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International Journal of Radiation Biology

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/irab20

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INTERNATIONAL JOURNAL OF RADIATION BIOLOGY
https://doi.org/10.1080/09553002.2024.2435329

ORIGINAL ARTICLE

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A mechanistic understanding of human magnetoreception validates the phenomenon of electromagnetic hypersensitivity (EHS)

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ABSTRACT

Background: Human electromagnetic hypersensitivity (EHS) or electrosensitivity (ES) symptoms in response to anthropogenic electromagnetic fields (EMFs) at levels below current international safety standards are generally considered to be nocebo effects by conventional medical science. In the wider field of magnetoreception in biology, our understanding of mechanisms and processes of magnetic field (MF) interactions is more advanced.

Methods: We consulted a range of publication databases to identify the key advances in understanding of magnetoreception across the wide animal kingdom of life.

Results: We examined primary MF/EMF sensing and subsequent coupling to the nervous system and the brain. Magnetite particles in our brains and other tissues can transduce MFs/EMFs, including at microwave frequencies. The radical pair mechanism (RPM) is accepted as the main basis of the magnetic compass in birds and other species, acting via cryptochrome protein molecules in the eye. In some cases, extraordinary sensitivity is observed, several thousand times below that of the geomagnetic field. Bird compass disorientation by radio frequency (RF) EMFs is known.

Conclusions: Interdisciplinary research has established that all forms of life can respond to MFs. Research shows that human cryptochromes exhibit magnetosensitivity. Most existing provocation studies have failed to confirm EHS as an environmental illness. We attribute this to a fundamental lack of understanding of the mechanisms and processes involved, which have resulted in the design of inappropriate and inadequate tests. We conclude that future research into EHS needs a quantum mechanistic approach on the basis of existing biological knowledge of the magnetosensitivity of living organisms.

Abbreviations: CRY: cryptochrome protein molecules expressed by (italised) *CRY* or *cry* genes; hCRY: human cryptochrome; DECT: Digital Enhanced Cordless Telecommunications (a wireless Standard); EF(s): electric field(s); ES: electrosensitivity; EHS: electromagnetic hypersensitivity (EHS); ELF: extremely low frequency magnetic fields, 3 Hz to 3 kHz; ELF-EMFs: extremely low frequency electric and magnetic fields, 3 Hz to 3 kHz; EMF(s): electric and magnetic field(s) or electromagnetic field(s) (EMFs can refer only to the magnetic component and used interchangeably with MFs, reflecting their use in the literature); EMR: electromagnetic radiation; FAD: Flavin adenine dinucleotide; FADH: Flavin radical (FADH•); GM-field or GMF: geomagnetic field; GM-storms: geomagnetic storms; HPA: Hypothalamic-pituitary-adrenal axis; ICNIRP: International Commission on Non-Ionizing Radiation; IEI-EMF: idiopathic environmental intolerance attributed to EMF; ISCA1 (MagR): protein involved in assembly of iron-sulfur clusters; LAN: Light at night; MF(s): magnetic field(s); PEMF: pulsed electromagnetic fields; RF EMF(s): radio frequency electromagnetic field(s); RPM: radical pair mechanism; RP(s): radical pair(s); ROS: reactive oxygen species; rTMS: repetitive transcranial magnetic stimulation; S-T: singlet – triplet (in RPM mechanism); Trp: Tryptophan; μT: microtesla; nT: nanotesla; ULF-MFs: ultra-low frequency magnetic fields; VGIC: voltage gated ion channels; VLF: 3–30 kHz; WHO: World Health Organization

ARTICLE HISTORY
Received 26 September 2024
Revised 8 November 2024
Accepted 22 November 2024

KEYWORDS
Magnetic fields; EMF; electromagnetic hypersensitivity; EHS; magnetoreception; cryptochromes

1. Introduction

Human *electromagnetic hypersensitivity* (EHS) or simply *electrosensitivity* (ES), known in the past as *microwave syndrome*, is a general term describing adverse responses to exposure to one or more of the features of *electromagnetism* (Schliephake 1932). These include time-varying *electric fields* (EFs), *magnetic fields* (MFs), *extremely low-frequency electric and magnetic fields* (ELF-EMFs), such as those associated with power lines, and *radio frequency electromagnetic fields* (RF-EMFs) from modern wireless devices, such as mobile phones, together with their *electromagnetic radiation* (EMR).

Increasing numbers of people (in the region of 3%) claim they are sensitive to such man-made *time-varying* EMFs,

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particularly those at radio frequencies. The reported EHS symptoms are wide ranging and include headaches, tinnitus, fatigue, and skin symptoms, such as prickling, burning sensations, and rashes. These reactions occur at exposure levels well below the natural MF strength of the Earth and many orders of magnitude below current international guidelines for EMF exposure (Figures 1 and 2, Appendix A) (ICNIRP 2010, 2020; IEEE 2019).

Conventional medical science usually attributes EHS symptoms as being psychologically driven by '*electrophobia*' or the '*nocebo*' response. The World Health Organization (WHO) currently states that '*EHS has no clear diagnostic criteria and that there is no scientific basis to link EHS symptoms to EMF exposure*'. The WHO uses the term *idiopathic environmental intolerance attributed to EMF* (IEI-EMF) (WHO 2005).

Most subjective provocation studies fail to confirm EHS as an environmental illness. However, a fundamental lack of understanding of the mechanisms and processes involved has resulted in the design of completely inappropriate provocation tests (Leszczynski 2022) and in unsustainable interpretation of their findings (Bosch-Capblanch et al. 2024).

Interdisciplinary research has established in numerous species that all forms of life respond to MFs, in some cases with extraordinary sensitivity. Many species also respond to EFs, although the body of available research is limited in comparison to that concerning magnetoreception.

This study investigates whether EHS in people is a syndrome that adversely affects human well-being caused by environmental exposures and if so, by what mechanism(s) it occurs. We ask the following key questions:

i. *How are some living organisms, including humans, sensitive to EMFs from natural and anthropogenic sources at levels well below the essentially static geomagnetic (GM) field of between 23 and 65 microtesla (μT) and many orders of magnitude below current human exposure guidance levels?*
ii. *What are the biophysical processes by which EMF signals may be sensed?*
iii. *Which biological processes account for responses to exposures?*
iv. *Which of these factors may be related to human electromagnetic hypersensitivity* (EHS)*?*

By examining in detail the latest systematic reviews of human epidemiological and experimental research (Röösli et al. 2024;

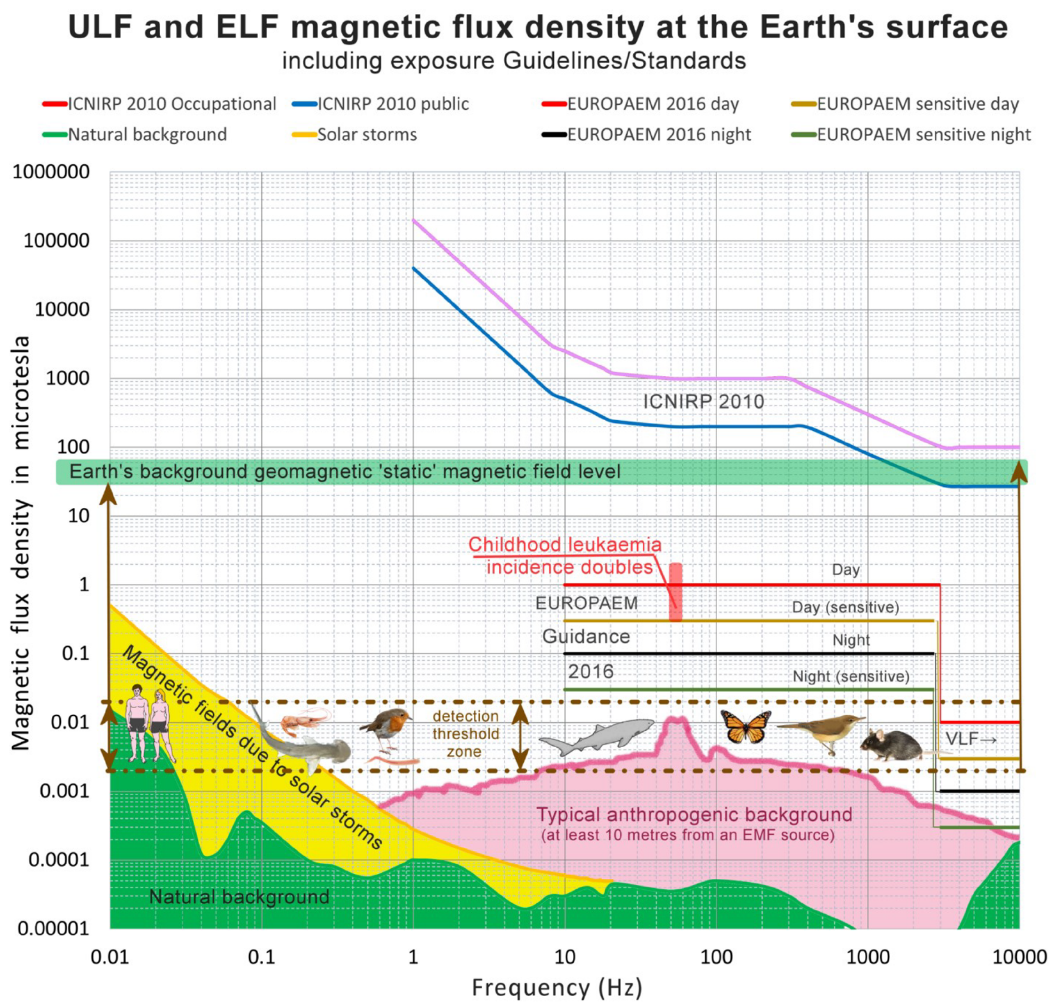

Figure 1. A contextual guide to DC–10 kHz environmental magnetic fields and their interactions. Illustrative natural and anthropogenic magnetic flux levels are shown along with the ICNIRP and EUROPAEM maximum exposure guidance levels (ICNIRP 2010; Belyaev et al. 2016). Common daily exposures at 50/60 Hz are in the range of 0.1–10 microteslas. The threshold detection range for other species is discussed in detail in the main article text. Background levels are derived from a number of sources (ITU-R P.372-16 2022; NASA Report CR-166661 1981; NASA Report SP-8017 1969).

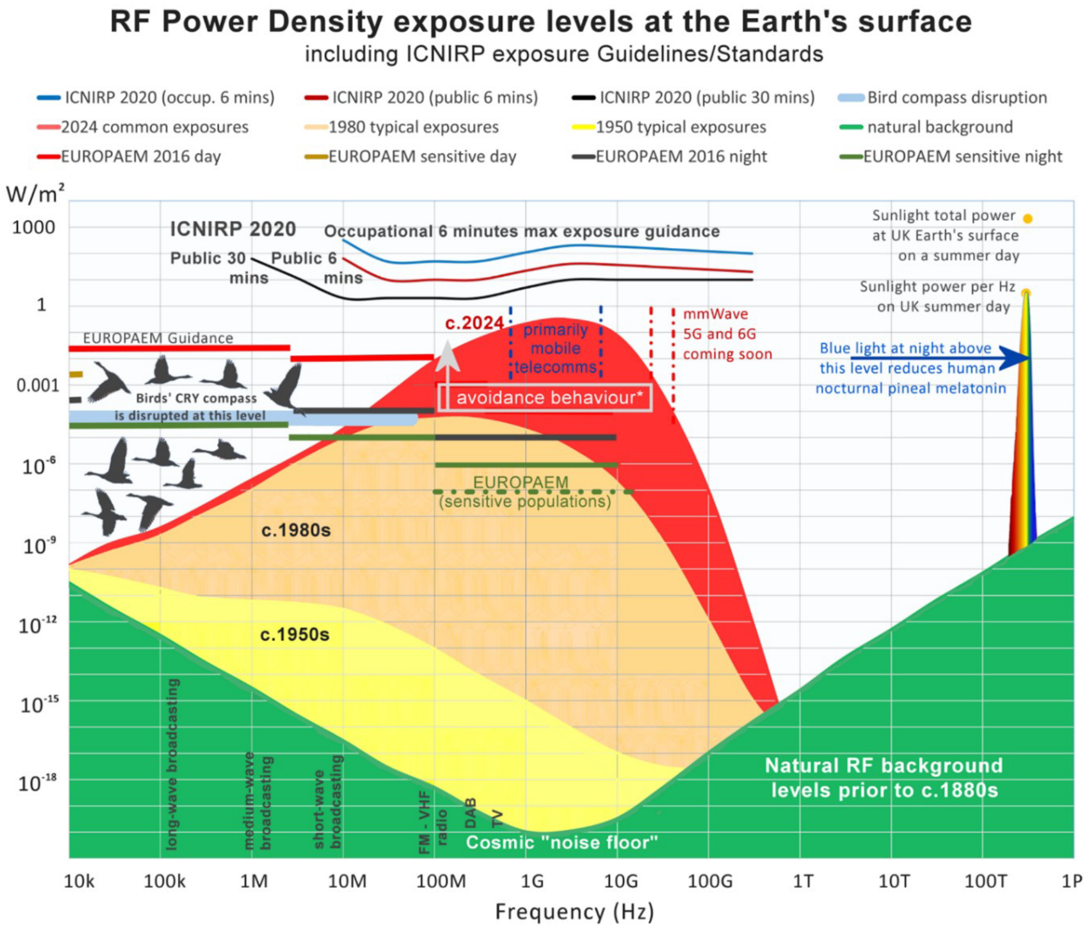

Figure 2. A contextual guide to EMR (10 kHz–1 PHz) power density exposure and interactions. Illustrative anthropogenic and natural EMR levels are shown for several periods in the evolution of wireless communication technologies, along with other relevant information, including exposure guidance levels provided by EUROPAEM (Belyaev et al. 2016) and other bodies (ICNIRP 2020; IEEE 2019). The 2024 levels are now experienced daily by most members of the general public for short or long periods of time. The values were ascertained from a wide variety of sources, including scientific, and engineering papers, formal RF surveys and field measurements made by coauthor Alasdair Philips. For *'avoidance behavior'*, see Pophof et al. (2023). Background levels are derived from a number of sources (ITU-R P.372-16 2022; Kraus and Fleisch 1999; NASA Report CR-166661 1981; NASA Report SP-8017 1969). The natural atmospheric RF levels at some frequencies are relatively high near the equator (Granger et al. 2022).

Bosch-Capblanch et al. 2024; Schmiedchen et al. 2019), we find them not fit for purpose. A major problem is the vast heterogeneity of modern anthropomorphic exposures and outcomes, making these studies impossible to assess as an overall group. This is made worse by inadequate measurement and reporting of the MFs involved (frequency, strength, and morphology). In addition, inadequate electromagnetic hygiene used for sham exposures in experimental studies, especially with respect to complex mixes of EMF signals, results in uncontrolled exposures that do no more than act as confounders.

The underlying design of many human studies is often based on ICNIRP EMF exposure guidance documents, which only recognize exposures that cause thermal effects or electric shock. (ICNIRP 2010, 2020; IEEE 2019).

