Disrupting Magnetic Compass Orientation with Radio Frequency Oscillating Fields

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Abstract: I have investigated the influence of a weak oscillating electromagnetic field in the radio frequency (RF) range on radical pair reactions in the presence of the geomagnetic field by solving the stochastic quantum mechanical equations describing the radical pair reaction. The results show that the radical pair reaction yields obtained in the presence of only the geomagnetic field are altered by RF oscillating fields. Using a linear transduction model, the three-dimensional response patterns of a magnetoreceptor based on an ordered array of radical pairs are evaluated in the presence and absence of the oscillating field. The calculated response patterns can be used to predict the outcome of behavioral experiments. An important result is that the presence of weak RF magnetic fields would lead to disruption of magnetic compass orientation if the magnetic compass were based on a radical pair mechanism. In contrast, RF fields should have no effect on magnetic compass orientation if it were based on magnetite particles. On the basis of the theoretical studies, behavioral experiments of magnetic compass responses in the presence of RF fields are proposed as a means to elucidate the biophysical mechanism of vertebrate magnetoreception.

1 Introduction

Many animals use the geomagnetic field as a source of directional information (Wiltschko and Wiltschko 1995). However, neither the biophysical mechanism nor the receptor molecules for this physiological compass have been identified with certainty.

Among the many theoretical suggestions for the primary mechanism responsible for magneto-reception, two physically very different mechanisms appear to be particularly promising on theoretical and experimental grounds: (1) magnetoreception based on reorientation of ferromagnetic material, e.g., magnetite, and (2) magnetoreception based on the interaction of the geomagnetic field with the magnetic moments of electrons and nuclei, e.g., a compass based on radical-pair reactions (Schulten et al. 1978, Schulten 1982) or on a resonance process (Leask 1977).

Theoretically, both types of mechanisms are feasible, i.e., the weak geomagnetic field is expected to alter the respective processes to a large enough extend that its effect can be detected in the presence of thermal fluctuations and noise. This is since long known in the case of ferromagnetic particles with a ship's compass being a prime example, while changes in radical-pair reaction yields through the geomagnetic field have only recently been demonstrated (Batchelor et al. 1993).

Experimentally, efforts to corroborate a magnetite-based reception mechanism have focused on the detection of biogenic magnetic material in animals with known orientation abilities (Kirschvink et al. 1995, Walker et al. 1997). Most recently, reorientation of magnetite domains was demonstrated in trout (Diebel et al. 2000).
While the latter finding suggests strongly that the magnetite domains are part of a compass system, it has not been shown whether and how these domains are connected to the nervous system. Moreover, even if one showed conclusively that a particular animal employs a magnetite-based compass, this would not rule out that other primary magneto-reception mechanisms are employed in other animals, as suggested by, e.g. varying responses of different animals to an inversion of the vertical/horizontal components of the magnetic field (polarity vs. inclination compass; Wiltschko and Wiltschko 1995a).

For the hypothesis that magnetoreception is based on magnetic moments of electrons and nuclei, theoretical considerations led to the suggestion that light with a sufficiently high energy is required to excite a photoreceptor which then activates the hypothetical magnetoreception system. Consequently, experiments have been conducted under varying ambient light conditions. Under low-energy, i.e., long-wavelength monochromatic light, either a shift in orientational response or disorientation was observed (Phillips and Borland 1992, Wiltschko et al. 1993, Deutschlander et al. 1999, Wiltschko et al. 2000). The suggestion of testing magnetic responses under varying ambient light conditions has proven very fruitful, if only in adding additional results from experiments that might have not been performed without this suggestion. However, a change in ambient light conditions is ill suited to discriminate between the different suggested magneto-reception mechanisms. Disruption of magnetic responses is not sufficient to prove that magneto-reception is based on molecular magnetic moments, because models can be built that show how a primary reception mechanism based on magnetite domains can be affected by light (Edmonds 1996) and because the change in ambient light may affect parts of the animal's nervous system other than the magnetoreception system. On the other hand, activation of the hypothetical magneto-reception system could occur through other mechanisms than photoactivation. Thus, the absence of an effect of ambient light or the ability of an animal to orient in darkness do not rule out that magnetoreception is based on electron and nuclear magnetic moments.

