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Review

Biological effects of electromagnetic fields on insects

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Abstract

Worldwide, the number of insects is decreasing at an alarming rate. It is known that among other causes, the use of pesticides and modern agricultural practices play a particularly important role. The cumulative effects of multiple low-dose toxins and the spread of toxins in nature have not yet been methodically researched, or only in the early stages.

Existing research indicates another factor of anthropogenic origin, which might cause subtle adverse effects: the increasingly frequent use of artificial electromagnetic fields (EMF) such as high voltage, mobile telephony and Wi-Fi. The infrastructure of the next generation of mobile communications technologies, 5G, is being deployed without having been previously tested for possible toxic effects. With mankind's aspirations for omnipresence of technology, even modest effects of electromagnetic fields on organisms might eventually reach a saturation level that can no longer be ignored.

This systematic review evaluates the state of knowledge regarding the toxic effects of electromagnetic fields (EMF) on insects. Also included is a general review of reported effects and mechanisms of EMF exposure, which addresses new findings in cell biology. 72 of 83 analyzed studies found an effect. Negative effects that were described in studies include: disturbance of the sense of orientation, reduced reproductive ability and fertility, lethargy, changes in flight dynamics, failure to find food, reduced reaction speeds, escape behavior, disturbance of the circadian rhythm, blocking of the respiratory chain and damage to the mitochondria, misactivation of the immune system, increased number of DNA strand breaks.

Some mechanisms of action leading to these damages are identified. EMFs affect the metabolism, among other things affecting voltage-gated calcium channels, e.g. in neurotransmission and in muscle tissue, which can lead to an overactivation of signal transduction and of the respiratory chain with production of free oxygen radicals and consequently leading to oxidative cell stress.

The results show that EMF could have a serious impact on the vitality of insect populations. In some experiments it was found that despite low levels of exposure to transmitters, harmful effects occurred after several months. Field strengths 100 times below the ICNIRP limits could already have effects. Against the background of the rapid decline of insects and the further expansion of high-frequency electromagnetic field sources, there is not only an urgent need for further research, but also in particular on the interactions with other harmful noxious agents, such as pesticides. When planning the expansion of mobile networks, insect habitats should be protected from high-intensity EMF exposure already now.

1. Biological effects of electromagnetic fields (EMF)

The recently publicly announced insect decline, the beginnings of which go back several decades, seems to be caused by a multitude of factors with cumulative effects (Hallmann et al. 2017; Sánchez-Bayo and Wyckhuys 2019, Fig. 1). Although it is assumed that the main causes are to be found in the use of pesticides and in the restructuring or destruction of natural habitats, additional negative effects of other kinds cannot be excluded – e. g. the effects of hormone-like substances, heavy metals and electromagnetic fields, all factors whose occurrence in nature has drastically increased in recent decades (Sharma et al. 2016; Rhind 2009; Bandara and Carpenter 2018).

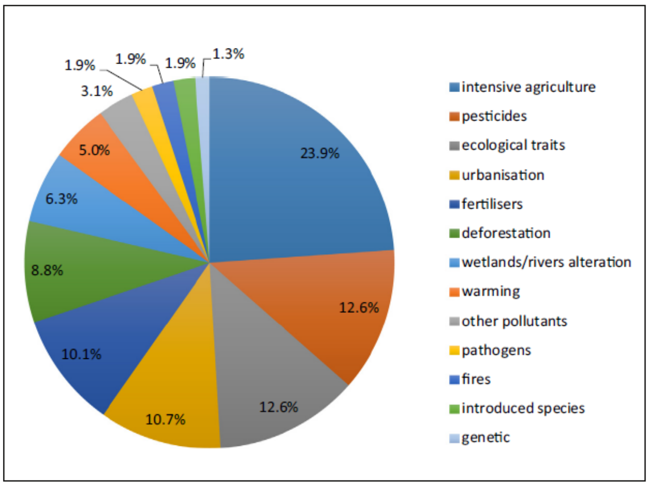

Figure 1: Main causes of recent insect decline.
Source: Sánchez-Bayo and Wyckhuys 2019

This review deals primarily with the effects of low- and high-frequency electromagnetic fields on insects. The effects of low-frequency magnetic fields (and EMF) from power lines (at 50 Hz power frequency) have been relatively well studied already, e. g., in terms of incidence of leukemia in humans (ARIMMORA final report 2015), or toxicity to insects (Wyszkowska et al. 2016; Maliszewska et al. 2018; Shepherd et al. 2018).

High voltage and mains electricity became standard in Europe from 1950 onward. Less well researched are the newer, high-frequency electromagnetic fields (HF-EMF) in the microwave range, as used for mobile phone networks, but also Wi-Fi and similar applications (from 1990 on). In the case of low-frequency EMF, adequate experimental devices to apply the characteristic EMF to organisms in the laboratory, so-called Helmholtz coils, have existed for decades. Hereby the field strength can also be adjusted. In comparison, there are no adequate emulations for high-frequency EMF, such as those emitted by mobile phone towers or Wi-Fi routers – or they are very expensive and/or require a permit (mobile phone repeaters). The most realistic approach at the moment is to use mobile phones as emulation of mobile phone masts for laboratory tests, and actual Wi-Fi routers.

Since we are about to develop the next generation of mobile phones (5G), whose infrastructure could include a further increase of radiated energy in the urban sector, the safety of this technology should be demonstrated in advance - as is inevitable when marketing new drugs (Bandara and Carpenter 2018).

In general, a distinction is made between thermal and non-thermal biological effects of electromagnetic fields. The thermal effect is based on direct heating of tissue (as in a microwave oven). Below the intensities where tissue heating can be measured, several additional non-thermal effects have been described, e. g. microwave hearing (in humans), also known as the Frey effect, whose mechanism has been known for several decades (electroelastic transformation of microwaves into sound waves in the skull, see Chou, Guy, and Galambos 1982; Belyaev and Markov 2015).

Furthermore, parametric resonance, which is accompanied by a change of the human and animal electroencephalogram, is regarded as scientifically proven (Hinrikus et al. 2017; Mohammed et al. 2013). There is increasing evidence that parametric resonance is a by-product of the activation of voltage-gated ion channels and is associated with calcium release (Agnati et al. 2018; Pall 2016; Sun et al. 2016; Belyaev and Markov 2015) – and thus affects all animal and plant organisms.

In summary, it could be said that biological effects of chronic EMF exposure follow this general pattern: EMF act (directly or indirectly) on voltage-gated calcium channels (VGCC), opening them and leading to calcium release.