1.1. Study selection methodology

The central aim of this study is to identify the key advances in understanding the mechanisms behind magnetoreception across the wide kingdom of animalia for a wide range of natural and anthropomorphic MFs in our environment.

To find appropriate studies, we consulted the Web of Science, PubMed, and the EMF portal. For animal magnetoreception, we also consulted the Royal Institute of Navigation database, which routinely searches 78 core journals. We include some recently published findings. Such cases are discussed as work in progress.

The mode of literature selection for this study differs from that in the field of epidemiology. It is not necessary to weigh the results of a wide range of heterogeneous studies. Once established, mechanistic discoveries are characterized by their exactness. An example is the radical pair mechanism (RPM), by which low-intensity MFs can alter chemical reaction rates and reaction products. This mechanism is well established and does not require further validation.

2. Background

From magnetotactic bacteria to humans, the ability to respond to MFs is ubiquitous among the so-called five kingdoms of life (Pazur et al. 2007; Wang et al. 2019; Chae et al. 2022). Many species also respond to EFs as well as MFs

(Wever 1979; Henshaw et al. 2008). In terms of sensing, scientific evidence shows that *ES* is universal. This article addresses primarily MF/EMF sensitivities due to external fields. An additional overview study of EF sensitivity is also desirable, but is discussed only briefly here since the available literature on EF interactions is more limited.

Some MF responses are beneficial, such as the ability of birds, fish, amphibians, and insects to detect changes in the Earth's MF (the geomagnetic field [GMF]) for the purposes of navigation and migration and in the clinical use of pulsed EMFs for treating major depressive disorders (Blumberger et al. 2018) and nonunion bone fracture healing (Markov 2015). However, other MF and EMF responses from both natural and anthropogenic sources are also reported to be linked to adverse effects on health and well-being.

Over the past two decades, the search for plausible causal pathways of MF and EMF interactions with biological systems has gained considerable traction. A specific focus in relation to adverse health effects is the established 2-fold increase in the risk of childhood leukemia associated with time-weighted average exposure to power frequency (ELF) MFs above 0.4 microtesla and, more recently, a 1.2-fold increase in the risk above 0.2 microtesla (Ahlbom et al. 2000; Greenland et al. 2000; Zhao et al. 2014; Seomun et al. 2021). A number of authors have explored a mechanistic pathway involving MF disruption of melatonin and circadian rhythms via action on cryptochrome protein molecules in the eye (Henshaw and Reiter 2005; Vanderstraeten and Burda 2012; Vanderstraeten et al. 2012; Henshaw and Reiter 2005; CwCUK 2014; Vanderstraeten et al. 2015; Juutilainen et al. 2018; Landler and Keays 2018; Sherrard et al. 2018; Henshaw et al. 2024).

Two primary MF sensing mechanisms are widely discussed. Magnetic particles in the human brain are large enough to transduce MFs/EMFs, including at microwave frequencies. In some cases, such transduction is sufficient to open mechanically sensitive transmembrane ion channels and, in turn, has the potential to influence a wide range of cellular processes (Kirschvink, Kobayashi-Kirschvink, Woodford, 1992; Kirschvink, Kobayashi-Kirschvink, Diaz-Ricci, et al. 1992). The quantum mechanically based radical pair mechanism (RPM) has successfully described the basis of the magnetic compass of birds and some other species, acting via cryptochrome protein molecules in the eye (Ritz et al. 2004; Pakhomov et al. 2017; Karki et al. 2021). More broadly, the RPM plays a central role in the emerging field of *quantum biology,* which describes a range of biological processes that cannot be accounted for by classical physics (Marais et al. 2018; Zadeh-Haghighi and Simon 2022).

Such recent advancements in understanding mean that it is timely to assess our current knowledge of the interaction of low levels of MFs and EMFs with biological systems. To address the above questions, we focused our attention on sensing by the brain of MFs or EMFs, either through direct or indirect neural pathways. We then attempt to unify our understanding across a range of topics, from magneto-sensing in animals to EMF treatment therapy and adverse health effects commonly known as EHS. Human EHS should be viewed as a particular case. Some reported effects may be due to *electrophobia* and are triggered by worry, but careful examination of the evidence also suggests effects occur from real exposures via plausible causal mechanisms.

Relatively rare biological responses need to be considered in a wider context. Prescription drugs, for example, generally have listed side effects of 1 in 10; 1 in 100 or even fewer. Moreover, an individual's basic maximum sensitivity to light, sound, touch, and smell varies by many orders of magnitude. Our senses are logarithmic in response and have significant '*integrated active gain control*' that attempts to optimize sensitivity for the current relevant incoming environmental exposure (Beckon et al. 2008).

3. Examples of magnetic sensing

3.1. Magnetoreception in plants and animals, navigation, and migration

There is now a high degree in understanding how birds and certain other species detect changes in the Earth's MF as low as 10 nanoteslas (nT) for purposes of navigation and migration (Pakhomov et al. 2017). It has been repeatedly shown that the bird compass can be disrupted with RF MHz fields in the low nT range. As explained below, much-discussed is the RPM, which acts on cryptochrome protein molecules in the eye. Moreover, a second mechanism based on magnetic particles in the body is postulated to provide magnetic intensity information in birds and many other species.

Magnetosensitivity has been demonstrated in numerous animal species. Further details together with a discussion of the mechanisms of action may be found elsewhere: in avian species (Wiltschko and Wiltschko 2009; Wiltschko et al. 2021), fish (Naisbett-Jones and Lohmann 2022), and amphibians (Phillips et al. 2022). A particularly interesting example is mole rats. Some species spend their entire life living in total darkness, where they are able to use the GMF to help construct an underground maze of tunnels (Burda et al. 1990; Burda 2021).

Many insect species are magnetosensitive, including bees, cockroaches, firebugs, fruit flies, desert ants, the monarch butterfly, and the Australian Bogong moth, both of which use the GMF as an aid to navigation (Merlin 2023; Dreyer et al. 2018). Cryptochromes are present in the eyes and brains of all insects, and their role as magnetoreceptors has been critically reviewed (Merlin 2023). Numerous biological effects of RF-EMFs on insects have been identified, and their coupling to the nervous system has been examined (Thill et al. 2024).

Plant microorganisms and fungi also display magnetosensitivity, with much interest in their mechanisms (Galland and Pazur 2005; Pazur et al. 2007; Thoradit et al. 2023).

3.2. Human and animal responses to GM storms

The GMF plays an important role in the existence of life on Earth (Sarimov et al. 2023a, 2023b; Zhang et al. 2021).

GM storms are associated with adverse effects on health and well-being, and 10–15% of tsshe population seems susceptible

Table 1. Effects of geomagnetic storms on human biology and health.

Increased ↑ Decreased ↓	
Depression	↑
Suicide incidence	↑
Heart rate and attacks	↑
Arterial pressure	↑
Stroke	↑
Nocturnal melatonin	↑↓
Basophils and leucocytes	↑
Cholesterol	↑
Migraine headaches	↑
Basophils and leucocytes	↑
Platelet aggregation	↑
Fibrinogen concentration	↑
Skin blood perfusion rate	↑

to them (Table 1). These include increased incidence of depression and effects on mental health; increased risk of suicide in vulnerable individuals; and heart rate variability, blood pressure changes, stroke, and melatonin disruption (Kay 1994; Nishimura et al. 2020; Vieira et al. 2022; Palmer et al. 2006; Feigin et al. 2014; Ghione et al. 1998; Dimitrova et al. 2004; Azcárate et al. 2016; Azcárate and Mendoza 2017; Burch et al. 1999; Weydahl et al. 2000; Burch et al. 2008; Krylov 2017). Two up-to-date reviews point to the extensive literature that now exists on the health effects of GM storms and low-intensity MFs, including a major contribution from research in the field of space medicine (Sarimov et al. 2023a, 2023b).

Remarkably, these acute effects are associated with small, ultralow-frequency MF variations of around 150 nT over a 3-h period in GM storms lasting up to 5 days. There are approximately 4–5 such events annually. GM storms result from streams of charged particles from the Sun reaching the Earth. At sea level, this results in small fluctuations of 50–250 nT, under 1% of the otherwise relatively stable GMF (which varies around the world between ~23 and 65 μT).

Some of the above findings have been demonstrated in objective human provocation studies involving healthy volunteers who do not claim to be adversely sensitive to EMFs. In separate experiments, healthy volunteers were exposed to previously recorded GM storms under laboratory conditions (Caswell et al. 2016; Gurfinkel et al. 2018; Pishchalnikova et al. 2019). In each experiment, statistically significant changes in cardiovascular parameters were observed compared with exposure to quiet GMF conditions.

Similar provocation experiments involving exposure to simulated EMFs under controlled laboratory conditions have also been carried out on various species. A time-compressed simulated GM storm was reported to influence the nest-exiting flight angles of bees (Esquivel et al. 2014). Wistar male rats exposed to MFs based on real GM storm activity exhibited statistically significant changes in arterial blood pressure when a real GM storm occurred during the experimental period (Martinez-Breton and Mendoza 2016; Martinez-Breton et al. 2016).

Simulated GM storms disrupted nocturnal migratory activity in songbirds (Bianco et al. 2019), and changes in GMF intensity altered migration-associated traits in the brown planthopper *Nilaparvata lugens* (Wan et al. 2020). Normal fluctuations in the GM field have been reported to affect the initial orientation of pigeons (Kowalski et al. 1988).

Powerline ELF-EMFs have been reported to exert strong physiological stress on honeybees (Molina-Montenegro et al. 2023). California poppies growing within 10–25 m of ELF-EMF sources with MF exposures of 7–9 μT received fewer honeybee visits and produced fewer seeds than did plants growing far from sources. High-voltage powerline ELF-MFs were shown to disrupt the alignment of the bodies of ruminants with the GMF (Burda et al. 2009). Cattle exposed to various MFs directly beneath or in the vicinity of powerlines trending in various magnetic directions exhibited distinct patterns of alignment. The disturbing effect of the ELF-MFs on body alignment diminished with increasing distance from the conductors.

RF fields as low as 1 nT anthropogenic electromagnetic noise in the MHz range were shown to disrupt magnetic compass orientation in migratory European robins, *Erithacus rubecula* (Engels et al. 2014). The magnetic orientation of the Antarctic amphipod *Gondogeneia antarctica* was disoriented in an RF field as low as 2 nT, indicating the extraordinary sensitivity of animal magnetoreception to weak RF fields in marine invertebrates (Tomanova and Vacha 2016).

3.3. Human responses to Earth-strength magnetic fields under controlled laboratory conditions

Here, we outline two independent studies that were carefully designed and well conducted and demonstrated human magnetoreception of the GM field under controlled laboratory conditions (Wang et al. 2019; Chae et al. 2022). Details of the purported sensing mechanisms are discussed more fully in Section 4.

In the first study, each of 36 volunteers sat inside an electrically screened chamber, housing three orthogonal sets of square coils that allowed the ambient GM field to be altered around the participant's head (Wang et al. 2019). All exposures were carried out in the dark. The authors reported strong, specific human brain responses to ecologically relevant rotations of Earth-strength MFs. Following geomagnetic stimulation, a decrease in the amplitude of electroencephalography (EEG) alpha oscillations (8–13 Hz) occurred in a repeatable manner. Biophysical tests revealed that the neural response was sensitive to static components and the polarity of the applied MFs. This rules out a purely quantum-mechanical mechanism based on the RPM, the RPM, which can detect only axial alignment. These observations are consistent with a sensing mechanism involving magnetic particles.

In the second study, each of 34 male volunteers sat on a rotatable chair was exposed to a variety of GMF-like MFs with various intensities, inclinations, and magnetic north directions (Chae et al. 2022). Prior to each experiment, the subjects underwent short-term starvation or were fed normally. In an *association phase*, subjects facing the ambient magnetic north were either conditioned or not conditioned to associate this direction with food. During the *test phase*, in which the modulated magnetic north was randomly set to true magnetic north or true magnetic south, the subjects were asked to indicate the modulated magnetic north direction.

Under full-wavelength visible light (350–800 nm), subjects who had been starved to produce a significant reduction in blood glucose levels and with food previously conditioned to be associated with magnetic north, showed a significant increase in the ability to orient correctly using the rotating chair compared with subjects who had not been conditioned.

Further tests revealed that human geomagnetic orientation is highly sensitive to light wavelength and that blue light plays a critical role. No significant differences between orientation rates in dark conditions were observed, indicating that light was crucial for correct magnetic orientation.

The presence of RF-EMFs in the MHz range was tested on the volunteers, as described elsewhere in relation to the orientation of birds (Ritz et al. 2000, 2004). Exposure to 1.260 MHz, the electron Larmor frequency in the ambient GMF (45.0 μT), and lower-frequency broadband MFs, but not a 1.890 MHz field, significantly disrupted the magnetic orientation, suggesting EMF interference with a RPM.

These reported results are inconsistent with magnetite-based magnetoreception but support the notion that light-activated radical pairs probably mediate magnetic orientation in humans.

Thus, a study that is consistent with magnetosensing involving magnetic particles (Wang et al. 2019) appears to contradict a study that supports a light-dependent RPM mechanism (Chae et al. 2022). However, the two studies used very different experimental assays that could be probing different receptors. Humans may have two methods of magnetoreception, in common with birds, which are thought to have a radical pair-based compass in the eyes for direction sensing and magnetic particles elsewhere for intensity sensing.

In summary, the results of several provocation experiments and natural observations in animals mimic the findings of adverse health effects of GM storms in humans. They are characterized by blinded exposures and objective measurements, which, in the case of humans, do not assume conscious sensing of the applied EMFs.

3.4. Human EHS associated with RF-EMF exposure

A significant increase in the number of people reporting adverse health effects due to EHS has occurred in recent years, along with a corresponding increase in environmental anthropogenic EMFs, most commonly from modern wireless devices.

Conventional medical science usually diagnoses EHS effects as psychosomatic 'nocebo' effects. EHS effects cover a wide range of health problems, including headaches, tinnitus, fatigue, stress, skin symptoms, such as prickling, burning sensations and rashes, musculoskeletal pain, sleep disorders, mood issues, dizziness, and many other health problems (Landgrebe et al. 2009; Medeiros and Sanchez 2016; Leszczynski 2022). These effects are largely self-reported, but their veracity is supported by objective measurements of MF sensing in humans and various species cited above.

While many of these symptoms are specific to man-made EMFs, they overlap with some of the acute symptoms associated with GM storms. However, whereas MF fluctuations from GM storms result in comparatively rare exposures, in today's environment, there is chronic exposure to a wide range of EMF fluctuations from man-made sources (Figures 1 and 2).