The physics of the interaction of magnetic fields with magnetic moments of electrons and nuclei opens an avenue for a new type of experimental tests that are, in theory, better suited to discriminate between the two magnetoreception hypotheses, namely the use of high-frequent electromagnetic fields in the range of 1-50 MHz during testing for magnetic responses. In the present article, I will provide an overview over the effects of such radio frequency (RF) fields on the interconversion reactions between molecular states with different magnetic moments, using radical-pair systems as an exemplary system. In an ensuing discussion, I will describe the expected effects of RF fields on behavioral experiments. It is hoped that experimentalists are encouraged to conduct behavioral tests in the presence of such fields.

2. Effects of RF Fields on Radical-Pair Reactions

2.1. Interaction of Magnetic Fields with Molecules

Electrons and nuclei carry an intrinsic magnetic moment which is proportional to their spin. Likewise, molecules consisting of many electrons and nuclei form quantum states with different spins and magnetic moments, namely singlet states with spin zero and triplet states with spin one. Molecules in different spin states are chemically different, e.g., they have different energies and engage in different reactions. A transition from a singlet to a triplet state can therefore act as a molecular switch initiating a sensory reaction. For example, if only the triplet states give rise to the production of a neurotransmitter, the yield of triplet states will correlate to a nervous signal. Let us assume for the sake of illustration that the triplet yield gives rise to a nervous signal and that molecules are initially in a singlet state. The question arises then by which mechanism a magnetic field can influence the triplet yield. The mechanism depends on the strength of the magnetic field.

If the magnetic field is sufficiently strong, its interaction with the spin states will change the energy of the triplet states, typically increasing the energy gap between singlet and triplet states. Due to the increased energy gap, transitions from singlet to triplet states are encumbered and therefore the yield of triplet states decreases. This energetic effect occurs, however, only for magnetic fields of at least ten times the geomagnetic field strength.

A magnetic field as weak as the geomagnetic field can only have an effect on singlet-triplet transitions for special classes of molecules, e.g., spin-correlated radical pairs. While in most molecules electrons form pairs with a net spin of zero, a radical has an unpaired electron with a spin of ½ and a non-vanishing magnetic moment. The magnetic moment of the electron interacts with the magnetic moment of the nuclei. This interaction is termed the hyperfine coupling and results in a periodic movement of the electron magnetic moments. In a spin-correlated radical pair, the two unpaired electrons on the two radical molecules obey a phase relationship, and, thus, the radical pair (rather than an individual radical) exists in either a triplet or a singlet state. Due to the above mentioned periodic movement of electron magnetic moments in the field of the nuclei, the radical pair periodically changes from a singlet to a triplet state. It is in this special case that an additional weak magnetic field can change the speed of singlet-triplet interconversion, and, thus, the triplet yield. The reaction scheme described here is illustrated in Figure 1.

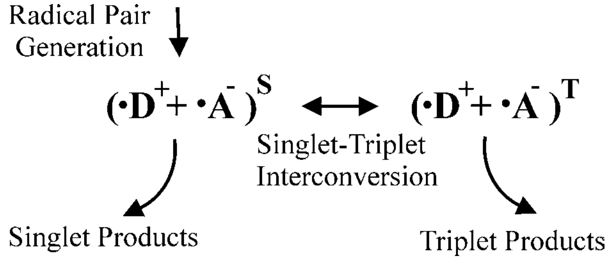

Figure 1: Reaction scheme for a radical-pair reaction with magnetic field-dependent reaction products. An external magnetic field affects interconversion between the singlet and triplet states.

A magnetic compass as opposed to a pure magnetic sensor requires that the triplet yield changes with the orientation of the radical pair with respect to the geomagnetic field. This is the case when the hyperfine coupling is anisotropic. A possible model for a magnetic compass based on radical pairs with anisotropic hyperfine couplings has been presented in (Ritz et al. 2000).

Transitions between singlet and triplet states can occur by another, fundamentally different mechanism. If an external electromagnetic field provides an amount of energy which equals the energy difference between singlet and triplet states, it can induce a transition between these states. Electromagnetic fields in the radio frequency range, i.e., between 1 and 50 MHz carry suitable energy to induce singlet-triplet transitions. The effect of RF oscillating fields should thus be to alter the triplet yield of radical pairs and change the response of a magnetic compass based on radical-pair processes.

