Magnetic Orientation and RF Fields: Possible Mechanisms of Interaction

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The Bird

European Robin, 
*Erithacus rubecula*

Wiltschko Lab, Frankfurt
Method used to record directions in captive birds:

Funnel cage by Emlen & Emlen (1966)

Funnel cage lined with coated paper

Funnel paper on a light desk
The Response
(Magnetic Compass)

European Robin

Wiltschko Lab, Frankfurt

Wiltschko and Wiltschko, Science 176: 62 (1972)
Experimental Set-up for Tests Under Monochromatic Light
Experimental Set-up for Tests Under Monochromatic Light
Light Affects Magnetic Compass

LED - Spektra

Wavelength (nm)

Austr. Silvereye
European Robins
Garden Warbler
Carrier Pigeon
Domestic Chicken
Change of Vertical Component

Local geomagnetic field  Vertical component reversed
Inclination Compass

Inclination = angle of the magnetic field with horizon

Birds detect inclination angle, not polarity of the magnetic field

Wiltschko and Wiltschko, Science 176: 62 (1972)
Strength of geomagnetic field in Frankfurt ca. 46 000 nT

Avian magnetic compass operates in a narrow functional window that adapts to local magnetic field conditions.
Diagnostic test for radical pairs: Radio Frequency Magnetic Fields

High-frequency magnetic fields will affect radical pairs via resonances if high-frequency field is strong enough and has right frequencies.

Resonances with hyperfine interactions: 0.1-50 MHz
Free electron resonance (Larmor-frequency) for 50 µT: 1.4 MHz

will not affect iron oxide particles
Iron oxide particles cannot track weak oscillating fields above 100 Hz
Ferromagnetic resonances are in 500 MHz-GHz range

High-frequency fields should affect behavior
Effects of RF fields on magnetic compass responses

Testing different frequencies
Test in the local geomagnetic field at three frequencies and various intensities:

- 0.65 MHz
- 1.315 MHz = Larmor frequency of free electron
- 2.63 MHz
Summary of the behavioral tests:

Ritz et al., Biophys J, 2009
Strong resonance at Larmor Frequency has been observed in 4 species:

- **Chicken**: Keary et al., Front. Zool. 6 (2009)
- **Zebra Finch**: Vacha et al., J Exp Biol 212 (2009)
- **Mole-rats**: no effect

Thalau, Ritz et al. (2006), J. R. Soc. Interface 3
Shift of strong resonance to 2.63 Mhz in 92 µT field
No effect
if high-frequency field is parallel to static field

Magnetic field effects on spin-selective reactions

\[ D_{\uparrow} + A \rightarrow \text{Singlet} \]

\[ k_S \]

\[ \text{Singlet Products} \]

\[ D_{\uparrow} + A \rightarrow \text{Triplet} \]

\[ k_T \]

\[ \text{Triplet Products} \]
Magnetic field changes concentrations

Singlet + A \rightarrow D + A

Triplet + A \rightarrow D + A

magnetic nuclei + external field

\[ H(\vec{B}) = H_1(\vec{B}) + H_2(\vec{B}) \]

\[ H_j(\vec{B}) = g\mu_B \vec{S}_j \cdot (\vec{B} + A_j\vec{I}_j) \]

Signal

Singlet Products

Triplet Products

light

electron transfer

k_S

k_T
Yield as Measure of MFE

\[ F_S(t) = \text{Tr}[P^S \sigma(t)] \quad \Phi_S = \int_0^\infty k_S F_S(t)dt \]

\[ \dot{\sigma}(t) = -\frac{i}{\hbar} [H, \sigma(t)] - \frac{k_s}{2} [P^S, \sigma(t)] + \frac{k_T}{2} [P^T, \sigma(t)] \]