3.5. Electromagnetic field treatment

A large body of basic science and clinical evidence demonstrates that time-varying MFs of millitesla strength, well above normal ambient exposures, can modulate molecular, cellular, and tissue functions in a physiologically and clinically significant manner. While the cellular mechanisms remain unclear, MFs are used in a range of conditions to treat depression, reduce pain, improve wound and bone healing, increase blood circulation, and stimulate the immune and endocrine systems (Markov 2015). The use of pulsed electromagnetic fields (PEMFs) for the treatment of major depressive disorders is of particular interest because it illustrates the direct influence of EMFs on the human brain (Blumberger et al. 2018).

4. Mechanisms of action

By what mechanism(s) do animals and some people display sensitivity associated with MF and/or EMF exposure, be it from natural or anthropogenic sources, at exposure levels well below that of the GMF, in some cases below 10 nT? (Engels et al. 2014; Tomanova and Vacha 2016).

One approach is to identify biological markers of EHS in a manner similar to that used for chemical sensitivity (Belpomme et al. 2015; Belpomme and Irigaray 2020, 2022, 2023). However, it is unclear whether such markers are consequential rather than causal of EHS or whether they contribute to predisposition. The challenge in understanding EHS is the shear selectivity of the response to EMF exposures. This, in turn, suggests a cognitive response, regardless of any intrinsic biological susceptibility.

To address this question further, we need to understand the difference between the primary sensor (based on physical or chemical principles), the transducer, which is biological in nature, and the whole-organism response involving cognitive input (Figure 3). A well-known model for a cognitive response is the so-called *'Orchestra analogy'*. Imagine a music connoisseur listening to a piece of orchestral music. Suddenly, an otherwise faint instrument plays a wrong note. The connoisseur hears this immediately and may be quite disturbed by it, while the less discerning may be oblivious to the wrong note being played.

By what mechanism does the music connoisseur know that a wrong note was played? It is not the ear, whose function is to simply detect the sound; rather, it is the brain, which interprets sounds as constructed music and provides a biological and resulting cognitive response to hearing a wrong note.

The presence of magnetic particles in the brain of sufficient size to potentially transduce MFs directly is of particular interest (Kirschvink, Kobayashi-Kirschvink, Diaz-Ricci,

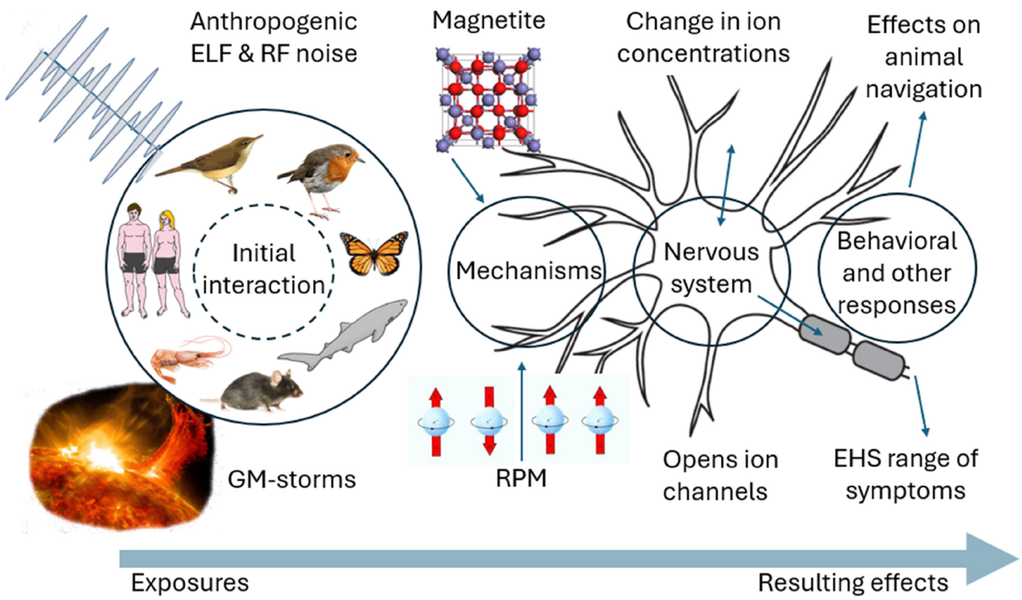

Figure 3. Conceptualization of exposure to low intensity magnetic and electromagnetic fields and how this may lead to adverse behavioral and other responses. Anthropogenic ELF and RF noise interacts with biological systems by two principal mechanisms of interest: magnetic particles in the body and the quantum-mechanical radical pair mechanism. Such interactions can lead to the opening of cell membrane ion channels, which in turn result in cellular and extra-cellular changes in ion concentrations. These in turn couple to the nervous system subsequently driving behavioral and other responses, including EHS.

et al. 1992). In the case of GM storms, it has been argued that the cryptochrome compass system in animals mediates stress responses more broadly across the hypothalamic–pituitary–adrenal (HPA) axis, including alterations to circadian behavior, in response to changes in the GM field (Close 2012). This notion is supported by findings in rats exposed to mobile phone EMFs (Zufry et al. 2023).

Some types of EMF signals result in adverse responses in some individuals; these signals are particularly bioactive for EHS people. The brain reacts adversely to these signals and this is communicated, albeit unconsciously, to the rest of the body, resulting in adverse health symptoms. The situation is not unlike the side effects of prescription drugs, which may affect only a small percentage of people.

What, then, is the *primary* interaction at the physical or chemical level between MFs and biological systems, especially humans? We discuss two mechanisms from the field of animal magnetoreception, their coupling to the nervous system and communication with the brain, and a third that is newly emerging.

4.1. Magnetic particles in the brain

The presence of magnetic nanoparticles in living organisms is well-known and has been extensively researched. A particular example is the evolution, some two billion years ago, of the magnetotactic bacteria which contain chains of magnetite-bearing magnetosomes in their bodies, enabling them to swim along geomagnetic field lines (Bazylinski and Frankel 2004). The presence of such particles in the bodies of many species, including humans, may act as a method of magnetoreception. This is supported by both theoretical considerations and the fact that magnetite has been detected in sensory neurons (Winklhofer 2009; Shaw et al. 2015).

Magnetite (Fe^3o^4) biomineralization has been characterized in the human brain (Kirschvink, Kobayashi-Kirschvink, Woodford, 1992). Individual particle energy in a MF, U, often exceeded the thermal energy kT. Thus, individual grain sizes were bimodal: most were in the range 10–70 nm, while a proportion was in the range 90–200 nm with some examples 600 nm in size. Overall, the measurements implied the presence of 5 million single-domain crystals per gram for most tissues in the brain and over a 100 million crystals per gram for pia and dura. Magnetic property data indicated that the crystals were in clumps of between 50 and 100 particles, with U/kT values between 20 and 150.

In autopsy samples covering an age range of 3–89 years, the abundant presence of magnetite nanoparticles has been identified in the human brain, separate from those ascribed to endogenous sources (Maher et al. 2016). These findings suggest that external sources, such as combustion-derived particles, can enter the brain directly via the olfactory bulb. Median saturation remanent magnetizations from the cerebellum were reported to be approximately twice as high as those from the cerebral cortex (Gilder et al. 2018). The magnetization of the brain stems was more than two times greater on average than that of the cerebral cortex. The authors concluded that magnetite is preferentially partitioned in the human brain, specifically in the cerebellum and brainstem.

A role for magnetite particles in human tissues, especially the brain is unknown. Those observed to date lack the ordered architecture seen in animals. The sizes of particles present indicate the ability of a proportion to orientate in the GM and anthropogenic fields, exerting mechanical pressure directly on brain cells (Kirschvink, Kobayashi-Kirschvink, Diaz-Ricci, et al. 1992). The possibility that such action may be sufficient to open mechanically sensitive transmembrane ion channels has also been proposed.

Magnetite and related particles also have the ability to transduce RF-EMF energy from approximately 500 MHz to at least 10 GHz (Kirschvink 1996). The possible consequences of MF coupling to magnetite particles were tested via a bacterial analog (*Magnetospirillum magnetotacticum*), which produces intracellular biogenic magnetite similar to that present in the human brain (Cranfield et al. 2003). Compared with sham exposure, exposure to 900 MHz mobile phone emissions resulted in a consistent and significantly greater proportion of cell death in exposed cultures.

In a demonstration video, trout olfactory epithelial cells containing magnetic material were visually identified by their rotational behavior in a MF (Eder et al. 2012). Magnetic inclusions, with dipole moments in the range 4–10 fAm^{2}, were found to be firmly coupled to the cell membrane, enabling demonstration of direct transduction of mechanical stress produced by magnetic torque acting on the cellular dipole in situ.

Strong evidence supporting the involvement of magnetite particles and their ferromagnetism in human magnetoreception is presented in Section 3.3 (Wang et al. 2019). However, to date, there has been no explicit demonstration that such particles couple to neurons in a manner that results in a behavioral response. The evidence may also support the action of a proposed magnetoreceptor based on MagR (Section 4.4). Overall, magnetic particles constitute a viable biophysical mechanism for sensory transduction and provide a basis for investigating the behavior of human magnetoreception.

4.2. The radical pair mechanism (RPM)

The RPM is the only established mechanism by which low-intensity MFs can alter chemical reaction rates and reaction products. They do so by operating on the spin states of radical pairs, in particular, driving conversion from the short lifetime (~nanoseconds) singlet, S-state to the longer-lived (~microseconds) triplet, T-state. Longer-lived radicals have more time to take part in chemical reactions that are usually inaccessible in the S-state, including the opportunity to cause biological damage (Schulten et al. 1978; Brocklehurst and McLauchlan 1996; Rodgers 2009; Hore and Mouritsen 2016). Such changes in reaction products, if coupled to the nervous system in vivo, could constitute a signal leading to a number of biological outcomes (Zadeh-Haghighi and Simon 2022). Strong evidence for the involvement of the RPM in human magnetoreception was presented in Section 3.3 (Chae et al. 2022).

Notably, the RPM operates at energy levels some ten million times below thermal energy. While understanding originated in the 1970s in spin chemistry, further roots may be found in the 1896 discovery of the *Zeeman Effect* and the subsequent 1902 Nobel Prize award to Pieter Zeeman. Such *quantum mechanical* effects are nonintuitive but are borne out by experimental observations.

In terms of MF interactions, the RPM is known to have a frequency limit of about 10–100 MHz. Consequently, the RPM cannot explain telecommunication carrier wave frequency effects on, for example, the production of reactive oxygen species (ROS), as supported in the theoretical analysis by Talbi et al. (2024). At such frequencies, other mechanisms of interaction need to be considered such as transduction by magnetite nanoparticles and electric field effects, without frequency limit at radio frequencies. This issue is discussed in more detail in Section 4.6 below.

4.2.1. RPM in the magnetic compass of avians, and other species

The role of cryptochrome protein molecules in accommodating magnetoreception via the RPM has been extensively investigated (Karki et al. 2021). The compass used by birds and other species is postulated to operate in cryptochrome photoreceptor protein molecules in the eye, where radical pairs are produced by blue-light absorption and electron transfer (Ritz et al. 2000).

Evidence that the migratory orientation of European robins exposed to 1–10 MHz fields, as low as 85 nT, disrupted their migratory orientation by affecting the S-T interconversion process offered strong support for an RPM-based magnetic compass (Ritz et al. 2004). These findings were replicated and found across a number of species. Estimates of the MF detection threshold have been progressively revised downwards and reported to start at a level below 2.4 nT in garden warblers (Pakhomov et al. 2017).

There is now compelling evidence that the prime magnetic compass of migratory birds operates via a RPM, which requires the presence of cryptochromes (Leberecht et al. 2023).

4.2.2. Human cryptochromes are magnetosensitive

Human cryptochromes (specifically hCRY2) have been shown to be magnetosensitive (Foley et al. 2011). When engineered without their corresponding *CRY* genes, *Drosophila melanogaster* fruit flies lose their magnetosensitivity. However, sensitivity is restored with the introduction of human *CRY2* genes. Human CRY2 is present in most tissues, including the brain (see Section 4.5). The evidence suggests that CRY2 proteins are related to human navigation (Xu et al. 2021).

4.3. RPM in cryptochromes and coupling to nerve cells

Cryptochromes are ubiquitously expressed in the organs and tissues of all organisms (Lin and Todo 2005; Sancar 2016). In the context of MF reception, there is an ongoing debate as to whether the presence of cryptochromes is sufficient for MF reception or whether they function as downstream signaling molecules of the actual MF receptor (Giachello et al. 2016; Bradlaugh et al. 2023; Merlin 2023; Zhang and Malkemper 2023). There are further questions, namely can MF reception take place in the complete absence of light, and how is MF information coupled to nerve cells? Laboratory experiments addressing these issues have looked directly at the MF-induced cryptochrome response in nerve cells, where the questions become intertwined. Here, we address those questions separately by summarizing several key experimental findings.

4.3.1. Is a cryptochrome a magnetic sensor or a transducer of the actual sensor?

In the avian compass, it is assumed that relevant radical pairs are created in cryptochromes by blue light excitation of the flavin adenine dinucleotide cofactor (FAD), followed by electron transfer across a chain of three tryptophans (Trp). In the case of the plant *Arabidopsis thaliana* cryptochrome, a schematic picture of the full radical-pair reaction pathway has been proposed (Solov'yov et al. 2007). In *Drosophila*, evidence suggests the presence of a fourth Trp (Nohr et al. 2016).

This picture does not explain many physiological and behavioral observations and has been challenged in studies in *Drosophila* (Gegear et al. 2010; Fedele et al. 2014). The studies detailed in Section 4.3.4 report the first direct experimental evidence that MF modulation of cryptochrome activity is capable of influencing neuronal activity to allow animal magnetoreception (Giachello et al. 2016). This observation does not require the Trp chain, but the CRY C-terminus is essential for CRY-dependent MF sensitivity. This work has been extended to detailed studies of the precise workings of the RPM (Figure 4; Bradlaugh et al. 2023). The authors reported that the 52 C-terminal amino acid residues of the *Drosophila* cryptochrome, lacking the canonical FAD-binding domain and Trp chain, are sufficient to facilitate magnetoreception. High levels of FAD alone are sufficient to cause blue-light neuronal sensitivity and the potentiation of this response in the additional presence of a MF. These observations suggest that alternative radical pairs, which are not directly photochemically generated, may also contribute to magnetoreception.

Overall, the results suggest that 'sensing' and 'transducing' of MFs are separate properties that do not need to be carried out by the same molecule. Furthermore, while blue light appears necessary to trigger the RPM process, there is a growing list of examples reporting that key steps relevant to magnetoreception take place in the dark (Vieira et al. 2012; Wiltschko et al. 2016; Höytö et al. 2017; Pooam et al. 2019; Hammad et al. 2020). The example of subterranean mole rats is particularly relevant here (Burda et al. 1990; Burda 2021).

Insight into the workings of magnetosensitivity in the dark may be obtained by considering the cryptochrome photocycle (Hammad et al. 2020, Figure 4). In general, as long as an initial step occurs that generates the flavin radical (FADH•), the magnetically sensitive step can be decoupled from illumination (Aguida et al. 2024). Mammalian-type cryptochromes appear to function independently of light and are expected to retain the ability to respond to MFs (Sherrard et al. 2018).