More precisely, voltage-gated ion channels (Na^+, K^+), as well as the NMDA receptor, seem to be sensitive to non-thermal (i. e. very low) EMF levels and this is probably related to useful functions of the perception of endogenous EMF ("ephaptic coupling"), which are produced by the activity of neurons and astrocytes (Martinez-Banaclocha 2020; Chiang et al. 2019; Hales and Pockett 2014). Thus, the mechanism of ephaptic coupling seems to play an active role in the synchronous activity of heart cells (Weinberg 2017), as well as in the olfactory processing of odorant mixtures (antennas or olfactory nerve) (Zhang et al. 2019; Bokil et al. 2001), and also in the coordination of movement in the cerebellum (Han et al. 2018).

In these cases, however, voltage-gated sodium channels (Weinberg 2017; Han et al. 2018), potassium channels (Fogle et al. 2015) or NMDA receptors (Chiang et al. 2019) – which are voltage-sensitive and channel sodium and calcium ions – have been shown to be the macromolecules directly affected by EMF. In addition, it is assumed that astrocytic calcium waves, through ephaptic coupling, influence and regulate neuronal activity over wide areas and to a large extent (Agnati et al. 2018; Martinez-Banaclocha 2020).

The EMF-induced activation of voltage-gated sodium and potassium channels or NMDA receptors leads indirectly, by triggering or amplifying action potentials, to increased activation of synaptic VGCC and release of calcium (Pilla 2012); neurotransmission based on action potentials via chemical synapses requires activation of VGCC (Atlas 2013).

Calcium is one of the most common secondary messengers in all organisms, and elevated levels of calcium have an activating effect, e. g. on the respiratory chain and muscle (Kim et al. 2019). Calcium in turn releases nitric oxide (NO) via calmodulin. An overactivation of calcium-dependent neurotransmission (and possibly metabolic pathways) leads to the production of free oxygen radicals (reactive oxygen species, ROS) such as peroxynitrite, i. e. to oxidative stress.

Chronically increased oxidative stress has a toxic effect on organisms in many different ways, e. g. by blocking the respiratory chain, causing damage to mitochondria, misactivation of the immune system and an increase in the genetic mutation rate (Valko et al. 2007; Saliev et al. 2019).

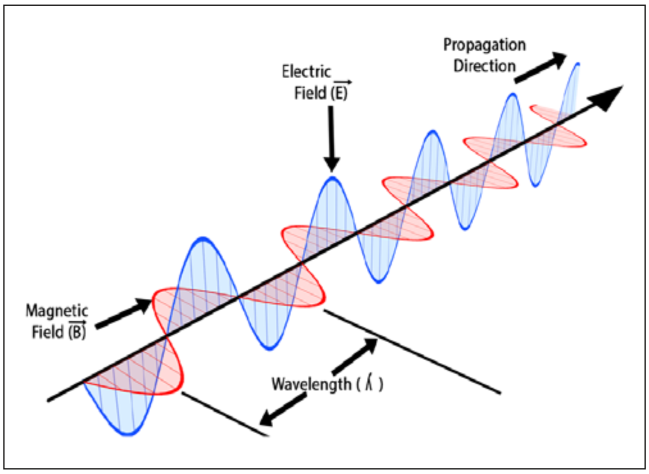

Figure 3: Electromagnetic wave. Electric field strength in blue, magnetic field strength in red. The radiation intensity or power density of an EMF can be derived from both field strengths (see appendix).
Source : https://byjus.com/physics/characteristics-of-em-waves/

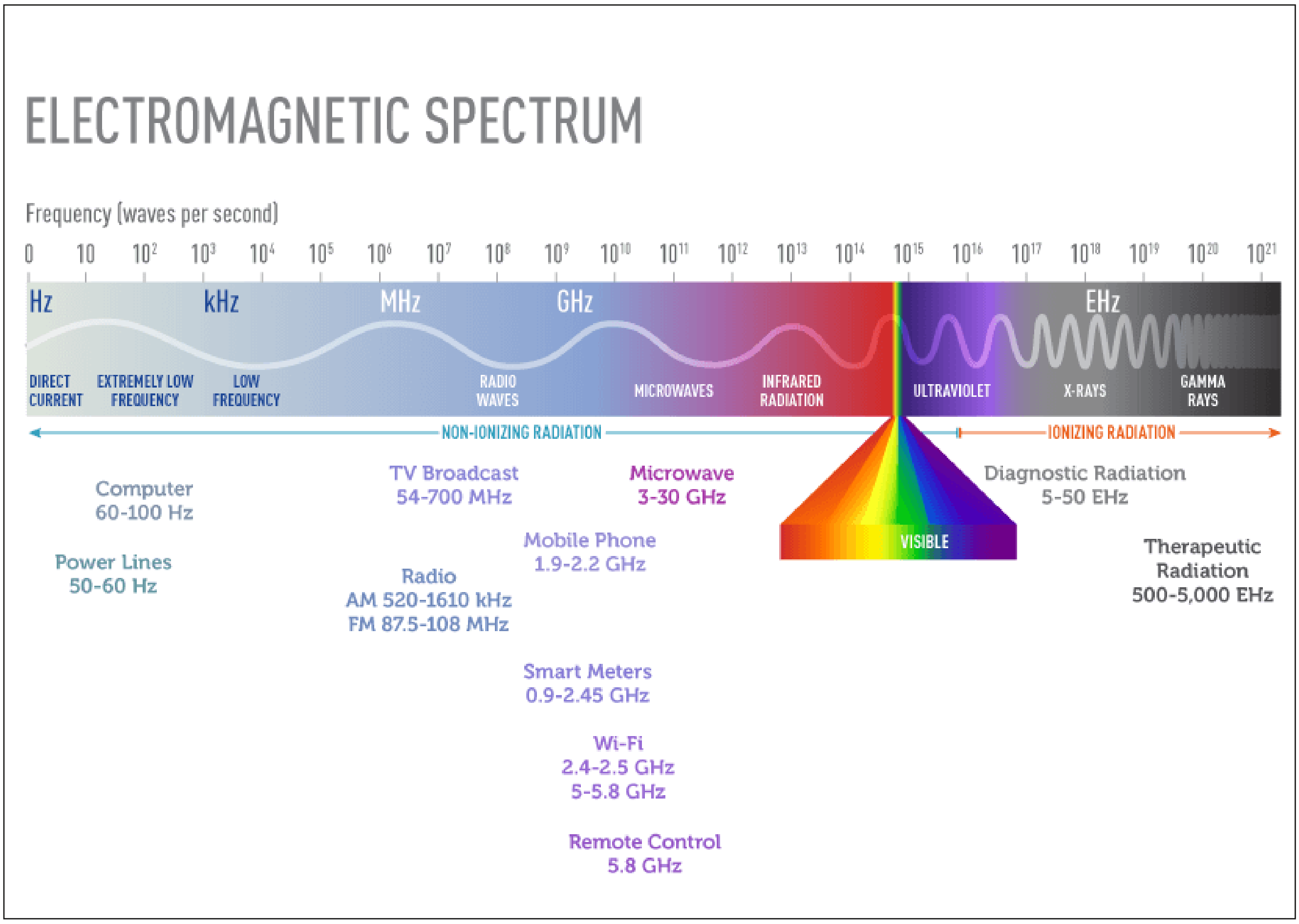

Figure 2: Electromagnetic spectrum. Source: https://thinktankgreen.com/emf-testing/facts-education/electromagnetic-spectrum/

1.1 Magnetic sense

Natural variations in the Earth's magnetic field ("geomagnetic field", GMF), e. g. due to solar flares, have been shown to cause stress in animals. The effect is well documented by the research group around Krylov in fish and daphnia (Krylov 2017). A strong correlation was also found for honeybees (Ferrari and Tautz 2015).

