluctuations in the earth's magnetosphere may occur due to major coronal eruptions under the sun's influence. Such fluctuation disturbs a forager's homing ability and even leads to the loss of this ability. Biomineralization of iron helps understand the basis for MR. Tracking EMF direction using magnetite reveals that mechanical orientation of crystals alters signal transduction, which in turn alters the ion channels of the cellular membrane (Winklhofer and Kirschvink, 2010).

The bees form superparamagnetic magnetite iron granules in the trophocytes of the abdomen (Hsu and Li, 1994). They deposit iron minerals intracellularly. Biomineralization in *Apis mellifera* is completed

in two steps. In step 1, the iron deposition vesicles (IDVs) enlarge due to fusion with one another. In step 2, dense particles (7.5 nm in diameter) produce the iron granules with the help of a layer beneath the membrane of IDVs (Hsu and Li, 1993). EMFs may expand or contract the superparamagnetic particles in an orientation-specific manner. Variations in particle size trigger the increase, resulting in the release of intracellular Ca++. A neural response starts upon receiving the magnetic signal from the associated cytoskeleton. In bees, the responses of the proboscis extension reflex (PER) exist (Liang et al., 2016). PER is used to train the bees to associate an odour with it. The trained bees can associate with the magnetic stimulus. Bees fail to recognize magnetic stimuli if a cut in the ventral nerve cord (VNC) occurs, indicating the function of the VNC in signal transmission. But they respond to an olfactory PER task.

Bees identify the fluctuations in static intensity as weak as 26 nT against the background EMF. MR decreases rapidly with increasing EMF frequency (Kirschvink et al., 1997). A honeybee can detect small fluctuations in the EMF and weak earth-strength magnetic fields. The disorder study explains the loss of homing potential of the forager bee (Ferrari, 2014). Bees exploit the GMF for aligning the combs within the hives and for orientation in foraging. In the case of unaltered polarity, they respond to the magnetic anomaly but do not respond to it in reversed polarity (Lambinet et al., 2017). Thus, they must have a polarity-sensitive magnetoreceptor. The waggle dance, foraging, and flight of *Apis mellifera* show the existence of MR. Bees find cues for the direction of the food source from the foragers' waggle dance (Wajnberg et al., 2010; Liang et al., 2016; Lindale and Martin, 1972; Wajnberg et al., 2010).

In the abdomens of *A. mellifera*, the magnetite retains a residue of magnetization at the normal temperature (Gould et al., 1980). The absence of such particles in the head and thorax shows only a diamagnetic contribution (Takagi, 1995). The antennae contain the highest amount of magnetic material in *A. milliner* (Wajnberg et al., 2010). Squid magnetometry confirms the presence of SPM magnetite in trophocyte granules in the abdomens. Purified iron granules (IGs) show high intrinsic coercivity (Hsu et al., 2007; Weinberg et al., 2010). The low hydration level of crushed abdomens decreases the average magnetic volume of SPM particles (Wajnberg et al., 2001). He intensity in the abdomen is higher than in other body parts. Thus, accessing a small amount of magnetic material is difficult in body parts of *Schwarziana quadripunctata*. The properties of magnetic material in various bees differ.

Phosphorus and calcium remain in a clear, non-crystalline arrangement in IGs (Hsu and Li, 1993). The fat body of A. mellifera and Scaptotrigon apostica queens contains iron granules. These granules originate from holoferritin, calcium, and phosphorus (Keim et al., 2002). Changes in IG size of trophocytes provide further support for MR function (Hsu et al., 2007; Wajnberg et al., 2010). A group researchers could not de-magnetize the magnetic material of honeybees because it was in the form of superparamagnetic crystals (Gould et al., 1978; 1980). Honeybees can distinguish between the presence or absence of magnetic anomalies. They fail to do so when a magnetic wire is attached to the anterodorsal surface of their abdomen (Walker, 1989). This shows the likely location of the magnetoreceptor in the abdomen. Response to EMF of varying intensity and frequency shows that bees can distinguish between alternating fields when the frequency remains below 10Hz (Kirschvink et al., 1997). But they need the stronger fields to do so when the frequency is raised. This finding supports the magnetite-based MR hypothesis.

After returning from foraging, foragers inform other bees about the location of food materials by exhibiting a dance relative to the vertical direction of hive combs. The angle between the direction of dance and vertical points indicates the angle between food and the sun. Worker honeybees travel up to 12 km to collect food away from their hive and memorize visual landmarks to find their way home. They get directional information from the sun. The bees utilize the spectral pattern in the sky to guess the position of the sun in the presence of a cloud. They measure the distance information and integrate it for navigation. Honeybees detect EMFs most likely through granules (magnetoreceptors) in their abdomens. Although CRY occurs in the honeybee brain, its use in MR is seemingly unknown. The cytochrome remains a potential MR effector in honeybees. Although iron granules have the potential to be magnetoreceptors, the association of the iron granules with MR has not yet been confirmed and is still not convincing because they respond to changes in the magnetic azimuth in total darkness.