Thus, there is ample evidence that cryptochromes play a critical role in magnetosensitivity, although it remains to be seen whether they function as receptors or downstream signaling molecules. More generally, MF effects from the perspective of the RPM show that magnetosensitivity is widespread in biology (Zhang and Malkemper 2023; Zadeh-Haghighi and Simon 2022).

4.3.2. EMFs release reactive oxygen species

A key part of the magnetoreception process is the release of free radical ROS. The subject has been discussed in the context of cells exposed to ELF-MFs in vitro (Mattsson and Simkó 2014) and in the context of the neuropsychiatric effects of EHS (Pall 2013, 2016; Stein and Udasin 2020). This includes the proposal that oscillating electric fields (EFs) may lead to the opening or closing of voltage-gated ion channels (VGICs) (Panagopoulos et al. 2000, 2002, 2021). The effects of EMFs on neuronal ion channels have been extensively studied, revealing that VGICs represent major transducers of EMF-related effects on the central nervous system (Bertagna et al. 2021). A recent case report in

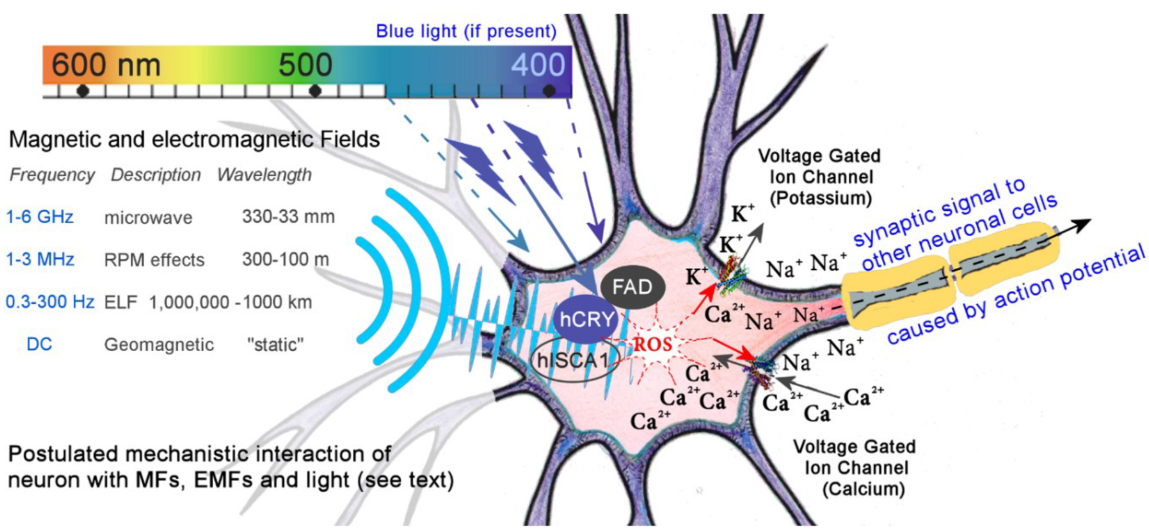

Figure 4. Postulated signaling pathways of the cryptochrome in Drosophila. In the presence of blue (or white) light and EMF, cryptochrome is activated and produces free radicals (ROS). This causes the opening of the potassium channel and the triggering of action potentials, leading to an increase in the intracellular calcium content, which in turn activates synaptic VGIC signaling (Bradlaugh et al. 2023).

an EHS patient revealed correlations with immune responsivity to oxidative stress (Thoradit et al. 2024).

Some studies address the role of the RPM in the process of ROS release. These include changes in nuclear spin orientations that lead to changes in chemical reaction rates and concentrations of important signaling molecules (Henbest et al. 2004; Usselman et al. 2014, 2016; Smith et al. 2021; Zadeh-Haghighi and Simon 2021).

A comprehensive discussion describes the biological effects of EMFs on insects, from the standpoint of a primary EMF receptor followed by ephaptic coupling and the perception of EMF through ion channels for the synchronization of neuronal activity (Thill et al. 2024). The effects of both ELF and RF EMFs are considered, encompassing sources such as mobile and DECT phones, base stations, signal generators, and coil systems. Deleterious effects are reported in all cases.

4.3.3. Pulsed EMFs induce human cryptochromes to modulate intracellular reactive oxygen species

PEMFs induce the production of ROS in human cells, and this process requires the presence of cryptochrome (Sherrard et al. 2018). It was first shown that transgenic *Drosophila* larvae engineered without their own cryptochrome genes (*cry*^{b} and *cry*^{02}) lost their MF sensitivity, specifically to PEMFs. However, *Drosophila* larvae re-engineered with human cryptochrome-1 (HsCry1) protein responded to PEMFs in the form of 10 Hz, 1.8 millitesla-pulsed MFs.

Using human embryonic kidney 293 (HEK293) cells in vitro, it was determined that the ROS synthesized in the cryptochrome are released by PEMFs. This PEMF stimulation leads to the accumulation of intracellular ROS, and this effect requires the presence of cryptochromes. Prolonged exposure to PEMFs indicated the toxicity of accumulated ROS in HEK293 cells. In a further assay relevant to the therapeutic consequences observed in humans, PEMF stimulation was found to regulate the expression of ROS-responsive genes.

4.3.4. Specific involvement of cryptochromes in MF coupling to the nervous system

One study provided critical evidence that MFs potentiate the ability of light-activated CRY to increase neuronal action potential firing in *Drosophila*, indicating that CRY is sensitive to an external MF that can modify animal behavior (Giachello et al. 2016). The authors employed electrophysiological recordings from larval-identified motoneurons, in which CRY is ectopically expressed, to show that the blue-light-dependent depolarization of the membrane potential and the increased input resistance are markedly potentiated by MF exposure, which evokes increased action potential firing.

This work has been extended (Bradlaugh et al. 2023). When filled with FAD alone, the MF increased the action potential firing of neuronal cells, even in the absence of CRY. These results reveal the essential components of a primary magnetoreceptor in flies, providing strong evidence that non-CRY-dependent radical pairs can elicit MF responses in cells (Section 4.3.1).

4.3.5. Signal processing in the brain from the avian MF compass

An area of the brain of migratory songbirds where information from the Earth's MF is processed has been identified (Mouritsen et al. 2005). The authors designated this area *Cluster N*, which is situated close to the *Wulst* visual area. The functioning of *Cluster N* and the existence of cognitive maps in animal navigation have since been investigated by several authors (Heyers et al. 2022; Shirdhanka and Malkemper 2024).

4.3.6. EMF treatment does not require light but may require cryptochrome

In MF and EMF treatment, a particularly effective example is the use of PEMFs. For patients with treatment-resistant depression, an emerging option is noninvasive brain stimulation using techniques, such as repetitive transcranial magnetic stimulation (rTMS) of the left dorsolateral prefrontal cortex (Blumberger et al. 2018).

The efficacy of this treatment has been developed empirically with little or no understanding of the fundamental processes at work. What is apparent is that the treatment is delivered directly to specific areas of the brain, strongly suggesting that exposure to light is not involved. Indeed, this is evident for other EMF treatments, such as bone healing.

To address these mechanistic aspects, the use of low-intensity repetitive transcranial magnetic stimulation (LI-rTMS) to trigger intrinsic brain neural circuit repair mechanisms has been investigated (Dufor et al. 2019). The authors compared cerebellar reinnervation in explants from wild-type (WT) mice and cryptochrome double knockout (*Cry1−/−Cry2−/−*) mice. These findings indicate that LI-rTMS induces axon outgrowth and synaptogenesis to repair neural circuits. This type of repair is dependent on the stimulation pattern and the presence of cryptochromes.

This is the first direct evidence in the mouse central nervous system that mammalian cryptochromes are necessary for LI-rTMS-induced axon growth and neosynaptogenesis and involve MFs delivered focally to only part of the brain. Rather than neuronal activation by induced electric currents, weak MFs may act through cryptochromes to activate cellular signaling cascades. This study provides another example of EMF action in the absence of light. In EMF treatment, the mechanistic role of cryptochrome with respect to the RPM or any other mode of interaction remains to be elucidated.

4.4. Cryptochromes, circadian rhythms, and melatonin

Cryptochromes are best known for their control of circadian rhythms (Van der Horst et al. 1999; Sancar 2004, 2016). An important aspect of such control is the nocturnal production of the powerful natural antioxidant and anticancer agent melatonin in the pineal gland. Pineal secretion of nocturnal pineal melatonin is reduced at exposure levels of dim white light at approximately 10 lux and is fully suppressed once exposure to light-at-night (LAN) exceeds 200 lux (approximately 300 mW m^{-2}) (Brainard et al. 2001; Zeitzer et al. 2005). Blue light from light-emitting diodes is particularly effective in the suppression of melatonin in humans (West et al. 2011). Nightshift work, with its associated LAN exposure, is classed as a 2 A probable carcinogen (IARC 2010).

In contrast to LAN, MFs appear to be less effective at suppressing melatonin, with maximum suppression ranging from 20 to 30%. However, people exposed to elevated fields living under high-voltage powerlines, for example, may be chronically exposed, so the overall effect may be greater.

Experimental demonstration of MF-induced melatonin suppression must overcome the large natural person-to-person variation in nocturnal melatonin production (Sack et al. 1986). This suggests that studies with only a few tens of subjects will lack the resolving power to detect an effect (Touitou and Selmaoui 2012). In a well-conducted study involving 203 women and a dose–response design, melatonin suppression was noted for nocturnal 60 Hz EMF exposure as low as 0.2 μT, with an overall 14% reduction (Davis et al. 2001). Overall, studies of MF disruption of melatonin and circadian rhythms are inconsistent with no effect, suggesting that effects do occur (Henshaw 2014; CwCUK 2014).

Weak RF EMFs have been demonstrated to affect the insect circadian clock (Bartos et al. 2019).

4.5. ISCA1, MagR iron–sulfur (Fe-S) clusters, and cryptochromes

ISCA1, also known as MagR, is a protein involved in the biogenesis and assembly of iron–sulfur (Fe-S) clusters found in mitochondria and other locations (Qin et al. 2016). These clusters are essential cofactors found in all kingdoms of life and play essential roles in fundamental processes, including respiration, photosynthesis, and nitrogen fixation (Shi et al. 2021).

MagR has been reported to form a rod-like complex with cryptochrome and co-localizes with CRY in the pigeon retina (Figure 5) (Qin et al. 2016). The complex exhibits spontaneous alignment in MFs. As such, this constitutes a putative magnetoreceptor, having the attributes of a magnetic compass based on the basis of both chemical action by the RPM and magnetic particles. The authors further tested the formation of a complex between CRY and MagR in six selected species: fruit fly, monarch butterfly, pigeon, mole rat, minke whale, and human (Qin et al. 2016). In humans, two CRY isoforms have been identified, hCry2-1 and hCry2-2. Of these, hCry2-2 was found to form a complex with hMagR.

The authors also speculated that the dynamics of the CRY/MagR protein complex and the polymer structure formed by MagR alone may act as a biocompass in the dark in some cell types and animal species. Further studies have characterized the nature of Fe-S cluster binding in MagR (Guo et al. 2021; Zhou et al. 2023). Using small angle X-ray scattering, the magnetic orientation mechanism of the purported pigeon CRY/MagR structure was investigated (Arai et al. 2022). Clarification was provided that the *Columba livia* pigeon cryptochrome clCRY4 enhances the magnetic orientational property of the clCRY4/clMagR complex when MagR acts as a scaffold for the photochemical reaction of clCRY4.

Our primary concern is MF transduction to the nervous system in the context of EHS. In humans, the *hCRY2* and *hISCA1/hMagR* genes are expressed together in most organs and tissues of the body (Figure 6) (Gene ID: 1408 2024; Gene ID: 81689 2024). This provides an opportunity to form hCRY/hMagR complexes as a general phenomenon.

4.6. Electric field (EF) effects

As the body is a good conductor, external EFs are strongly attenuated in the human body. Disruptive internal EFs are mostly induced by time-changing external MFs.

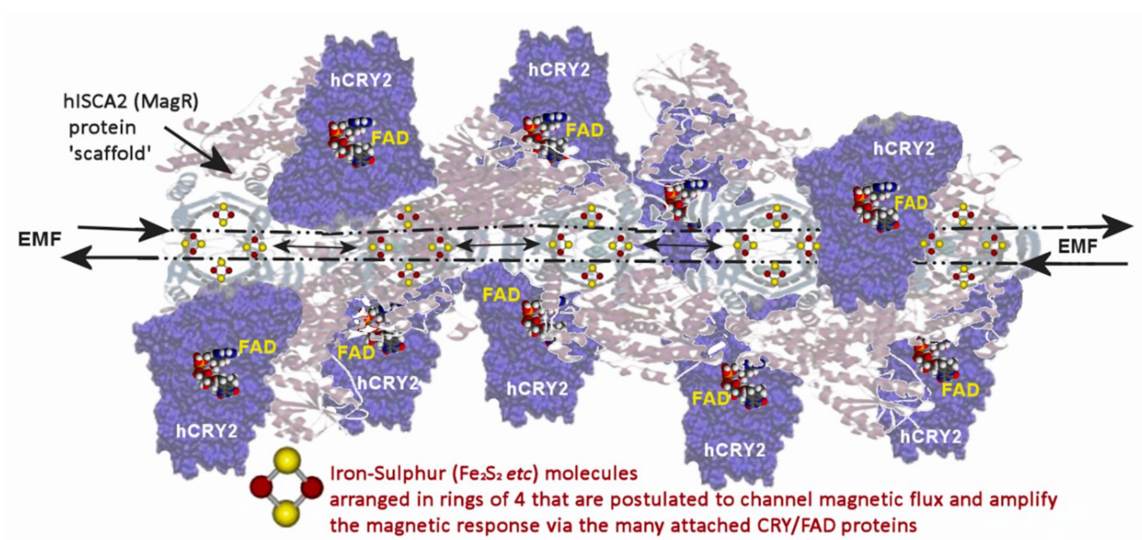

Figure 5. A possible structural model of the cry/MagR magnetosensor with up to 10 cry molecules attached to the MagR core (based on Qin et al. (2026), Figure 3 and other sources).