Guijun Wan et al. 2019 have provided experimental evidence that in the absence of the natural geomagnetic field the feeding behavior and development of locusts is disturbed. Quote: *"These results support the hypothesis that strong changes in GMF intensity may influence the feeding behavior of insects and the underlying regulatory processes. Our results provide further evidence that magnetoreception and regulatory responses to changes in GMF can influence a variety of biological processes."*

The existence of a magnetic sense is described in most insect orders: for example, in butterflies, beetles, flies, ants and bees (Hymenoptera) as well as termites and cockroaches (Guerra, Gegear, and Reppert 2014; Gegear et al. 2008; Oliveira et al. 2010; Lambinet et al. 2017; Vacha, Puzova, and Kvicalova 2009).

However, the question of the magnetic sense is quite complex and not yet conclusively elucidated, since different organisms use different mechanisms (Clites and Pierce 2017; Nordmann, Hochstoeger, and Keays 2017). At the molecular level, two typical but different magnetoreception systems have been discovered: cryptochrome and magnetite.

1.2 Cryptochrome

Cryptochrome (CRY) is a molecule from the blue light receptor family that regulates the circadian rhythm in insects. In addition, cryptochrome is magnetosensitive (Georgiou 2010) once it has been activated by high-energy light (via the radical pair mechanism). CRY is found both in the eyes of most insects and vertebrates and in their brains (i. e. ventro-lateral neurons of insects or in the suprachiasmatic nucleus – SCN of vertebrates), where it is part of the circadian rhythm (molecular clock, see Solov'yov and Schulten 2014).

Fedele et al. 2014 showed by means of cryptochrome mutant Drosophila fruit flies, that cryptochrome is necessary for light- and EMF-induced delay of circadian rhythms, and that these effects actually occur in the brain of Drosophila but not in the SCN of mice. Furthermore, they could show that the actual magnetoreceptor does not have to be cryptochrome itself. Qin et al. 2016 have shown that cryptochrome is associated with the protein CG8198 (MagR – the putative magnetoreceptor), both located in the eye.

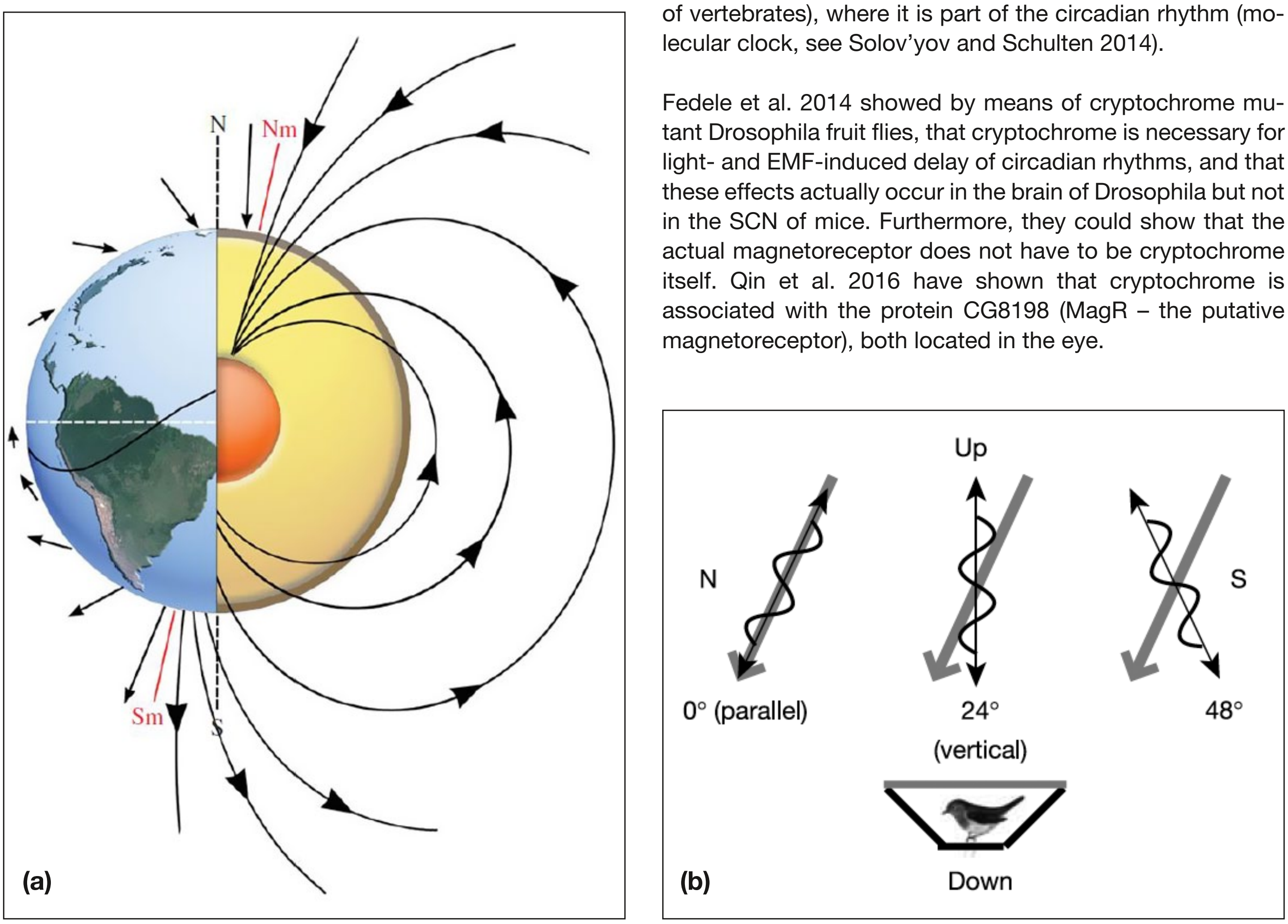

Figure 4a + b: (a) Earth's magnetic field. Source: Shaw et al. 2015. (b) Effect of the angle of the incoming EM field on the birds' magnetic sense. Grey arrow: Inclination of the Earth's magnetic field. From Ritz et al. 2004.