Cryptochromes become ineffective in the absence of UV-A/blue light (420 nm). As bees become older, iron granules (suspected magnetoreceptors) become clumped. The state of iron granules and the age of bee's influence MR. However, the relationship of iron granules with MR is yet to be

confirmed. The role of iron-containing cells in the neural system is yet to be confirmed. The cry functions, on the other hand, are light-dependent. The honeybee can detect the magnetic field in their hive in a dark environment. Such a detection mechanism could not explain the CRYbased MR in insects, but it can be easily explained by the magnetite-based MR. In *S. quadripunctata* bees, the highest amount of magnetic material is believed to be present in the head and antennae. Bees can discriminate between oscillating magnetic fields at frequencies of at least 60 Hz. with very good directional magnetic compass sensitivity. These data have been extensively reviewed (Kirschvink, 1982; Kirschvink et al., 2001).

5.4 Magnetoreception in Ants

Reversal of the local magnetic field reverses the orientation of *Oecophyllas maragdina* (Jander and Jander, 1998; Wajnberg et al., 2010). *P. marginata* also uses a magnetic compass for orientation during migration. They use the GMF to find the axial migratory routes. In *Solenopsis interrupta* and *S. substitute*, a higher magnetic content is found in the head and antenna than in other body parts (Acosta-Avalos et al., 1999; Abraçado et al., 2005). The abdominals of workers of *S. invicta* mediate the MR. Magnetic particles and magnetic sensors were extracted using magnetic precipitation methods from *P. marginata* (Acosta-Avalos et al., 1999; de Oliveira et al., 2010; Wajnberg et al., 2010). The antenna contains a high concentration of pure Fe/O (or Fe oxides) particles as sensorial materials. Johnston's organ perceives the EMF and gravity in *M. ruginodis* and *M. laevinodis* (Vowles, 1954; Wajnberg et al., 2010).

Iron and other particles perhaps cover the proprioceptor in the pedicelscape joint. Magnetic particles close to mechanosensitive tissues along the antenna reveal the physiology of MR (Vowles, 1954; de Oliveira et al., 2010). Ants perhaps collect magnetic materials from the soil. Ants explore the surrounding areas for food. During the return to the nest, they mark the way back with pheromones that are straight in the direction of the exit of the tunnel. Ants such as *Pachycondyla marginata* use the EMF for orientation (Acosta-Avalos et al., 2001). Tests showed that the most promising parts for MR in ants are the antennae (Acosta-Avalos et al., 1999; Wajnberg et al., 2000; 2004). A group researcher were finally able to find iron-rich crystals in the Johnston's organ in the antennae of *Pachycondyla marginata* and identified the magnetite, maghemite, and the relatively weakly magnetic goethite and haematite (Oliveira et al., 2010).

In principle, the magnetic moments of the magnetic crystals in the EMF can produce a mechanical moment that can be transmitted into a neuronal signal via a mechanosensitive structure (Kirschvink and Gould,1981; Shcherbakov and Winklhofer, 1999; Davila et al., 2003; 2005; Ferreira et al., 2005). The Johnston's organ, a mechanosensitive structure, also works as a graviceptor or an acceleration receptor (for hearing or flight control) (Sandeman, 1976). With the recent finding of magnetic minerals, the Johnston's organ could also serve as a magnetoreceptor (Oliveira et al., 2010). The characteristic magnetic properties of these iron-mineral deposits have not been determined yet, and it remains unclear if the structure meets the basic requirements for MR.

6. DISCUSSIONS

Biophysics is unwinding the components of bio-magnetic impact that results in further development of MR in terrestrial organisms (Kobayashi and Kirschvink 1995). The role of CRY helps unravel the mechanism of MR. Insects contain Type 1 (found only in fruit flies), Type 2 or both types of CRY. Type 1 CRY and both CRYs play a role in circadian clock regulation (Zhu et al., 2005). *Drosophila*-like Type 1 CRY are sensitive to ultraviolet-A/blue wavelengths of light and serve as circadian photoreceptors (Ozturk et al., 2008). The slow drift of the geomagnetic reference frame accumulates with time, which helps in the periodic calibration of the magnetic compass. In the absence of familiar landmarks, organisms find a target in true navigation by using a map and a compass (Gould and Gould, 2012; Kirschvink, 1982). Biomineralization produces a variety of biomaterials in animals (Bauerlein, 2005). Insects have very few neural components. So, information from insects can reveal the vital components for navigation.

The role of associative links between long-term memories has been found in bees and ants in their MR (Merlin et al., 2012). Magnetic orientation is widespread among animals. However, the role of the neurosensory system and magnetoreceptors is enigmatic in insects. EMF serves as a cue for navigation and orientation in insects, but environmental factors like the position of the sun influence navigation and orientation remarkably. Further study is required to understand how insects calibrate with EMP from various parts of the world and navigate in the absence of suitable environmental cues. Sensory mechanisms behind magnetoreception along with its genetic basis may be elucidated for furtherance of this field of neuroethology. Magnetoreception studies have been carried out in few sample insects. These experimental studies have revealed the existence of two possible but hypothesized mechanisms of magnetoreception. Presently we cannot preclude the existence of other mechanism of magnetoreception in insects. Thus, it is safe to conclude that further studies are required to gain information on the possible theories that could integrate the existing knowledge of magnetoreception in insects in a consolidated scientific framework.

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