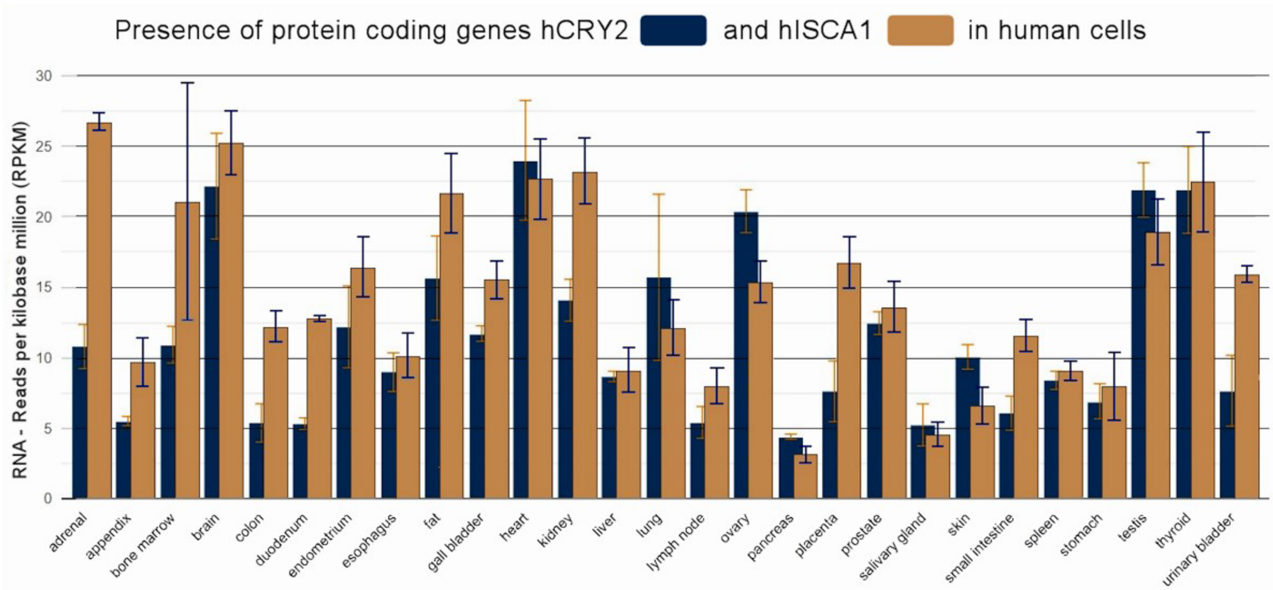

Figure 6. Human cryptochrome and iron-sulfur cluster assembly proteins are expressed in a wide range of human cells, especially in their mitochondria.

4.6.1. ELF EFs

In a long series of experiments, human subjects were housed in isolated test facilities, shielded from the variable atmospheric electric field, typically ~150 V m^{-1} (Wever 1979). The subjects were then exposed to 10 Hz continuous square waves for up to several weeks, and field intensities from zero to 300 V m^{-1}.

For zero exposure, statistically significant lengthening in the 24 h circadian rhythm was observed and the occurrence of internal desynchronization. For square wave exposures as low as 2.5 V m^{-1}, subjects were immediately entrained to the external signal, resulting in shortening of circadian rhythms, indicating that ELF EFs acted as zeitgebers.

These and further related studies in humans and animals are reviewed in Henshaw et al. (2008). In addition to alteration of circadian rhythms and other findings, disruption of nocturnal melatonin was also observed.

4.6.2. Mobile-phone frequencies

Talbi et al. (2024) cite examples of nine studies which report increased ROS levels with exposure to RF EMFs. Four of these use a pure RF carrier wave (Luukkonen et al. 2009; De Iuliis et al. 2009; Sefidbakht et al. 2014; Pooam et al. 2022).

The remaining five studies use actual mobile phone devices, which contain low frequency modulations in various forms. Mobile phones are known to generate ELF and VLF MFs from the battery current, up to tens of microteslas in value (Tuor et al. 2005). Human exposures to RF EMFs from mobile phones and related devices include lower frequency modulation signals, which are likely to fall in the domain of the RPM.

4.6.3. Mechanistic considerations

For external EF exposure, Panagopoulos et al. (2000) proposed a model in which an oscillating external electric field exerts an oscillating force on free ions that exist on both sides of all plasma membranes and can cross via transmembrane proteins. This external oscillating force causes a forced vibration of free ions, leading to opening or closing of VGICs as described in Section 4.3.2 above.

The model predicts that EF frequencies below 1 kHz (ELF fields) can be bioactive, even at very low intensities of several volts per meter. At RF frequencies, a field of 100 MHz must have an intensity of at least 10^5 V m^{-1}, which is orders of magnitude greater than ICNIRP's limit of 62 V m^{-1}.

For RF EMFs, the theoretical analysis by Talbi et al. (2024) supports the known frequency limit of 10–100 MHz in which the RPM can operate. Thus, the findings of ROS release from pure RF carrier wave exposures, could by hypothesis arise from transduction by magnetite nanoparticles, or by the EFs generated internally by the MF EMF component, or by some other presently unknown pathway.

4.7. Nonlinear and multiphasic responses

Most human responses to environmental factors are nonlinear and involve feedback mechanisms that control sensitivity and downstream biological and cognitive consequences (Beckon et al. 2008). This applies to touch, sight, hearing, smell, and taste, which have gain and adaption functionality that achieve extremely wide dynamic ranges, and also apply to other signals, including pain.

One example is our response to DNA damage by ionizing radiation. After much debate, the most appropriate model for radiation protection is the linear no threshold (LNT). Minor genetic damage is not always repaired because imperfect repair processes can produce greater damage (Huang and Zhou 2021). As damage detection increases, immune system communication triggers repair or apoptosis (Nastasi et al. 2020). This explains earlier claims that '*a little radiation exposure is protective*'; however, we now know that 'minor' damage can result in future genomic instability.

A series of studies have shown the damaging effects of weak ELF MF exposure on ornithine decarboxylase activity and the morphology of chick embryos as well as the mitigating effects of the superposition of an incoherent ELF noise field (Farrell et al. 1997; Farrell et al. 1998). Related studies have shown similar effects at microwave frequencies and amplitudes modulated by ELF (Litovitz et al. 1997).

5. Discussion

In the scientific field of magnetoreception, we find that all forms of life respond to MFs, as has been extensively researched in many species. The literature is bourgeoning.

In 2020 alone, PubMed lists 600 articles with keywords '*magnetic field biology*' (Sarimov et al. 2023b). This includes examples of extraordinary sensitivity, in some cases several thousand times below the level of the natural background geomagnetic field.

It should therefore come as no surprise that humans are able to detect MFs, albeit unconsciously, as evidenced by the established literature relating to GM storms and carefully controlled laboratory experiments (Wang et al. 2019; Chae et al. 2022).

The mechanistic understanding of magnetoreception in biology has, in recent decades, been driven largely in response to animal navigation and migration utilizing, to varying degrees, the GM field. Our focus is on mechanisms of magneto-sensing and coupling to the nervous system, regardless of a specific behavioral purpose.

The role of magnetite and related particles as primary MF/EMF detectors, including the demonstration of energy coupling to cells, has been widely discussed (Eder et al. 2012). Of particular interest is the ability of magnetite nanoparticles to absorb and transduce EMR at microwave frequencies up to 10 GHz through the process of ferromagnetic resonance (Kirschvink 1996).

Cryptochromes, including those in humans, have been shown to play a central role in magnetoreception. They couple to the nervous system and have also been shown to play a key role in cerebellar reinnervation. Cryptochrome action involving the RPM is supported in many animal and plant species. Studies in molecular biology and genetics are probing the exact workings of the RPM, including whether the mechanism can operate in the complete absence of light.

The observation that MagR forms a rod-like complex with cryptochromes is work in progress that could open up a new possibility of increased magnetosensitivity. This hypothesis suggests that CRY/MagR complexes have the capacity to transduce MF/EMFs in most tissues and organs. This could explain the range and diversity of adverse effects reported by individual EHS sufferers.

Most EHS people report sensitivities to EMF levels many orders of magnitude below all official exposure guidance levels, and many do not report an increase in effects at higher exposures. An attempt to improve protective guidance was set out the EUROPAEM guidance (Belyaev et al. 2016). These levels are indicated in Figures 1 and 2. Unfortunately, almost all published EHS provocation studies have assumed a linear dose response and only consider exposures close to the mainstream international guidance levels (IEEE 2019; ICNIRP 2010, 2020). They also have failed to ensure that 'sham' exposures have extremely low levels of background ELF and RF fields.

We can therefore offer some replies to questions (i)–(iv) in the introduction.

i. Numerous animal and insect species react adversely to minute MF/EMF changes, notably in interference with magnetonavigation. There is ample evidence, notably from GM storms, that humans can sense low-intensity EMFs, albeit unconsciously. Adverse responses, typical of those reported as human EHS, reflect that the brain regards some EMF signals as disturbing, especially those of a pulsatile nature and whether ELF and/or RF are present.
ii. The leading candidates for primary MF/EMF detection are magnetic particles and the RPM via cryptochromes. Both offer routes for coupling to the nervous system and to the brain, as supported by laboratory studies with human volunteers. Both processes may be at work in human MF/EMF sensing.
iii. The acute activation of VGICs by EMFs in relation to both MFs and EFs has been discussed elsewhere (Pall 2013, 2016; Panagopoulos et al. 2021). The demonstration that EMFs act on human cryptochromes in *Drosophila* to release ROS, leading to the activation of VGICs in neurons, provides further mechanistic insight into this process (Sherrard et al. 2018). ROS constitute potentially toxic metabolites with multiple roles in the stress response and cellular aging, including a potential role in cancer promotion, exacerbated by chronic EMF exposure.

We have dealt here mainly with MFs. People have also been shown to be sensitive to EFs (McCarty et al. 2011), but as indicated in Section 4.6 our understanding of EF mechanisms of action are more limited.

6. Conclusions and recommendations

1. At the scientific level, researchers working in the field of *magnetoreception in biology* should be made aware of EHS as a human public health concern and funded to address the issue as part of their scientific research.
2. All interested parties, especially EHS sufferers and medical professionals, should be made aware of the considerable growth in understanding in recent decades of the mechanisms by which all forms of life sense MFs/EMFs, even at extremely low levels. EHS research to date has been significantly hindered by a fundamental lack of knowledge among many medical scientists and EHS researchers regarding the current scientific understanding of quantum biology mechanisms and processes. This has resulted in the design and analysis of inappropriate provocation tests.

3. Almost all existing epidemiological and provocation studies have failed adequately to determine and measure the necessary dependent and independent variables. In particular:

i. to characterize in proper technical detail the EMF/RF exposures (including electric and MF levels; average and peak power-density levels; frequencies involved; and modulation characteristics).
ii. to triage participants effectively to remove 'electrophobic' and other volunteers self-reporting apparent EHS-related problems.
iii. in provocation studies, to fail to recognize the non-linear nature of EHS responses and the extremely low levels of exposure (<100 nT) that have effects and, instead, use relatively high exposures fairly close to the ICNIRP and IEEE guidance levels.
iv. in provocation studies, to provide a participant-comfortable extremely low EMF/RF test location, screened from anthropogenic sources and allow adequate time (days rather than hours) for adverse effects to washout between exposures.

5. EHS studies should move away from current, nonforensic epidemiological approaches and human subjective provocation studies (Leszczynski 2022; Röösli et al. 2024). Instead, objective measurements of biological parameters, such as heart rate variability, brain wave activity (e.g. fMRI and wide-bandwidth EEG), and the immune response to oxidative stress should be investigated (Caswell et al. 2016; Gurfinkel et al. 2018; Pishchalnikova et al. 2019; Wang et al. 2019; Thoradit et al. 2024). We caution that these approaches require sophisticated design and analysis and advanced design personal exposure meters.
6. We recommend that the WHO properly reevaluates its understanding of EHS to align it with the substantial body of available scientific literature showing mechanistic evidence of interactions of all forms of life, including humans, with low levels of electric and magnetic fields.

Acknowledgments

We thank Peter Bowell for help with the literature searches. We also thank Michael Bevington, Michael Kundi, Brian Stein and Eric Warrant for helpful discussions.

Ethics approval

None required (only used anonymized published data).

Consent for publication

Original work by the two authors – no external consent required.

Authors' contributions

The authors discussed jointly which topics to include in the article. The various sections were first written by one author and then checked by the second author. Each author contributed equally to this process.

Disclosure statement

DLH declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article. AP, as an unpaid volunteer, has helped run Powerwatch (a small UK NGO that provides free public information on the possible effects of EMF exposure) for approximately 30 years. AP declares that no financial or related interests or personal relationships have influenced him in co-authoring this article.

Funding

No funding was provided for the preparation of this manuscript.

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Availability of data and materials

All data sources are cited and available in the references.

References

Aguida B, Babo J, Baouz S, Jourdan N, Procopio M, El-Esawi MA, Engle D, Mills S, Wenkel S, Huck A, et al. 2024. 'Seeing' the electromagnetic spectrum: spotlight on the cryptochrome photocycle. Front Plant Sci. 15:1340304. doi:10.3389/fpls.2024.1340304.

Ahlbom A, Day N, Feychting M, Roman E, Skinner J, Dockerty J, Linet M, McBride M, Michaelis J, Olsen JH, et al. 2000. A pooled analysis of magnetic fields and childhood leukaemia. Br J Cancer. 83(5):692–698. doi:10.1054/bjoc.2000.1376.

Arai S, Shimizu R, Adachi M, Hirai M. 2022. Magnetic field effects on the structure and molecular behaviour of pigeon iron–sulphur protein. Protein Sci. 31(6):e4313. doi:10.1002/pro.4313.

Azcárate T, Mendoza B. 2017. Influence of geomagnetic activity and atmospheric pressure in hypertensive adults. Int J Biometeorol. 61(9):1585–1592. doi:10.1007/s00484-017-1337-x.

Azcárate T, Mendoza B, Lev JR. 2016. Influence of geomagnetic activity and atmospheric pressure on human arterial pressure during the solar cycle 24. Adv Space Res. 58(10):2116–2125. doi:10.1016/j.asr.2016.05.048.

Bartos P, Netusil R, Slaby P, Dolezel D, Ritz T, Vacha M. 2019. Weak radiofrequency fields affect the insect circadian clock. J R Soc Interface. 16(158):20190285. doi:10.1098/rsif.2019.0285.

Bazylinski DA, Frankel RB. 2004. Magnetosome formation in prokaryotes. Nat Rev Microbiol. 2(3):217–230. doi:10.1038/nrmicro842.

Beckon W, Parkins C, Maximovich A, Beckon A. 2008. A general approach to modeling biphasic relationships. Environ Sci Technol. 42(4):1308–1314. doi:10.1021/es071148m.

Belpomme D, Campagnac C, Irigaray P. 2015. Reliable disease biomarkers characterizing and identifying electrohypersensitivity and multiple chemical sensitivity as two etiopathogenic aspects of a unique pathological disorder. Rev Environ Health. 30(4):251–271. doi:10.1515/reveh-2015-0027.

Belpomme D, Irigaray P. 2020. Electrohypersensitivity as a newly identified and characterized neurologic pathological disorder: how to diagnose, treat, and prevent it. Int J Mol Sci. 21(6):1915. doi:10.3390/ijms21061915.

Belpomme D, Irigaray P. 2022. Why electrohypersensitivity and related symptoms are caused by non-ionizing man-made electromagnetic fields: an overview and medical assessment. Environ Res. 212(Pt A):113374. doi:10.1016/j.envres.2022.113374.

Belpomme D, Irigaray P. 2023. Combined neurological syndrome in electrohypersensitivity and multiple chemical sensitivity: a clinical study of 2018 cases. J Clin Med. 12(23):7421. doi:10.3390/jcm12237421.