Fogle et al. 2015 showed that CRY activates the voltage sensor (or redox sensor) of the voltage-controlled potassium channel Kvß (in the brain of Drosophila), which leads to an increased firing rate of action potentials, whereby free radicals formed by CRY in an intermediate step, which has not yet been clarified, are transferred to "hyperkinetic" (Hk).

Sherrard et al. 2018 investigated the production of free radicals in Drosophila. PEMF devices ("pulsed electomagnetic field") are Helmholtz coils with predefined characteristics, which e. g. cause faster healing of bone fractures or wounds (Pilla 2012). Wild type Drosophila showed an aversion reaction and a formation of free radicals (ROS) after irradiation with a medical PEMF device with non-thermal power (2 mT). This was not the case with mutant Drosophila, whose cryptochrome had been removed. An effect in the wild type was found only when blue (or white) light was additionally present, since insect cryptochrome requires high-energy blue photons to activate (no effect was observed under red light). Although not postulated by the authors, this allows the conclusion that the toxicity of EMF in Drosophila cumulates with the presence of (blue light-intensive) artificial light.

Sherrard et al. 2018 were able to show in cell cultures of the Owl Butterfly (Spodoptera frugiperda) that cryptochrome is necessary for the formation of free radicals when treated with PEMF coils – and this probably concerns all low-frequency EMF sources. Whether cryptochrome is also necessary for oxidative cell stress (in insects) when irradiated with radiofrequency EMF has not yet been investigated.

Bartos et al. 2019's experiment with German cockroaches (Blatella germanica) proves that additional complex interactions between the local geomagnetic field (or artificial magnetic fields) and EMF are crucial in the quantum mechanical processes (radical pair mechanism) that activate cryptochrome, as previously shown for birds (Ritz et al. 2004, Fig. 4) and theoretically analyzed in detail by Warnke (Warnke 2009).

In contrast to the VGCC activation hypothesis, the activation of cryptochrome by EMF has been clearly proven, in birds and insects, and has been largely elucidated, and leads to the activation of VGCCs in a further step, at least in Drosophila. The VGCC hypothesis is based on numerous observations, that EMF cause a release of calcium ions, and that calcium channel blockers protect from negative effects (Pall 2013) – however, calcium and VGCCs are involved in many processes of neurotransmission – e. g., at excitatory synapses (Caddick et al. 1999; Atlas 2013). In principle, however, there is nothing to be said against the assumption that VGCCs can be activated (opened) by EMF, both directly and indirectly via cryptochrome (and other macromolecules) (Damulewicz and Mazzotta 2020; Catterall 2010; Littleton and Ganetzky 2000). However, only the pathway of light-dependent activation of cryptochrome (by EMF) in the clock neurons of Drosophila, which leads to an increased action potential firing rate, and produces described, but not yet fully understood adverse effects, presumably by increased calcium release at the synapses, has so far been experimentally proven.

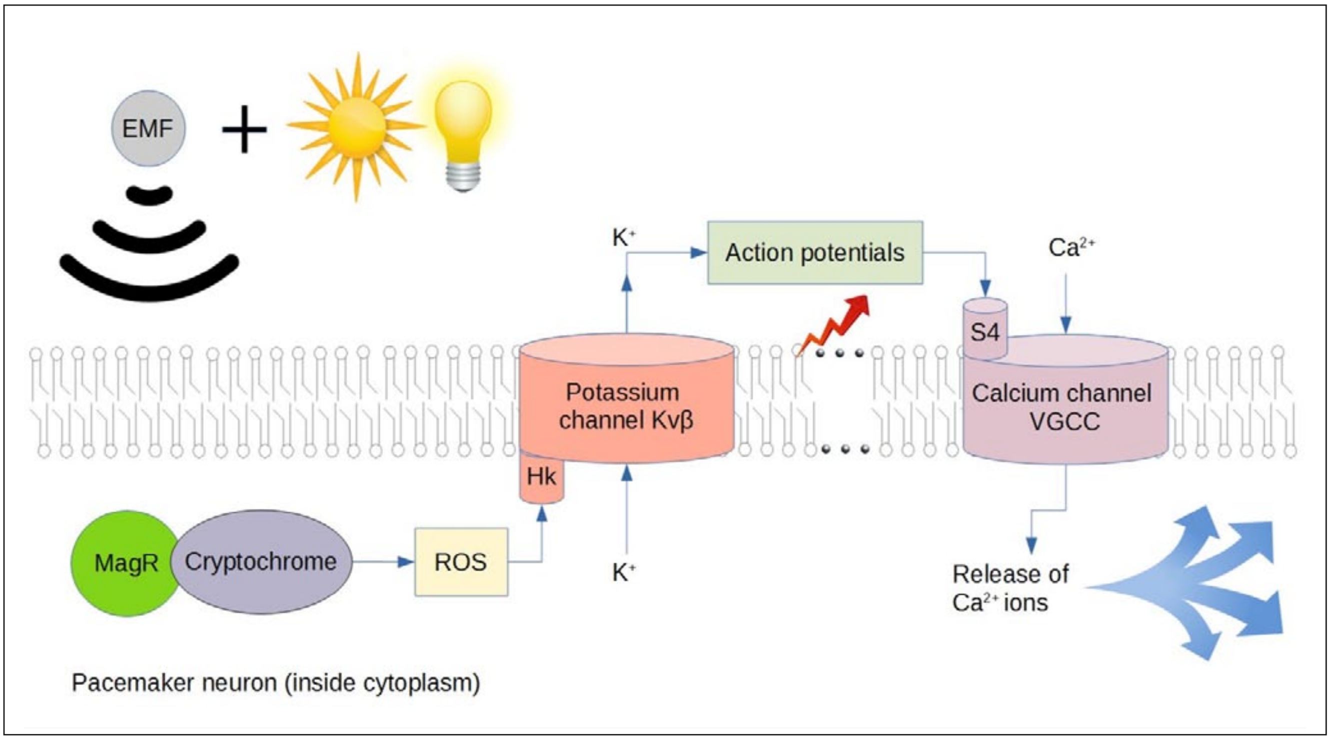

Figure 5: Mechanism of cryptochrome activation in Drosophila. In the presence of blue (or white) light and EMF, cryptochrome is activated and produces free radicals (ROS). ROS lead to the opening of potassium channels and the triggering of action potentials, which in turn activate synaptic VGCC. This leads to an increase in intracellular calcium content and release of neurotransmitters.

1.3 Magnetite

All insects possess cryptochromes in the retina and brain. However, the retinal cryptochromes only function as magnetosensors when blue light is present. Insects that are (also) active in the dark seem to use a magnetite-based magnetic sense instead; this has been experimentally confirmed in bees, ants and termites (Lambinet et al. 2017; Liang et al. 2016; Shaw et al. 2015). In organisms whose magnetic sense is not based on cryptochrome but on magnetite (mouse, bee, turtle, human), changes in the size of the magnetite crystals, which are mechanically (and possibly piezoelectrically) transferred to VGCC by the cytoskeleton, cause a release of calcium (Hsu et al. 2007).