Spin-independent decay kinetics: \( k = k_S = k_T \)

\[ F_S(t) = \frac{1}{N} e^{-kt} \cdot \sum_{m=1}^{4N} \sum_{n=1}^{4N} |P^S_{mn}|^2 \cos[\omega_{mn} t] \]

\[ \Phi_S = \frac{1}{N} \sum_{m=1}^{4N} \sum_{n=1}^{4N} |P^S_{mn}|^2 \frac{k^2}{k^2 + \omega^2_{mn}} \]

Upper bound for \( k \): about 1 MHz
Optimal Sensitivity: Free Electron Radical Pair

Symmetry in zero-field Hamiltonian broken by Zeeman interaction + coherent link = additional oscillation channels:

Decreased singlet yield in singlet-born RP
In Vitro Proof-of-Principle

Peter Hore lab, Oxford

RF Field Effects: Expectations

Low-frequency cut-off if field becomes effectively static $\omega_{RF} \ll k$

High- and low-frequency cut-off if field outside of HFI-induced splittings
Testing different frequencies
RF Field Effects on Free-Electron RP: Expectations

Sharp Resonance at Larmor Frequency: $\omega_{\text{res}} = \gamma_e B$

(1.315 MHz for 46 $\mu$T; 2.63 MHz for 92 $\mu$T)

Relative strength to other resonances: $\sim$30x stronger

No effects if RF field is parallel to static field
RF Effects: Expectations for Free-Electron RP

1.315 MHz (for 0°-parallel)

Shift for other static field
Quantitative interpretation requires more information.

0.1% at 10 µs, rapid increase around $\gamma_e B_{RF}$ saturation at > 1ms.

Noise level?
Signal Transduction? informs required $\Delta \Phi$
Alternative Mechanisms?

Ferromagnetic Resonances: Typically at much higher frequencies (GHz)

Resonances with other interactions (spin-orbit couplings, nuclear spin resonances)

What could we do next?

Observation:
RF Fields can “switch off” magnetic orientation respin birds (and cockroaches)

1. “Switching on” magnetic orientation in birds

2. Interfacing with other responses: light responses, viability(?)
   Any response affected by static magnetic fields via a radical-pair mechanism should also be affected by RF fields

3. Genetic engineering of novel phenotypes
   (via cryptochrome as molecular transducer)
   If cryptochrome responses are affected by magnetic fields and RF fields, then introducing cryptochromes into organisms might create new RF-sensitive phenotypes
Molecular Transducer: Cryptochrome?

Only photoreceptor known in birds to form **radical pairs**
Found in retina of birds

Flavin (fully oxidized)

- 450 nm

Flavin (semiquinone)

- 520 - 620 nm

Flavin (fully reduced)

$+O_2$
MFE on purified protein in steady-state fluorescence

% change
(B=0.5G) - (B=5 G)

time
MFES on Light Responses Regulated by Cry

An anthocyanin accumulation graph is shown, comparing treatments under different magnetic field strengths (40μT and 500μT) across three trials.

A bar graph illustrates hypocotyl growth inhibition with treatments under different light intensities (465 nm blue light, 633 nm red light) compared to the dark control.

Cry stability is shown through a Western blot, indicating protein expression levels under different light and magnetic field conditions.

Ahmad, Galland, Ritz et al. Planta (2007)
Avoidance responses of 5 G field
Differences between trained/untrained responses
Effects require functional Cry

Light entrainment of circadian rhythm affected by 5G field

Substituting human Cry in flies leads to similar responses

Reppert lab
Ahmad lab
New Phenotypes sensitive to MFE?

Selective pressure on magnetic avoidance responses: “super-sensitive” fruit flies?

Introducing cryptochromes into bacteria: changes in viability, light responses changes in magnetic sensitivity? oriented responses?
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Alexandre Colavin, Gabe Dilanji, Anita Vora

Collaborators

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Do we have a magnetic compass?

Highly controversial “Manchester Experiments” (Robin Baker, 1970s)

Potentially more meaningful: modulation of visual threshold (Thoss, 2003)

Verdict still out, but even if we have a compass it is not very trustworthy