Bertagna F, Lewis F, Silva SRP, McFadden J, Jeevaratnam K. 2021. Effects of electromagnetic fields on neuronal ion channels: a systematic review. Ann N Y Acad Sci. 1499(1):82–103. doi:10.1111/nyas.14597.

Belyaev I, Dean A, Eger H, Hubmann G, Jandrisovits R, Kern M, Kundi M, Moshammer H, Lercher P, Müller K, et al. 2016. EUROPAEM EMF guideline 2016 for the prevention, diagnosis and treatment of EMF-related health problems and illnesses. Rev Environ Health. 31(3):363–397. doi:10.1515/reveh-2016-0011.

Bianco G, Ilieva M, Åkesson S. 2019. Magnetic storms disrupt nocturnal migratory activity in songbirds. Biol Lett. 15(3):20180918. doi:10.1098/rsbl.2018.0918.

Blumberger DM, Vila-Rodriguez F, Thorpe KE, Feffer K, Noda Y, Giacobbe P, Knyahnytska Y, Kennedy SH, Lam RW, Daskalakis ZJ, et al. 2018. Effectiveness of theta burst versus high-frequency repetitive transcranial magnetic stimulation in patients with depression (THREE-D): a randomised non-inferiority trial. Lancet. 391(10131):1683–1692. doi:10.1016/S0140-6736(18)30295-2.

Bosch-Capblanch X, Esu E, Oringanje CM, Dongus S, Jalilian H, Eyers J, Auer C, Meremikwu M, Röösli M. 2024. The effects of radiofrequency electromagnetic fields exposure on human self-reported symptoms: a systematic review of human experimental studies. Environ Int. 187:108612. doi:10.1016/j.envint.2024.108612.

Bradlaugh AA, Fedele G, Munro AL, Hansen CN, Hares JM, Patel S, Kyriacou CP, Jones AR, Rosato E, Baines AB. 2023. Essential elements of radical pair magnetosensitivity in Drosophila. Nature. 615(7950):111–116. doi:10.1038/s41586-023-05735-z.

Brainard GC, Hanifin JP, Greeson JM, Byrne B, Glickman G, Gerner E, Rollag MD. 2001. Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. J Neurosci. 21(16):6405–6412. doi:10.1523/JNEUROSCI.21-16-06405.2001.

Brocklehurst R, McLauchlan KA. 1996. Free radical mechanism for the effects of environmental electromagnetic fields on biological systems. Int J Radiat Biol. 69(1):3–24. doi:10.1080/095530096146147.

Bruno WJ. 2024. What does photon energy tell us about cellphone safety? https://arxiv.org/ftp/arxiv/papers/1104/1104.5008.pdf.

Burch JB, Reif JS, Yost MG. 1999. Geomagnetic disturbances are associated with reduced nocturnal excretion of a melatonin metabolite in humans. Neurosci Lett. 266(3):209–212. doi:10.1016/S0304-3940(99)00308-0.

Burch JB, Reif JS, Yost MG. 2008. Geomagnetic activity and human melatonin metabolite excretion. Neurosci Lett. 438(1):76–79. doi:10.1016/j.neulet.2008.04.031.

Burda H, Marhold S, Westenberger T, Wiltschko R, Wiltschko W. 1990. Evidence for magnetic compass orientation in the subterranean rodent *Cryptomys hottentotus* (Bathyergidae). Experientia. 46(5):528–530. doi:10.1007/BF01954256.

Burda H, Begall S, Cervený J, Neef J, Nemec P. 2009. Extremely low-frequency electromagnetic fields disrupt magnetic alignment of ruminants. Proc Natl Acad Sci USA. 106(14):5708–5713. doi:10.1073/pnas.0811194106.

Burda H. 2021. Sensory perception of mole-rats and mole rats: assessment of a complex natural global evolutionary "experiment". Chapter 7 in New horizons in evolution. Amsterdam, Netherlands: p. 161–191. 10.1016/B978-0-323-90752-1.00006-7. Elsevier Science;.

Caswell JM, Singh M, Persinger MA. 2016. Simulated sudden increase in geomagnetic activity and its effect on heart rate variability: experimental verification of correlation studies. Life Sci Space Res (Amst). 10:47–52. doi:10.1016/j.lssr.2016.08.001.

Chae KS, Kim SC, Kwon HJ, Kim Y. 2022. Human magnetic sense is mediated by a light and magnetic field resonance-dependent mechanism. Sci Rep. 12(1):8997. doi:10.1038/s41598-022-12460-6.

Close J. 2012. Are stress responses to geomagnetic storms mediated by the cryptochrome compass system? Proc Biol Sci. 279(1736):2081–2090. doi:10.1098/rspb.2012.0324.

Cranfield C, Wieser HG, Madan JA, Dobson J. 2003. Preliminary evaluation of nanoscale biogenic magnetite-based ferromagnetic transduction mechanisms for mobile phone bioeffects. IEEE Trans Nanobiosci. 2(1):40–43. doi:10.1109/TNB.2003.810155.

CwCUK. 2014. Report by Ian Jones on EMF Think Tank. Children with Cancer UK. September. [accessed 14 Aug 2024]. https://www.childrenwithcancer.org.uk/wp-content/uploads/2016/12/CwCUK-report-on-EMF-think-tank-September2014.pdf.

Davis S, Kaune WT, Mirick DK, Chen C, Stevens RG. 2001. Residential magnetic fields, light-at-night, and nocturnal urinary 6-sulfatoxymelatonin concentration in women. Am J Epidemiol. 154(7):591–600. doi:10.1093/aje/154.7.591.

De Iuliis GN, Newey RJ, King BV, Aitken RJ. 2009. Mobile phone radiation induces reactive oxygen species production and DNA damage in human spermatozoa in vitro. PLoS One. 4(7):e6446. doi:10.1371/journal.pone.0006446.

Dimitrova S, Stoilova I, Yanev T, Cholakov I. 2004. Effect of local and global geomagnetic activity on human cardiovascular homeostasis. Arch Environ Occup Health. 59(2):84–90. doi:10.3200/AEOH.59.2.84-90.

Dreyer D, Frost B, Mouritsen H, Günther A, Green K, Whitehouse M, Johnsen S, Heinze S, Warrant E. 2018. The Earth's magnetic field and visual landmarks steer migratory flight behavior in the nocturnal Australian Bogong moth. Curr Biol. 28(13):2160–2166.e5. doi:10.1016/j.cub.2018.05.030.

Dufor T, Grehl S, Tang AD, Doulazmi M, Traoré M, Debray N, Dubacq C, Deng Z-D, Mariani J, Lohof AM, et al. 2019. Neural circuit repair by low-intensity magnetic stimulation requires cellular magnetoreceptors and specific stimulation patterns. Sci Adv. 5(10):eaav9847. doi:10.1126/sciadv.aav9847.

Eder SHK, Cadiou H, Muhamad A, McNaughton PA, Kirschvink JL, Winklhofer M. 2012. Magnetic characterization of isolated candidate vertebrate magnetoreceptor cells. Proc Natl Acad Sci USA. 109(30):12022–12027. doi:10.1073/pnas.1205653109.

Engels S, Schneider NL, Lefeldt N, Hein CM, Zapka M, Michalik A, Elbers D, Kittel A, Hore PJ, Mouritsen M. 2014. Anthropogenic electromagnetic noise disrupts magnetic compass orientation in a migratory bird. Nature. 509(7500):353–356. doi:10.1038/nature13290.

Esquivel DMS, Corrêa AAC, Vaillant OS, Bandeira de Melo V, Gouvêa GS, Ferreira CG, Ferreira TA, Wajnberg E. 2014. A time-compressed simulated geomagnetic storm influences the nest-exiting flight angles of the stingless bee *Tetragonisca angustula*. Naturwissenschaften. 101(3):245–249. doi:10.1007/s00114-014-1147-5.

Farrell JM, Litovitz TL, Penafiel M, Montrose CJ, Doinov P, Barber M, Brown KM, Litovitz TA. 1997. The effect of pulsed and sinusoidal magnetic fields on the morphology of developing chick embryos. Bioelectromagnetics. 18(6):431–438. doi:10.1002/(sici)1521-186x(1997)18:6<431::aid-bem5>3.0.co;2-3.

Farrell JM, Barber M, Krause D, Litovitz TA. 1998. The superposition of a temporally incoherent magnetic field inhibits 60 Hz-induced changes in the ODC activity of developing chick embryos. Bioelectromagnetics. 19(1):53–56. doi:10.1002/(sici)1521-186x(1998)19:1<53::aid-bem6>3.0.co;2-3.

Fedele G, Green EW, Rosato E, Kyriacou CP. 2014. An electromagnetic field disrupts negative geotaxis in Drosophila via a CRY-dependent pathway. Nat Commun. 5(1):4391. doi:10.1038/ncomms5391.

Feigin VL, Parmar PG, Barker-Collo S, Bennett DA, Anderson CS, Thrift AG, Stegmayr B, Rothwell PM, Giroud M, Bejot Y, et al. 2014. Geomagnetic storms can trigger stroke: evidence from 6 large population-based studies in Europe and Australasia. Stroke. 45(6):1639–1645. http://stroke.ahajournals.org/content/early/2014/04/22/STROKEAHA.113.004577. doi:10.1161/STROKEAHA.113.004577.

Foley LE, Gegear RJ, Reppert SM. 2011. Human cryptochrome exhibits light-dependent magnetosensitivity. Nat Commun. 2(1):356. https://www.nature.com/articles/ncomms1364. doi:10.1038/ncomms1364.

Galland P, Pazur A. 2005. Magnetoreception in plants. J Plant Res. 118(6):371–389. doi:10.1007/s10265-005-0246-y.

Gegear RJ, Foley LE, Casselman A, Reppert SM. 2010. Animal cryptochromes mediate magnetoreception by an unconventional photochemical mechanism. Nature. 463(7282):804–807. doi:10.1038/nature08719.

Gene ID: 1408. 2024. Gene Database, National Library of Medicine, ID: 1408. [accessed 2024 Aug 10]. https://www.ncbi.nlm.nih.gov/gene/1408

Gene ID: 81689. 2024. Gene Database, National Library of Medicine, ID: 81689. [accessed 2024 Aug 10]. https://www.ncbi.nlm.nih.gov/gene/?term=hISCA1.

Ghione S, Mezzasalma L, Del Seppia C, Papi F. 1998. Do geomagnetic disturbances of solar origin affect arterial blood pressure? J Hum Hypertens. 12(11):749–754. doi:10.1038/sj.jhh.1000708.

Giachello CNG, Scrutton NS, Jones AR, Baines RA. 2016. Magnetic fields modulate blue-light-dependent regulation of neuronal firing by cryptochrome. J Neurosci. 36(42):10742–10749. doi:10.1523/JNEUROSCI.2140-16.2016.

Gilder SA, Wack M, Kaub L, Roud SC, Petersen N, Heinsen H, Hillenbrand P, Milz S, Schmitz C. 2018. Distribution of magnetic remanence carriers in the human brain. Sci Rep. 8(1):11363. doi:10.1038/s41598-018-29766-z.

Granger J, Cummer SA, Lohmann KJ, Johnsen S. 2022. Environmental sources of radio frequency noise: potential impacts on magnetoreception. J Comp Physiol A Neuroethol Sens Neural Behav Physiol. 208(1):83–95. doi:10.1007/s00359-021-01516-z.

Greenland S, Sheppard AR, Kaune WT, Poole C, Kelsh MA. 2000. A pooled analysis of magnetic fields, wire codes and childhood leukaemia. Epidemiology. 11(6):624–634. doi:10.1097/00001648-200011000-00003.

Guo Z, Xu S, Chen X, Wang C, Yang P, Qin S, Zhao C, Fei F, Zhao X, Tan PH, et al. 2021. Modulation of MagR magnetic properties via iron–sulfur cluster binding. Sci Rep. 11(1):23941. doi:10.1038/s41598-021-03344-2.

Gurfinkel YI, Vasin AL, Pishchalnikov YR, Sarimov RM, Sasonko ML, Matveeva TA. 2018. Geomagnetic storm under laboratory conditions randomized experiment. Int J Biometeorol. 62(4):501–512. doi:10.1007/s00484-017-1460-8.

Hammad M, Albaqami M, Pooam M, Kernevez E, Witczak J, Ritz T, Martino C, Ahmad M. 2020. Cryptochrome mediated magnetic sensitivity in Arabidopsis occurs independently of light-induced electron transfer to the flavin. Photochem Photobiol Sci. 19(3):341–352. doi:10.1039/c9pp00469f.

Henbest KB, Kukura P, Rodgers CT, Hore PJ, Timmel CR. 2004. Radio frequency magnetic field effects on a radical recombination reaction: a diagnostic test for the radical pair mechanism. J Am Chem Soc. 126(26):8102–8103. doi:10.1021/ja048220q.

Henshaw DL, Reiter RJ. 2005. Do magnetic fields cause increased risk of childhood leukaemia via melatonin disruption? Bioelectromagnetics. 7:S86–S97. doi:10.1002/bem.20135.

Henshaw DL, Ward JP, Matthews JC. 2008. Review: can disturbances in the atmospheric electric field created by powerline corona ions disrupt melatonin production in the pineal gland? J Pineal Res. 45(4):341–350. doi:10.1111/j.1600-079X.2008.00594.x.

Henshaw DL. 2014. ELF EMF and melatonin disruption. [accessed 14 Aug 2024]. https://www.powerwatch.org.uk/pdfs/Henshaw-2014-ELF%20EMF%20and%20melatonin%20disruption.pdf.

Henshaw DL, Belpoggi F, Mandrioli D, Philips A. 2024. Chapter 46. Electromagnetic fields. In: Ruth AE, Philip JL, editors. Textbook of children's environmental health. Oxford: Oxford University Press. doi: 10.1093/oso/9780197662526.003.0046.

Heyers D, Musielak I, Haase K, Herold C, Bolte P, Güntürkün O, Mouritsen H. 2022. Morphology, biochemistry and connectivity of Cluster N and the hippocampal formation in a migratory bird. Brain Struct Funct. 227(8):2731–2749. doi:10.1007/s00429-022-02566-y.

Hore PJ, Mouritsen H. 2016. The radical-pair mechanism of magnetoreception. Annu Rev Biophys. 45(1):299–344. doi:10.1146/annurev-biophys-032116-094545.

Höytö A, Herrala M, Luukkonen J, Juutilainen J, Naarala J. 2017. Cellular detection of 50 Hz magnetic fields and weak blue light: effects on superoxide levels and genotoxicity. Int J Radiat Biol. 93(6):646–652. doi:10.1080/09553002.2017.1294275.

Huang R, Zhou PK. 2021. DNA damage repair: historical perspectives, mechanistic pathways and clinical translation for targeted cancer therapy. Signal Transduct Target Ther. 6(1):254. doi:10.1038/s41392-021-00648-7.

Human Protein Atlas-CRY2. 2024. https://www.proteinatlas.org/ENSG00000121671-CRY2/tissue. Accessed 16 Aug 2024.