Hsu et al. 2007 report: "While we confirmed the presence of superparamagnetic magnetite in the iron granules, we observed changes in the size of the magnetic granules in the trophycytes upon applying additional magnetic field to the cells. A concomitant release of calcium ions was observed by confocal microscope. This size fluctuation triggered the increase of intracellular Ca^{2+}, which was inhibited by colchicines and latrunculin B, known to be blockers for microtubule and microfilament syntheses, respectively. The associated cytoskeleton may thus relay the magnetosignal, initiating a neural response. A model for the mechanism of magnetoreception in honeybees is proposed, which may be applicable to most, if not all, magnetotactic organisms." However, both mechanisms could equally well occur simultaneously but largely independently in the organism.

2 Overview of the research situation on the topic

2.1 Previous reviews

2.1.1 Cucurachis Review

Quoting Cucurachi et al. 2013: "Insects are a useful target system for the study of RF-EMF due to their limited size, short life cycle and the possibility to easily detect developmental errors (Schwartz et al., 1985)." Of 25 studies investigating EMF effects on insects, 22 were evaluated as "effect", and 3 as "no effect".

2.1.2 Balmoris Review

Balmori 2014 reports on five studies that prove or suggest effects in insects – for example, the hypothesis that flower recognition, which is demonstrably partly due to the perception of electric fields, could be disturbed (Clarke et al. 2013).

2.1.3 Friesens Report

Friesen 2014 lists around 64 studies concerning EMF effects in insects.

2.1.4 Redlarskis Review

Redlarski et al. 2015 reports 15 studies on Drosophila (all forms of EMF and also static magnetic fields) between 1985 and 2004, 13 of which found an effect.

2.1.5 Eklipse Report

In the framework of the European EKLIPSE initiative, a detailed report was written at the request of the british NGO "Bug-Life" (Malkemper et al. 2018; Goudeseune, Balian, and Ventocilla 2018). 39 studies were identified and evaluated according to ecological aspects, 26 of which were additionally evaluated according to technical aspects.

2.1.6 Vanbergen et al. Review

Vanbergen et al. 2019 is based on the Eklipse report (and comes from the same researchers). The report emphasizes the proven toxicity of artificial light at night, and the suspected but so far insufficiently proven toxicity of anthropogenic radiofrequency (HF) electromagnetic radiation. In addition to the Eklipse Report, whose literature search was completed in July 2017, a few more recent studies are included here (described further below), e. g. Shepherd et al. 2018; R. Odemer and F. Odemer 2019. In addition, according to the authors, the only clearly proven effect of electromagnetic radiation so far is the disturbance of orientation (Wan, Zhao, and J. Xu 2014; Sutton et al. 2016; Bae et al. 2016).

2.2 Further procedure

The bibliographies of these reviews were extracted and integrated into a collected Bibtex bibliography, using the open source program JabRef. This resulted in a total of 159 studies, 101 of which, after closer examination, dealt with the topic of insects and EMF.

Since the reviews only included an exhaustive overview of the literature until 2017 (and in detail only until 2014), a Google Scholar and Pubmed Central Search of the years 2015-2020 was additionally made, using the following search terms: one of each: "insect; invertebrate; animal; wildlife; biodiversity; bee; drosophila; pollinator" AND all the following terms (with "or"): "EMR; EMF; electrosmog; electromagnetic field; electromagnetic radiation; electromagnetic".

These two collections of literature were combined and more studies from the author's collection were added, resulting in a total of 190 studies. 44 studies were solely concerned with the magnetic sense of insects, and were already discussed in the chapter on magnetic sense. 39 other studies were reviews, or purely theoretical treatises.

There remained 107 studies, which concerned experiments with EMF in insects. 15 studies were excluded because of qualitative deficiencies (poor), or because they dealt solely with static magnetic or electric fields, or technical methods for studying insects using EMF (such as RFID or radar tracking), or thermal effects (heating insects with microwaves). 6 studies were double-publications, i.e. the same experiments were published twice; these studies were classified as irrelevant. 83 studies that specifically concerned experiments with EMF in insects were now all individually evaluated and recorded in a summary table. 2 HF-EMF studies, which are pure computer simulations (Thielens 2020, Thielens 2018), were treated separately. These studies are prospective but not empirical in nature and therefore did not provide data points for the graphs - but did provide statements on the effects to be expected in the future.

Number according to EMF used:

Low-frequency: 29 studies

High-frequency: 55 studies (encompassing 63 experiments)