However, the heuristic discussion in this section can not replace a realistic evaluation of the effect of static and oscillating magnetic fields on radical pair processes with anisotropic hyperfine couplings by solving the appropriate stochastic quantum mechanics equations. Effects of weak oscillating magnetic fields on isotropic radical pairs have been studied theoretically in Timmel et al. (1996) and experimentally in Stass et al. (2000). Effects of weak static magnetic fields on isotropic radical pairs have been studied theoretically by Timmel et al. (1998) and experimentally by Eveson et al. (2000). Very recently, effects of weak static magnetic fields on anisotropic radical pairs have been studied systematically (Timmel et al. 2001). Here, we follow the approach in (Ritz et al 2000) and choose an exemplary radical pair with anisotropic hyperfine couplings to illustrate the effect of weak oscillating magnetic fields on anisotropic radical pairs in the presence of a weak static magnetic field (the geomagnetic field). A systematic study of such effects is beyond the scope of this article and, in fact, still subject of ongoing research.

2.2 The Effect of RF Fields on a Sample Radical Pair

For the radical-pair reaction scheme illustrated in Figure 1, triplet yields are calculated using the theory and approximations presented in (Ritz et al. 2000). We employ a very simple radical pair with only one nucleus with non-vanishing magnetic moment per radical. Furthermore, we assume that the decay processes into singlet and triplet products (cf. Figure 1) occur with identical rates. Hyperfine couplings are taken to be a_{xx}= 2 G, a_{yy}= 0 G, a_{zz}= 20 G for radical 1 and b_{xx}=b_{yy}=b_{zz}= 2 G for radical 2 (0 G for elements not listed). In Figure 2, the triplet yields for this radical pair are shown as a function of the angle of the z-axis of the radical pair with the direction of a static magnetic field of 0.5 G (the geomagnetic field). Triplet yields are shown in the presence (top) and absence (bottom) of an additional oscillating magnetic field with a frequency of 22.4 MHz and amplitude of 0.25 G. The frequency of the oscillating magnetic field was chosen such that a maximal change in the triplet yield was induced by the oscillating magnetic field.

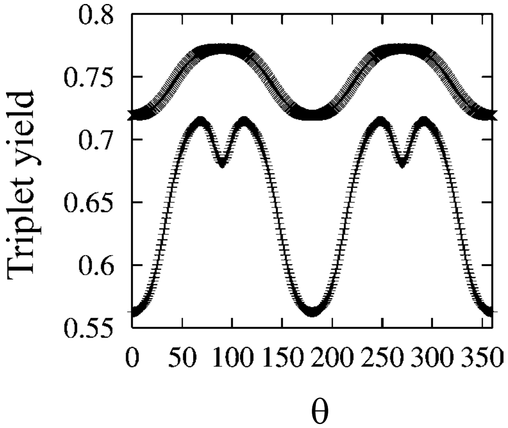

Figure 2: Triplet yield Φ_T as a function of the angle θ between the direction of the geomagnetic field and the z-axis of the radical pair. **Top:** Triplet yield in the presence of an RF oscillating field. **Bottom:** Triplet yield in the absence of an RF oscillating field. The RF field changes the amplitude and the shape of the yield.

Without the RF oscillating field, the triplet yields changes by more than 15% when the angle between radical pair and geomagnetic field is changed. The RF oscillating field reduces the size of this change to about 5%. Furthermore, the shape of the angular dependence is changed by the RF oscillating field; the dip around 90^o and 270^o vanishes in the presence of the RF field.

If one assumes that the radical pairs are arranged on a sphere, the modulation of triplet yield will result in three-dimensional response patterns as shown in Figure 3. In evaluating the response patterns, I have coded the response *s* by integers in the range 0 (black) –255 (white), with *s* =127 corresponding to the response for a triplet yield Φ_0 averaged over all angles. Deviations from this assumed baseline of response are then evaluated according to the linear transduction formula

$$s\,(\theta) = 127 + 255 * 4\,[(\Phi_T(\theta)-\Phi_0)]$$

The parameters in the above formula are chosen in such a way that the magnetic field effects become discernable to the human eye in a static picture. The values of the parameters may be very different in an animal's sensory transduction system.