IARC. 2010. International agency for research on cancer. Monographs of the evaluation of carcinogenic risks to humans. Vol. 98. Painting, Firefighting and Shiftwork. Lyon, France: International Agency for Research on Cancer. 150 cours Albert Thomas, 69372 Lyon Cedex 08, France. ISBN-13-978-92-832-1298-0.

IEEE. 2019. Standard for safety levels with respect to human exposure to electric, magnetic, and electromagnetic fields, 0 Hz to 300 GHz, Standard IEEE C95.1-2019; October. https://standards.ieee.org/ieee/C95.1/4940/.

ICNIRP. 2010. International commission on non-ionizing radiation protection. Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz–100 kHz). Health Phys. 99(6):818–836. doi:10.1097/HP.0b013e3181f06c86.

International Commission on Non-Ionizing Radiation Protection [ICNIRP]. 2020. Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). Health Phys. 118(5):483–524. doi:10.1097/HP.0000000000001210.

ITU-R P.372-16. 2022. International telecommunications union. https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.372-16-202208-I!!PDF-E.pdf.

Juutilainen J, Herrala M, Luukkonen J, Naarala J, Hore PJ. 2018. Magnetocarcinogenesis: is there a mechanism for carcinogenic effects of weak magnetic fields? Proc R Soc B. 285(1879):20180590. doi:10.1098/rspb.2018.0590.

Karki N, Vergish S, Zoltowski BD. 2021. REVIEW cryptochromes: photochemical and structural insight into magnetoreception. Protein Sci. 30(8):1521–1534. doi:10.1002/pro.4124.

Kay RW. 1994. Geomagnetic storms: association with incidence of depression as measured by hospital admissions. Br J Psychiatry. 164(3):403–409. doi:10.1192/bjp.164.3.403.

Kirschvink JL, Kobayashi-Kirschvink A, Woodford BJ. 1992. Magnetite biomineralization in the human brain. Proc Natl Acad Sci USA. 89(16):7683–7687. doi:10.1073/pnas.89.16.7683.

Kirschvink JL, Kobayashi-Kirschvink A, Diaz-Ricci JC, Kirschvink SJ. 1992. Magnetite in human tissues: a mechanism for the biological effects of weak ELF magnetic fields. Bioelectromagnetics. Suppl 1:101–113. doi:10.1002/bem.2250130710.

Kirschvink JL. 1996. Microwave absorption by magnetite: a possible mechanism for coupling nonthermal levels of radiation to biological systems. Bioelectromagnetics. 17(3):187–194. doi:10.1002/(SICI)1521-186X(1996)17:3<187::AID-BEM4>3.0.CO;2-%23.

Kowalski U, Wiltschko R, Fuller E. 1988. Normal fluctuations of the geomagnetic field may affect initial orientation in pigeons. J Comp Physiol. 163(5):593–600. doi:10.1007/BF00603843.

Kraus J, Fleisch D. 1999. Electromagnetics with applications. 5th ed. New York (NY): McGraw-Hill; p. 332–336.

Krylov VV. 2017. Review: biological effects related to geomagnetic activity and possible mechanisms. Bioelectromagnetics. 38(7):497–510. doi:10.1002/bem.22062.

Landgrebe M, Frick U, Hauser S, Hajak G, Langguth B. 2009. Association of tinnitus and electromagnetic hypersensitivity: hints for a shared pathophysiology? PLoS One. 4(3):e5026. doi:10.1371/journal.pone.0005026.

Landler L, Keays DA. 2018. Cryptochrome: the magnetosensor with a sinister side? PLoS Biol. 16(10):e3000018. doi:10.1371/journal.pbio.3000018.

Leberecht B, Wong SY, Satish B, Döge S, Hindman J, Venkatraman L, Apte S, Haase K, Musielak I, Dautaj G, et al. 2023. Upper bound for broadband radiofrequency field disruption of magnetic compass orientation in night-migratory songbirds. Proc Natl Acad Sci USA. 120(28):e2301153120. doi:10.1073/pnas.2301153120.

Leszczynski D. 2022. Review of the scientific evidence on the individual sensitivity to electromagnetic fields (EHS). Rev Environ Health. 37(3):423–450. doi:10.1515/reveh-2021-0038.

Lin C, Todo T. 2005. The cryptochromes. Genome Bio. 6:220. doi:10.1186/gb-2005-6-5-220.

Litovitz TA, Penafiel LM, Farrel JM, Krause D, Meister R, Mullins JM. 1997. Bioeffects induced by exposure to microwaves are mitigated by superposition of ELF noise. Bioelectromagnetics. 18(6):422–430. doi:10.1002/(SICI)1521-186X(1997)18:6<422::AID-BEM4>3.0.CO;2-4.

Luukkonen J, Hakulinen P, Mäki-Paakkanen J, Juutilainen J, Naarala J. 2009. Enhancement of chemically induced reactive oxygen species production and DNA damage in human SH-SY5Y neuroblastoma cells by 872 MHz radiofrequency radiation. Mutat Res. 662(1–2):54–58. doi:10.1016/j.mrfmmm.2008.12.005.

Maher BA, Ahmed ISAM, Karloukovski V, MacLaren DA, Foulds PG, Allsop D, Mann DMA, Torres-Jardón R, Calderon-Garciduenas L. 2016. Magnetite pollution nanoparticles in the human brain. Proc Natl Acad Sci USA. 113(39):10797–10801. doi:10.1073/pnas.1605941113.

Marais A, Adams B, Ringsmuth AK, Ferretti M, Gruber JM, Hendrikx R, Schuld M, Smith SL, Sinayskiy I, Krüger TPJ, et al. 2018. The future of quantum biology. J R Soc Interface. 15(148):20180640. doi:10.1098/rsif.2018.0640.

Markov M. 2015. XXIst century magnetotherapy. Electromagn Biol Med. 34(3):190–196. PMID26444192 doi:10.3109/15368378.2015.1077338.

Martínez-Bretón JL, Mendoza B. 2016. Effects of magnetic fields produced by simulated and real geomagnetic storms on rats. Adv Space Res. 57(6):1402–1410. doi:10.1016/j.asr.2015.11.023.

Martínez-Bretón JL, Mendoza B, Miranda-Anaya M, Durán P, Flores-Chávez PL. 2016. Artificial reproduction of magnetic fields produced by a natural geomagnetic storm increases systolic blood pressure in rats. Int J Biometeorol. 60(11):1753–1760. doi:10.1007/s00484-016-1164-5.

Mattsson MO, Simkó M. 2014. Grouping of experimental conditions as an approach to evaluate effects of extremely low-frequency magnetic fields on oxidative response in in vitro studies. Front Public Health. 2:132:1–11. doi:10.3389/fpubh.2014.00132.

McCarty DE, Carrubba S, Chesson AL, JrFrilot IIC, Gonzalez-Toledo E, Marino AA. 2011. Electromagnetic hypersensitivity: evidence for a novel neurological syndrome. Int J Neurosci. 121(12):670–676. doi:10.3109/00207454.2011.608139.

Medeiros LN, Sanchez TG. 2016. Tinnitus and cell phones: the role of electromagnetic radiofrequency radiation. Braz J Otorhinolaryngol. 82(1):97–104. doi:10.1016/j.bjorl.2015.04.013.

Merlin C. 2023. Insect magnetoreception: a Cry for mechanistic insights. J Comp Physiol A Neuroethol Sens Neural Behav Physiol. 209(5):785–792. doi:10.1007/s00359-023-01636-8.

Molina-Montenegro MA, Acuña-Rodríguez IS, Ballesteros GI, Baldelomar M, Torres-Díaz C, Broitman BR, Vázquez DP. 2023. Electromagnetic fields disrupt the pollination service by honeybees. Sci Adv. 9(19):eadh1455. doi:10.1126/sciadv.adh1455.

Mouritsen H, Feenders G, Liedvogel M, Wada MK, Jarvis ED. 2005. Night-vision brain area in migratory songbirds. Proc Natl Acad Sci USA. 102(23):8339–8344. doi:10.1073/pnas.0409575102.

Naisbett-Jones LC, Lohmann KJ. 2022. REVIEW: magnetoreception and magnetic navigation in fishes: a half century of discovery. J Comp Physiol A Neuroethol Sens Neural Behav Physiol. 208(1):19–40. doi:10.1007/s00359-021-01527-w.

NASA Report CR-166661. 1981. EMF interactions with the human body. https://ntrs.nasa.gov/api/citations/19810017132/downloads/19810017132.pdf.

NASA Report SP-8017. 1969. Magnetic fields - earth and extraterrestrial. https://ntrs.nasa.gov/api/citations/19690030884/downloads/19690030884.pdf.

Nastasi C, Mannarino L, D'Incalci M. 2020. DNA damage response and immune defense. Int J Mol Sci. 21(20):7504. https://www.mdpi.com/1422-0067/21/20/7504. doi:10.3390/ijms21207504.

Nishimura T, Tsai IJ, Yamauchi H, Nakatani E, Fukushima M, Hsu CY. 2020. Association of geomagnetic disturbances and suicide attempts in Taiwan, 1997–2013: a cross-sectional study. Int J Environ Res Public Health. 17(4):1154. doi:10.3390/ijerph17041154.

Nohr D, Franz S, Rodriguez R, Paulus B, Essen LO, Weber S, Schleicher E. 2016. Extended electron-transfer in animal cryptochromes mediated by a tetrad of aromatic amino acids. Biophys J. 111(2):301–311. doi:10.1016/j.bpj.2016.06.009.

Pakhomov A, Bojarinova J, Cherbunin R, Chetverikova R, Grigoryev PS, Kavokin K, Kobylkov D, Lubkovskaja R, Chernetsov N. 2017. Very weak oscillating magnetic field disrupts the magnetic compass of songbird migrants. J R Soc Interface. 14(133):20170364. doi:10.1098/rsif.2017.0364.

Pall ML. 2013. Electromagnetic fields act via activation of voltage-gated calcium channels to produce beneficial or adverse effects. J Cell Mol Med. 17(8):958–965. doi:10.1111/jcmm.12088.

Pall ML. 2016. Microwave frequency electromagnetic fields (EMFs) produce widespread neuropsychiatric effects including depression. J Chem Neuroanat. 75(Pt B):43–51. doi:10.1016/j.jchemneu.2015.08.001.

Palmer SJ, Rycroft MJ, Cermack M. 2006. Solar and geomagnetic activity, extremely low frequency magnetic and electric fields and human health at the earth's surface. Surv Geophys. 27(5):557–595. doi:10.1007/s10712-006-9010-7.

Panagopoulos DJ, Messini N, Karabarbounis A, Philippetis AL, Margaritis LH. 2000. A mechanism for action of oscillating electric fields on cells. Biochem Biophys Res Commun. 272(3):634–640. doi:10.1006/bbrc.2000.2746.

Panagopoulos DJ, Karabarbounis A, Margaritis LH. 2002. Mechanism for action of electromagnetic fields on cells. Biochem Biophys Res Commun. 298(1):95–102. doi:10.1016/s0006-291x(02)02393-8.

Panagopoulos DJ, Karabarbounis A, Yakymenko I, Chrousos GP. 2021. Human-made electromagnetic fields: ion forced-oscillation and voltage-gated ion channel dysfunction, oxidative stress and DNA damage (Review). Int J Oncol. 59(5):92. doi:10.3892/ijo.2021.5272.

Pazur A, Schimek C, Galland P. 2007. Magnetoreception in microorganisms and fungi. Cent Eur J Biol. 2(4):597–659. doi:10.2478/s11535-007-0032-z.

Phillips JB, Diego Rasilla FJ. 2022. REVIEW: the amphibian magnetic sense(s). J Comp Physiol A Neuroethol Sens Neural Behav Physiol. 208(5–6):723–742. - doi:10.1007/s00359-022-01584-9.

Pishchalnikov RY, Gurfinkel YI, Sarimov RM, Vasin AL, Sasonko ML, Matveeva TA, Binhi VN, Baranov MV. 2019. Cardiovascular response as a marker of environmental stress caused by variations in geomagnetic field and local weather. Biomed Signal Proces. 51:401–410. doi:10.1016/j.bspc.2019.03.005.

Pooam M, Arthaut LD, Burdick D, Link J, Martino CF, Ahmad M. 2019. Magnetic sensitivity mediated by the Arabidopsis blue-light receptor cryptochrome occurs during flavin reoxidation in the dark. Planta. 249(2):319–332. doi:10.1007/s00425-018-3002-y.

Pooam M, Jourdan N, Aguida B, Dahon C, Baouz S, Terry C, Raad H, Ahmad M. 2022. Exposure to 1.8 GHz radiofrequency field modulates ROS in human HEK293 cells as a function of signal amplitude. Commun Integr Biol. 15(1):54–66. doi:10.1080/19420889.2022.2027698.

Pophof B, Henschenmacher B, Kattnig DR, Kuhne J, Vian A, Ziegelberger G. 2023. Biological effects of radiofrequency electromagnetic fields above 100 MHz on Fauna and Flora: workshop report. Health Phys. 124(1):31–38. doi:10.1097/HP.0000000000001625.

Qin S, Yin H, Yang C, Dou Y, Liu Z, Zhang P, Yu H, Huang Y, Feng J, Hao J, et al. 2016. A magnetic protein biocompass. Nat Mater. 15(2):217–226. doi:10.1038/nmat4484.

Ritz T, Adem S, Schulten K. 2000. A model for photoreceptor-based magnetoreception in birds. Biophys J. 78(2):707–718. doi:10.1016/S0006-3495(00)76629-X.

Ritz T, Thalau P, Phillips JB, Wiltschko R, Wiltschko W. 2004. Resonance effects indicate a radical-pair mechanism for avian magnetic compass. Nature. 429(6988):177–180. doi:10.1038/nature02534.

Rodgers CT. 2009. Magnetic field effects in chemical systems. Pure Appl Chem. 81(1):19–43. doi:10.1351/PAC-CON-08-10-18.

Röösli M, Dongus S, Jalilian H, Eyers J, Esu E, Oringanje CM, Meremikwu M, Bosch-Capblanch X. 2024. The effects of radiofrequency electromagnetic fields exposure on tinnitus, migraine and non-specific symptoms in the general and working population: a systematic review and meta-analysis on human observational studies. Environ Int. 183:108338. doi:10.1016/j.envint.2023.108338.

Roussel A. 2024. ScienceClick: the origin of electromagnetic waves, and why they behave as they do. [accessed 14 Aug 2024]. https://www.youtube.com/watch?v=V_jYXQFjCmA.

Sack RL, Lewy AJ, Erb DL, Vollmer WM, Singer CM. 1986. Human melatonin production decreases with age. J Pineal Res. 3(4):379–388. doi:10.1111/j.1600-079x.1986.tb00760.x.

Sancar A. 2016. Nobel lecture: mechanisms of DNA repair by photolyase and excision nuclease. Angew Chem Int Ed Engl. 55(30):8502–8527. doi:10.1002/ANIE.201601524.