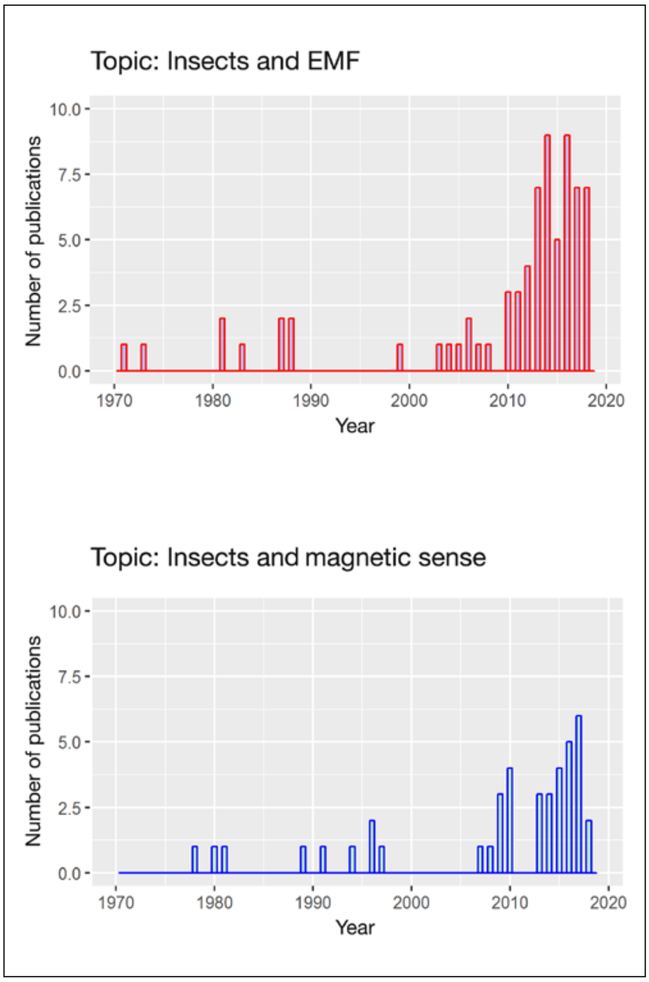

Figure 6: Number of publications per year

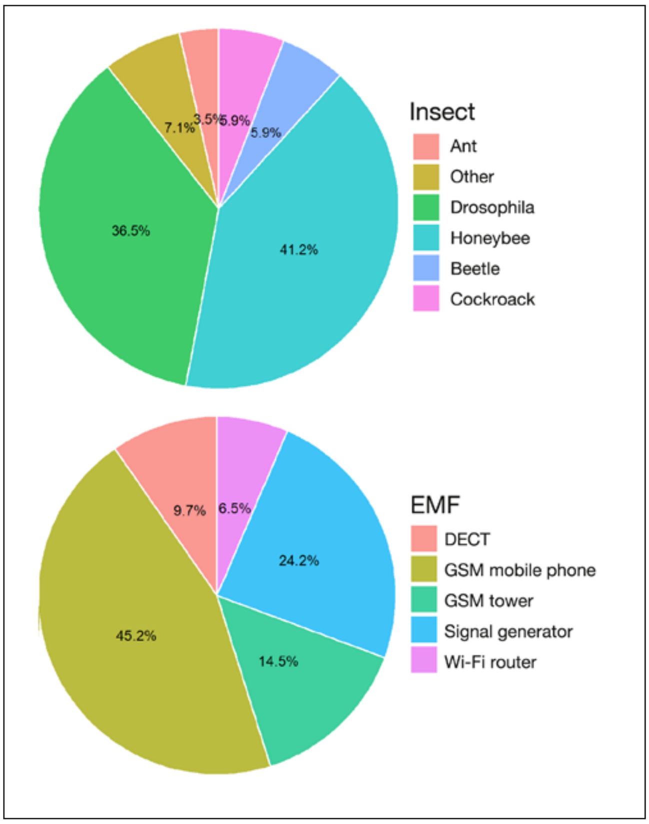

Figure 7: Publications by insect species and high-frequency EMF sources.

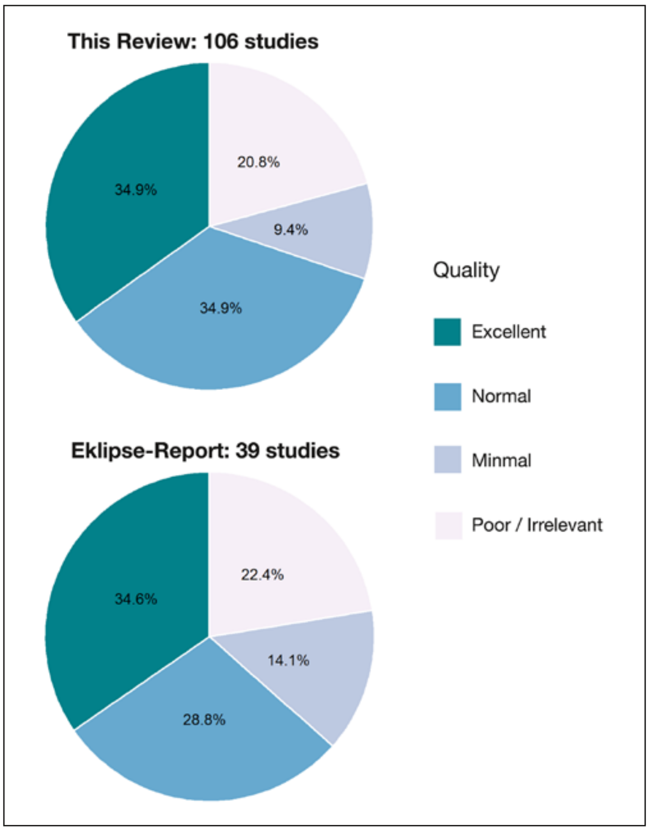

Figure 8: Quality of the studies. EKLIPSE report compared to this review. For the Eklipse Report: average score from evaluations according to biological and technical aspects.

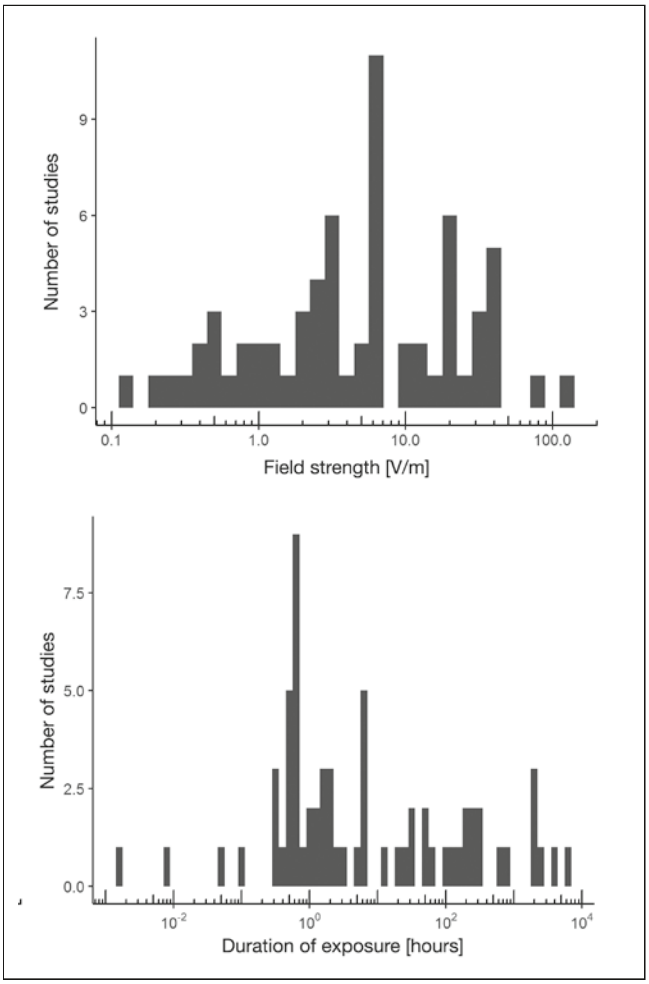

Figure 9: Publications by field strength and exposure duration (data points from 55 HF-EMF studies).

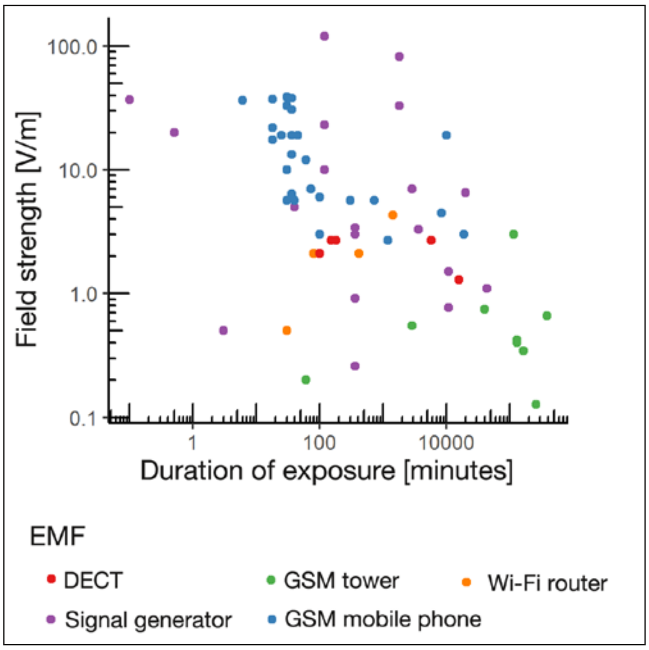

Figure 10: EMF field strength in relation to the duration of exposure (data points from 55 HF-EMF studies).