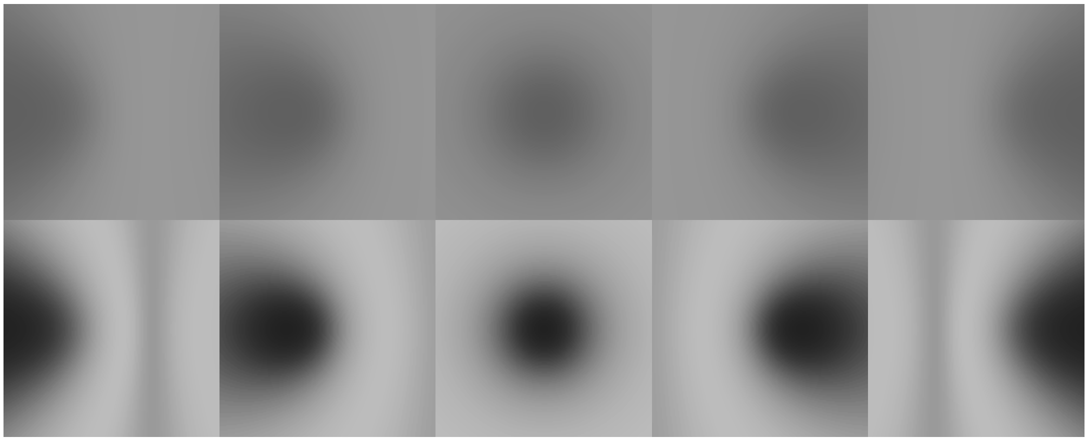

Figure 3: Response patterns for an animal oriented parallel to the magnetic field lines (0°) and veering to the left and right by 30° or 60°, respectively. **Top:** response patterns in the presence of an RF field. **Bottom:** response patterns without an RF field.

It has been discussed earlier (Ritz et al. 2000) how such response patterns can furnish an animal with the ability to obtain directional information from the geomagnetic field. The response patterns in the absence of an RF field (bottom row) correspond to undisturbed orientation. The presence of the RF field diminishes the contrast of the response patterns. The central disk feature in the response pattern, which is clearly visible in the absence of the RF field becomes hardly distinguishable in the presence of the RF field. Furthermore, the stripe feature which can be seen at the 60° angles, vanishes in the presence of the RF field. Because of this loss of contrast and structure, one expects that the ability of an animal to orient with respect to the geomagnetic field is disrupted in the presence of RF fields, provided that magnetoreception is based on a radical pair mechanism.

In the present calculations, it was assumed that the RF field has a similar amplitude as the geomagnetic field. However, effects on the orientational ability of animals may be found for much weaker RF oscillating fields depending on how sensitive the transduction system is to changes in the triplet yield. A 1% change in triplet yield can be induced by an RF oscillating field of only 0.005 G, i.e., a hundred times weaker than the geomagnetic field.

It should be noted that it is not clear in which way a change in the triplet yield and the associated theoretical response pattern, as shown in Figure 3, affects the behaviour of an animal. Under certain combinations of hyperfine couplings and RF field strengths, an animal's response may be changed rather than disrupted; in these cases the effect of an RF field could be to rotate the direction of the orientational response rather than to lead to complete disorientation.

3. Interaction of RF Fields with Magnetite

An oscillating field in the RF range changes its polarity about every 100 ns. Can a magnetite particle follow the fast oscillations of the RF field or is it too inert to do so? In (Diebel et al. 2000) magnetite domains of about 100 nm extension were observed with a magnetic dipole moment of 10^{-17}-10^{-16} Am^2. A magnetic field of 1 G exerts thus a torque of 10^{-21}-10^{-20} Nm on the magnetite particles, which corresponds to a force of 10^{-14}-10^{-13} N acting on the ends of a cylindrical magnetite particle of 100 nm length. The torque sets the magnetite particle in rotation, but has to overcome the drag of the surrounding environment, which I assume to have the viscosity of water, namely about $\eta=10^{-3}\text{kgm}^{-1}\text{s}^{-1}$. For simplicity, I only consider the drag on two spheres at the end of the magnetite particle according to the Stokes relation. The force F of 10^{-14}-10^{-13} N causes the spheres to move with a constant velocity $v=1/\gamma\ F$, where γ denotes the drag coefficient, which is $\gamma=6\pi a\eta$ for a sphere of radius a. I assume a radius of a=1 nm, which is certainly a low estimate. Calculating the time that is needed to move the distance of $\pi/4*100$ nm (corresponding to the circumference of a 100 nm particle rotating by 90^o), one arrives at a time constant of 10-100 μs, which is 100-1000 times longer than the oscillation period of the RF field. The actual rotation time of the magnetite particle is likely to be longer; the above rough estimate gives a lower limit.