Sancar A. 2004. Regulation of the mammalian circadian clock by cryptochrome. J Biol Chem. 279(33):34079–34082. doi:10.1074/jbc.R400016200.

Sarimov RM, Serov DA, Gudkov SV. 2023a. Biological effects of magnetic storms and ELF magnetic fields. Biology (Basel). 12(12):1506. doi:10.3390/biology12121506.

Sarimov RM, Serov DA, Gudkov SV. 2023b. Hypomagnetic conditions and their biological action (review). Biology. 12(12):1513. doi:10.3390/biology12121513.

Schliephake E. 1932. Arbeitsgebiete auf dem Kurzwellengebiet. [Fields of the Short-wave region]. Deut Med Wochenschrif. 32:1235–1240.

Schmiedchen K, Driessen S, Oftedal G. 2019. Methodological limitations in experimental studies on symptom development in individuals with idiopathic environmental intolerance attributed to electromagnetic fields (IEI-EMF) – a systematic review. Environ Health. 18(1):88. doi:10.1186/s12940-019-0519-x.

Schulten K, Swenberg CE, Weller A. 1978. A biomagnetic sensory mechanism based on magnetic field modulated coherent electron spin motion. Z Phys Chem. 111(1):1–5. doi:10.1524/zpch.1978.111.1.001.

Sefidbakht Y, Moosavi-Movahedi AA, Hosseinkhani S, Khodagholi F, Torkzadeh-Mahani M, Foolad F, Faraji-Dana R. 2014. Effects of 940 MHz EMF on bioluminescence and oxidative response of stable luciferase producing HEK cells. Photochem Photobiol Sci. 13(7):1082–1092. doi:10.1039/c3pp50451d.

Seomun G, Lee J, Park J. 2021. Exposure to extremely low-frequency magnetic fields and childhood cancer: a systematic review and meta-analysis. PLoS One. 16(5):e0251628. doi:10.1371/journal.pone.0251628.

Shaw J, Boyd A, House M, Woodward R, Mathes F, Cowin G, Saunders M, Baer B. 2015. Magnetic particle-mediated magnetoreception. J R Soc Interface. 12(110):0499. doi:10.1098/rsif.2015.0499.

Sherrard RM, Morellini N, Jourdan N, El-Esawi M, Arthaut LD, Niessner C, Rouyer F, Klarsfeld A, Doulazmi M, Witczak J, et al. 2018. Low-intensity electromagnetic fields induce human cryptochrome to modulate intracellular reactive oxygen species. PLoS Biol. 16(10):e2006229. doi:10.1371/journal.pbio.2006229.

Shi R, Hou W, Wang ZQ, Xu X. 2021. Biogenesis of iron–sulphur clusters and their role in DNA metabolism. Front Cell Dev Biol. 9:735678. doi:10.3389/fcell.2021.735678.

Shirdhanka RN, Malkemper EP. 2024. Cognitive maps and the magnetic sense in vertebrates. Curr Opin Neurobiol. 86:102880. doi:10.1016/j.conb.2024.102880.

Smith J, Zadeh-Haghighi H, Salahub D, Simon C. 2021. Radical pairs may play a role in xenon-induced general anesthesia. Sci Rep. 11(1):6287. doi:10.1038/s41598-021-85673-w.

Solov'yov IA, Chandler DE, Schulten K. 2007. Magnetic field effects in *Arabidopsis thaliana* cryptochrome-1. Biophys J. 92(8):2711–2726. doi:10.1529/biophysj.106.097139.

Stein Y, Udasin IG. 2020. Electromagnetic hypersensitivity (EHS, microwave syndrome) – Review of mechanisms. Environ Res. 186:109445. doi:10.1016/j.envres.2020.109445.

Talbi O, Zadeh-Haghighi H, Simon C. 2024. The radical pair mechanism cannot explain telecommunication frequency effects on reactive oxygen species. bioRxiv preprint. doi:10.1101/2024.06.23.600261.

Thill A, Cammaerts MC, Balmori A. 2024. Biological effects of electromagnetic fields on insects: a systematic review and meta-analysis. Rev Environ Health. 39(4):853–869. doi:10.1515/reveh-2023-0072.

Thoradit T, Thongyoo K, Kamoltheptawin K, Tunprasert L, El-Esawi MA, Aguida B, Jourdan N, Buddhachat K, Pooam M. 2023. Cryptochrome and quantum biology: unraveling the mysteries of plant magnetoreception. Front Plant Sci. 14:1266357. doi:10.3389/fpls.2023.1266357.

Thoradit T, Chabi M, Aguida B, Baouz S, Stierle V, Pooam M, Tousaints S, Akpovi CD, Ahmad M. 2024. Hypersensitivity to man-made electromagnetic fields (EHS) correlates with immune responsivity to oxidative stress: a case report. Commun Integr Biol. 17(1):2384874. doi:10.1080/19420889.2024.2384874.

Tomanova K, Vacha M. 2016. The magnetic orientation of the Antarctic amphipod *Gondogeneia antarctica* is cancelled by very weak radiofrequency fields. J Exp Biol. 219(Pt 11):1717–1724. doi:10.1242/jeb.132878.

Touitou Y, Selmaoui B. 2012. The effects of extremely low-frequency magnetic fields on melatonin and cortisol, two marker rhythms of the circadian system. Dialogues Clin Neurosci. 14(4):381–399. doi:10.31887/DCNS.2012.14.4/ytouitou.

Tuor M, Ebert S, Schuderer J, Kuster N. 2005. Assessment of ELF exposure from GSM handsets and development of an optimized RF/ELF exposure setup for studies of human volunteers. Zurich Switzerland: Foundation for Research on Information Technologies in Society. Report: BAG Reg. No 23.02.-18/02.001778, Zurich, January 2005.

Usselman RJ, Hill I, Singel DJ, Martino CF. 2014. Spin biochemistry modulates reactive oxygen species (ROS) production by radio frequency magnetic fields. PLoS One. 9(3):e93065. doi:10.1371/journal.pone.0093065.

Usselman RJ, Chavarriaga C, Castello PR, Procopio M, Ritz T, Dratz EA, Singel DJ, Martino CF. 2016. The quantum biology of reactive oxygen species partitioning impacts cellular bioenergetics. Sci Rep. 6(1):38543. doi:10.1038/srep38543.

van der Horst GT, Muijtjens M, Kobayashi K, Takano R, Kanno S, Takao M, de Wit J, Verkerk A, Eker AP, van Leenen D, et al. 1999. Mammalian Cry1 and Cry2 are essential for maintenance of circadian rhythms. Nature. 398(6728):627–630. doi:10.1038/19323.

Vanderstraeten J, Burda H. 2012. Does magnetoreception mediate biological effects of power frequency magnetic fields? Sci Total Environ. 417–418:299–304. doi:10.1016/j.scitotenv.2011.08.071.

Vanderstraeten J, Verschaeve L, Burda H, Bouland C, de Brouwer C. 2012. Health effects of extremely low-frequency magnetic fields: reconsidering the melatonin hypothesis in the light of current data on magnetoreception. J Appl Toxicol. 32(12):952–958. doi:10.1002/jat.2761.

Vanderstraeten J, Burda H, Verschaeve L, De Brouwer C. 2015. Could magnetic fields affect the circadian clock function of cryptochromes? Testing the basic premise of the cryptochrome hypothesis (ELF magnetic fields). Health Phys. 109(1):84–89. doi:10.1097/HP.0000000000000292.

Vieira CLZ, Chen K, Garshick E, Liu EM, Vokonas P, Ljungman P, Schwartz J, Koutrakis P. 2022. Geomagnetic disturbances reduce heart rate variability in the normative aging study. Sci Total Environ. 839:156235. doi:10.1016/j.scitotenv.2022.156235.

Vieira J, Jones AR, Danon A, Sakuma M, Hoang N, Robles D, Tait S, Heyes DJ, Picot M, Yoshii T, et al. 2012. Human cryptochrome-1 confers light independent biological activity in transgenic Drosophila correlated with flavin radical stability. PLoS One. 7(3):e31867. doi:10.1371/journal.pone.0031867.

Wan G, Liu R, Li C, He J, Pan W, Sword GA, Hu G, Chen F. 2020. Change in geomagnetic field intensity alters migration associated traits in a migratory insect. Biol Lett. 16(4):20190940. doi:10.1098/rsbl.2019.0940.

Wang CX, Hilburn IA, Wu DA, Mizuhara Y, Cousté CP, Abrahams JNH, Bernstein SE, Matani A, Shimojo S, Kirschvink JL. 2019. Transduction of the geomagnetic field as evidenced from alpha-band activity in the human brain. eNeuro. 6(2):ENEURO.0483-18.2019. e048323. doi:10.1523/ENEURO.0483-18.2019.

West KE, Jablonski MR, Warfield B, Cecil KS, James M, Ayers MA, Maida J, Bowen C, Sliney DH, Rollag MD, et al. 2011. Blue light from light-emitting diodes elicits a dose-dependent suppression of melatonin in humans. J Appl Physiol (1985). 110(3):619–626. doi:10.1152/japplphysiol.01413.2009.

Wever R. 1979. The circadian system of man – results of experiments under temporal isolation. New York (NY): Springer.

Weydahl A, Sothern RB, Cornélissen G, Wetterberg L. 2000. Geomagnetic activity influences the melatonin secretion at latitude 70° N. Biomed Pharmacolher. 55:s57–s62. doi:10.1016/S0753-3322(01)90006-X.

WHO. 2005. Fact sheet No. 296: electromagnetic fields and public health. World Health Organization. [accessed 14 Aug 2024]. http://www.emfandhealth.com/WHO_EMSensitivity.pdf.

Wiltschko R, Wiltschko W. 2009. REVIEW: avian navigation. The Auk. 126(4):717–743. doi:10.1525/auk.2009.11009.

Wiltschko R, Ahmad M, Nießner C, Gehring D, Wiltschko W. 2016. Light-dependent magnetoreception in birds: the crucial step occurs in the dark. J R Soc Interface. 13(118):20151010. doi:10.1098/rsif.2015.1010.

Wiltschko R, Nießner C, Wiltschko W. 2021. The magnetic compass of birds: the role of cryptochrome. Front Physiol. 12:667000. doi:10.3389/fphys.2021.667000.

Winklhofer M. 2009. The physics of geomagnetic-field transduction in animals. IEEE Trans Magn. 45(12):5259–5265. doi:10.1109/TMAG.2009.2017940.

Xu S, Kong X, Liu J. 2021. Expression of CRY2 gene in the brain is related to human navigation. Front Radiol. 1:731070. doi:10.3389/fradi.2021.731070.

Zadeh Haghighi H, Simon C. 2021. Entangled radicals may explain lithium effects on hyperactivity. Sci Rep. 11(1):12121. doi:10.1038/s41598-021-91388-9.

Zadeh-Haghighi H, Simon C. 2022. Magnetic field effects in biology from the perspective of the radical pair mechanism. J R Soc Interface. 19(193):20220325. doi:10.1098/rsif.2022.0325.

Zeitzer JM, Khalsa SBS, Boivin DB, Duffy JF, Shanahan TL, Kronauer RE, Czeisler CA. 2005. Temporal dynamics of late-night photic stimulation of the human circadian timing system. Am J Physiol Regul Integr Comp Physiol. 289(3):R839–844. doi:10.1152/ajpregu.00232.2005.

Zhang B, Wang L, Zhan A, Wang M, Tian L, Guo W, Pan Y. 2021. Long-term exposure to a hypomagnetic field attenuates adult hippocampal neurogenesis and cognition. Nat Commun. 12(1):1174. doi:10.1038/s41467-021-21468-x.

Zhang L, Malkemper EP. 2023. Cryptochromes in mammals: a magnetoreception misconception. Front Physiol. 14:1250798. doi:10.3389/fphys.2023.1250798.

Zhao L, Liu X, Wang C, Yan K, Lin X, Li S, Bao H, Liu X. 2014. Magnetic fields exposure and childhood leukemia risk: a meta-analysis based on 11,699 cases and 13,194 controls. Leuk Res. 38(3):269–274. doi:10.1016/j.leukres.2013.12.008.

Zhou Y, Tong T, Wei M, Zhang P, Fei F, Zhou X, Guo Z, Zhang J, Xu H, Zhang L, et al. 2023. Towards magnetism in pigeon MagR: iron- and iron-sulphur binding work indispensably and synergistically. Zool Res. 44(1):142–152. doi:10.24272/j.issn.2095-8137.2022.423.

Zufry H, Rudijanto A, Soeatmadji DW, Sakti SP, Munadi K, Sujuti H, Mintaroem K.,. 2023. Effects of mobile phone electromagnetic radiation on thyroid glands and hormones in Rattus norvegicus brain: an analysis of thyroid function, reactive oxygen species, and monocarboxylate transporter 8. J Adv Pharm Technol Res. 14(2):63–68. doi:10.4103/japtr.japtr_680_22.

Appendix A

Energy in electromagnetic fields and photons in relation to life on Earth

In addition to sunlight, life on Earth has developed in an electromagnetically quiet environment. Low-frequency EM fields originate from currents circulating in the core of the Earth, solar winds, and thunderstorm activity. In the last 100 years, anthropogenic activities have greatly increased the levels of environmental time-varying electric and magnetic fields.

Figure 1 shows low-frequency MF levels (0.01–10,000 Hz) with long wavelengths (30 Gm @ 0.01 Hz to 3 km @ 10 kHz). At these wavelengths, electric and magnetic fields are not mathematically related – one can exist without the other – and this region is known as the reactive near field.

Figure 2 shows the vast increase in the environmental radio-frequency power density (PD) across a wide frequency range. Above approximately 10 MHz, people are generally exposed to far fields where electric and magnetic fields are mathematically related. The RF peak, mostly due to modern telecommunication signals, lies between 300 MHz and 30 GHz, i.e. in the 'silent' part of the natural noise spectrum. The modern peak PD is approximately 10^{18} times greater.

To transmit an RF signal, an oscillating potential at a given frequency is applied to an antenna. In terms of *classical physics*, this results in the emission and propagation of EMR, in which the electric and magnetic fields are intricately linked by Maxwell's equations. In the *quantum physics* world, radio waves are 'streams of photons', which are usually highly coherent and linearly or circularly polarized. They add together by wave superposition in an n-photon wave train.

The total RF PD levels are now similar to those from bright sunlight. Individual RF photons have much less energy, but there are at least 100,000 of them for every sunlight photon. The total energy is calculated by integrating the PD across a relevant bandwidth.

On the basis of energy considerations, the annual absorbed dose from natural ionizing background radiation is approximately 2 mGy, which involves a transfer of 2 mJ kg^{-1} to tissue.

The current ICNIRP mobile phone SAR is 2 W kg^{-1}, which amounts to a total energy transfer of 2000 mJ kg^{-1} per second (=2 J kg^{-1} s^{-1}), albeit from photons with quite low individual energies. The possible long-term effects of this massive novel influx of photon energy on a person's well-being cannot readily be discounted. Further discussion can be found here (Roussel 2024; Bruno 2024).