In the 55 HF studies, radiation intensities (i.e. electric field strengths) ranged from 0.04 to 38200 mW/m2, respectively 0.13 to 120 V/m. The duration of EMF-exposure of insects ranged from 6 seconds to 9 months. The radiation dose (field strength x time) can be calculated from the quantities field strength and exposure duration. Statistical data necessary for a meta-analysis were only available in a handful of studies, although many studies showed significant findings ($p < 0.05$) and it would probably have been only a minor effort for the authors to provide additional information such as confidence intervals (CI) or standard deviations (SD). Thus, no "state-of-the-art" analysis with consideration of the publication bias was made.

Instead, adverse effects described in studies were estimated in detail and the general toxicity (of the EMF) was estimated with a 4 point scale (0 = none, 1 = minor, 2 = moderate, 3 = strong effect), according to the same system used by IPBES (Potts et al. 2016) and the EKLIPSE report (Malkemper et al. 2018; Goudeseune, Balian, and Ventocilla 2018). The cut-off values were set at a rate of change of 10 %, 25 % and 50 % of a variable respectively. The categories for observed effects (variables): general toxicity, memory, sensory function, reproduction/genes, orientation, preference, oxidative stress.

The general toxicity was determined by considering the variable with the highest degree of (significant) percentage change as the decisive one (e.g. assigning a 3 if DNA damage increases by 50 % or more, even if all other measured variables show less than 50 % deviation from control). The quality of each study was similarly estimated using a 4 point scale (Potts et al. 2016).

As the name implies, the estimated toxicity values are not exact and definitive findings, as they are based on studies which in the majority of cases have not been carried out according to the prevalent criteria of care (e.g. in toxicology) and in most cases have not been replicated. In addition, they are only based on a 4-point scale, which does not allow for precise information, but at least a rough estimate.

Looking back on the history of science, however, it can be said that adverse effects have often been identified and described early on, but have been ignored – e.g. concerning asbestos, lead and cigarettes – and it took decades to understand the mechanisms and for the official position to change. The European Environment Agency EEA has produced several reports on this specifically under the title 'Late lessons from early warnings' (Gee et al. 2013).

Regarding the suspected harmfulness of various EMF sources (Fig. 11): the signal generator seems to be less harmful than the actual commercial EMF types at the same field strength. Most signal generators do not produce the characteristic strong and random fluctuations that are emitted, for example, by a mobile phone in talk mode or active Wi-Fi.

Similarly, mobile phone towers are apparently less harmful than GSM mobile phones, although both have the same signal characteristics. The field strength of the signal of mobile phone towers was in the range of 1.7 V/m on average (median value 0.66 V/m), whereas the field strength at exposure with GSM mobile phones was 10.8 V/m on average (median value 6.5 V/m), cf. Fig. 10. Converted into power densities, the quantitative difference is easier to comprehend (median values): mobile phone tower 1.15 mW/m^2, GSM mobile phone 112 mW/m^2.

This indicates that the currently typical field strengths of mobile phone towers are relatively much less toxic than GSM mobile phones, DECT and Wi-Fi. Probably the currently typical field strengths of mobile phone towers are still too weak to cause strong biological effects quickly (within days or hours), although some experiments found harmful effects after several months. Estimated toxicity values were also calculated in a normalized way, i.e. by dividing with the radiation dose. In this consideration, the LF-EMF of power lines or Helmholtz coils are relatively much less toxic than all tested RF-EMF (see also Fig. 12).

3. Commented listing of individual studies

3.1 Low-frequency electromagnetic fields (LF-EMF)

As early as 1976, Altmann and U. Warnke 1976 reported: “Bees in the 50-Hz high voltage field show an increased metabolism as a result of increased motor activity. At low field strengths (below about 10 kV/m), the metabolic increase is not uniform among different caged bee groups. At medium field strengths (approx. 20 kV/m – 40 kV/m), the metabolic increase correlates with the field strength. At high field strengths (above approx. 50 kV/m) mutual stinging occurs.” Other researchers have confirmed these effects, as well as a disturbance of orientation: Wellenstein 1973; Greenberg et al. 1981; Bindokas, Gauger, and Bernard Greenberg 1988; Korall, Leucht and Martin 1988.

Ramirez et al. 1983 conducted the following experiment: A magnetic field of 100 µT strength at 50 Hz power frequency was applied to egg-laying Drosophila. This resulted in a significantly reduced egg deposition in the magnetic field group compared to the control.