One can conclude that rotation of magnetite particles as observed in (Diebel et al. 2000) is too slow to be significantly influenced by a weak (<1 G) RF oscillating field and one would therefore expect that weak RF fields do not influence the response of a magnetic sensory system based on the reorientation of magnetite. Indirect effects may occur such as, e.g., heating of the magnetite particles or the cell environment through excitation of molecules by the RF field; however the initial response of an animal to the geomagnetic field should be unaffected by the presence of an RF field.

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4. Experimental Tests

4.1. Essential Tests

Many behavioural assays exist in which magnetic compass orientation of animals can be demonstrated reproducibly. Using any of these assays, one can test for magnetic responses in the presence of RF fields. If the magnetic compass is based on a radical pair reaction, the response will be disrupted or changed in the presence of RF fields, whereas the response will not change if the magnetic compass is based on a magnetite system. This type of test had been suggested earlier by John Phillips (personal communication) on the basis of anecdotal observations. In the following, I attempt to suggest the most promising design on the basis of theoretical considerations.

Two parameters of the RF field need to be chosen, namely the amplitude and the frequency of the RF field. For testing, a broad band RF field covering the range from 1 to 50 MHz should be applied, because theory predicts that fields within this frequency range are most likely to induce transitions between spin states, however, the exact location of resonance frequencies depends on the unknown details of the radical pair system involved. The choice of suitable field strength is suggested by the patterns shown in Figure 2. A choice of a 0.25 G radio frequency field produced a pronounced change on the response patterns and thus appears to be a good choice as an initial test amplitude. For radical pairs with different anisotropic hyperfine couplings than the ones employed in the present calculations, the details of the RF field effects will vary, but RF fields of a similar strength as the geomagnetic field are expected to have an effect on the triplet yield for a large variety of radical pairs (Timmel et al. 1996, Stass et al. 2000). Therefore, an unchanged magnetic compass orientation in the presence of a 0.25 – 0.5 G RF field precludes that magnetoreception is based on radical-pair processes. On the other hand an RF field of this strength is not expected to change a magnetoreception mechanism based on magnetite domains as discussed above.

If a change or disruption of magnetic compass orientation can be observed, the amplitude should be decreased further to measure the sensitivity threshold. More importantly, one also needs to ensure that the RF fields affect the magnetic sensory system and not some other part of the animal's nervous system. In this regard, disruption through RF fields has a clear advantage over disruption through long-wavelength light. Whereas animals have developed sensory mechanisms to detect light, RF fields are essentially man-made, i.e., evolutionary new, and until now no sensory system is known that would enable animals to detect weak RF fields. Most likely, weak (<0.5 G) RF fields are not detected at all by an animal, except for their interaction with the hypothetical radical-pair-based magnetoreceptors. Therefore, RF fields are not expected to have an effect on assays in which an animal shows an orientational response to non-magnetic cues (e.g. sun or polarized light). Only disruption of magnetic compass orientation together with an undisrupted alternative compass orientation in the presence of RF fields furnishes a strong case for a radical-pair based magnetoreception mechanism.

4.2. Further Investigations

The changes in response patterns induced by the RF field as shown in Figure 3 are very similar to the changes induced when the strength of the static magnetic field is reduced to 0.1 – 0.2 G (cf. Figure 8 in Ritz et al. 2000). A change in field strength beyond a small window around 0.5 G resulted in the loss of the magnetic compass orientation of birds (Wiltschko and Wiltschko 1972), however, after acclimatization at the altered field strengths, birds were able to orient at the altered strengths. In analogy, given a loss of magnetic compass orientation in the presence of RF fields, one needs to investigate whether animals can adapt to the presence of RF fields.

Finally, the question arises whether RF fields with discrete frequencies could be used as a probe to identify the nature of the molecules involved in a radical-pair based magnetoreception mechanism. To answer this question one needs to study the effect of RF fields on more realistic radical pair systems than the one studied here. Recent results from a study of the interaction of weak *static* magnetic fields with radical pairs with anisotropic hyperfine couplings (Timmel et al. 2001) suggest that possibly only a very limited class of radical pair architectures is capable of detecting weak magnetic fields. If this assertion holds true it may indeed be possible to gain information about the size of the dominant hyperfine couplings in the radical pair system by probing at which discrete frequencies magnetic orientation is disrupted or changed.

However, before exploring this possibility further, one first needs to firmly establish that RF fields do have an effect on magnetoreception. Testing which animals, if any, change their magnetic compass orientation in the presence of RF fields will, regardless of the outcome of the experiments, provide a big step towards the elucidation of the magnetoreception mechanism(s) in animals.

Acknowledgement

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