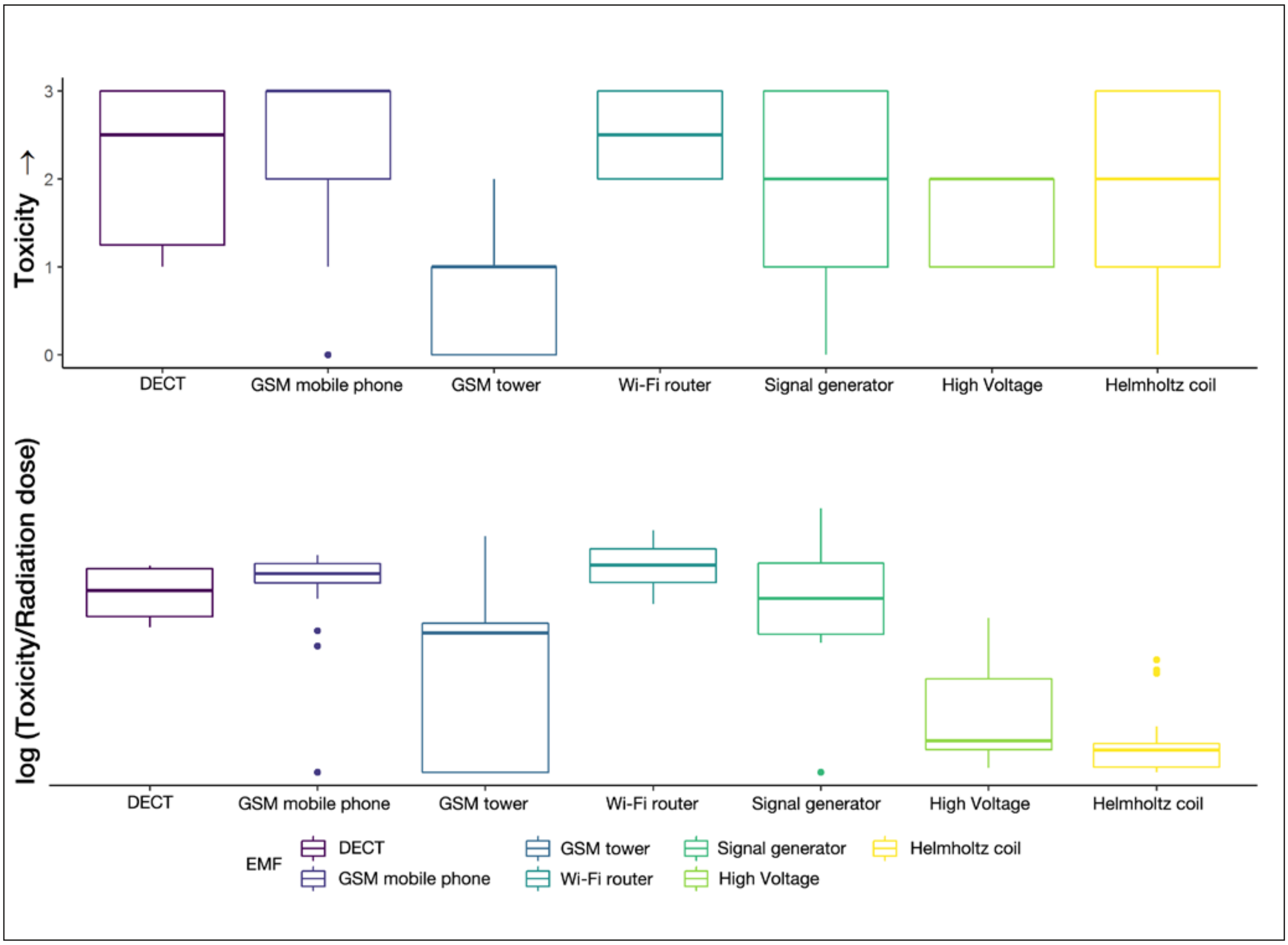

Figure 11: Above: Suspected toxicity to insects by EMF type (estimated value). Lower graph: relative toxicity by EMF type (estimated value), normalized to the radiation dose, i.e. divided by the product of field strength and exposure duration [V/m × min], displayed on a $\log_2$ scale. To compare the HF-EMF with the LF-EMF, all values of magnetic field strength [T] were converted to electric field strength [V/m] (see appendix).

3.1.1 Shepherd 2018, 2019

Shepherd et al. 2018 and Shepherd et al. 2019 investigated the effects of EMF from power lines (50 Hz power frequency) on honeybees (Apis mellifera). Specially designed coils were used to generate a magnetic field of 20 – 7000 µT, with the same characteristics as power lines. Low-frequency EMF significantly interfere with the parameters food intake, flight behaviour, learning (proboscis extension reflex) and memory formation at field strengths of 100 µT and above. At 7000 µT the wing beat frequency is also significantly increased.

Quote: *"ELF-EMF exposure was found to reduce learning, alter flight dynamics, reduce the success of foraging flights towards food sources, and feeding. The results suggest that 50 Hz ELF-EMFs emitted from powerlines may represent a prominent environmental stressor for honey bees, with the potential to impact on their cognitive and motor abilities, which could in turn reduce their ability to pollinate crops."*

Shepherd et al. 2019 also found increased aggression (by 60 %) in bees exposed to 100 µT compared to control, and confirmed the negative effects on short-term memory observed in their previous study. "These results indicate that short-term exposure to ELF EMFs, at levels that could be encountered in bee hives placed under power lines, reduced aversive learning and increased aggression levels."

In his doctoral thesis (Shepherd 2018), Shepherd also tested the combined effect of EMF with the neonicotinoid clothianidin, finding a reduced toxicity of EMF compared to the control. Quote: "These results provide a first indication that ELF-EMFs that may occur in the environment may influence critical behaviors and biological processes in important insects, supporting the need for larger field studies to determine the environmental effects of ELF-EMFs and suggesting further investigation to elucidate the mechanisms of biological effects of ELF-EMFs".

3.1.2 Erdoğan 2019

In the first experiment of Erdoğan 2019, 36 beehives were set up in 4 rows, and an electric fence was installed in front of the beehives. Part of the hives were screened from the low frequency EMF of the electric fence with earthed flyscreen. Number of workers, honey yields, and brood area were significantly lower in the exposed colonies compared to shielded controls.

In their second experiment, Erdoğan and Cengiz 2019 investigated the preference of food sources, with magnetic coils of 0, 50, 100, 150, and 200 µT placed together with food sources. This resulted in a strong preference for food sources with low field strength as well as longer residence times at these food sources.

3.1.3 Todorović 2019

Todorović et al. 2019 used 50 Hz power frequency (10 mT) on larvae of Argentine cockroaches (Blaptica dubia), during 5 months, and found significantly reduced digestive tract mass, GST activity, and significantly increased CAT and SOD activity, indicating increased oxidative stress.

3.1.4 Maliszewska 2018

Maliszewska et al. 2018 used 50 Hz power frequency (7 mT) on American cockroaches (Periplaneta americana) and found significantly increased malondialdehyde levels – an indicator of oxidative stress (after 24 h), as well as significantly reduced glutathione levels (GSH) after 7 days of irradiation. In addition, the reaction speed to noxious heat decreased considerably.

3.1.5 Wyszkowska 2016

Wyszkowska et al. 2016 placed desert locusts in an alternating magnetic field (4 mT, 50 Hz) and found reduced activity. In the cell assay at 7 mT, significantly increased heat shock protein HSP70 was measured, similarly high values as in a heated sample. Observation of the extensor tibiae (jumping muscle) and its ganglion revealed altered action potentials (longer and stronger at 7 mT compared to control), as well as reduced muscle strength.

3.1.6 Zhang 2016

Zhang et al. 2016 showed that thermal stress (35 °C) and EMF exposure (50 Hz, 3 mT) produce a synergistic effect that enhances the negative effect of EMF on lifespan, locomotion and oxidative stress in Drosophila melanogaster.

3.2 High-frequeny electromagnetic fields (HF-EMF): Recent publications

3.2.1 Panagopoulos 2019, [...] 2006

Panagopoulos has made a series of experiments with Drosophila, here in the following only an excerpt, since a detailed description of the entirety of the experiments would go beyond the scope of this article (Panagopoulos 2019; Panagopoulos 2017; Panagopoulos, Cammaerts et al. 2016; Panagopoulos, Johansson and Carlo 2015b; Panagopoulos, Johansson and Carlo 2015a; Panagopoulos, Karabarbounis and Liolіousis 2013; Panagopoulos 2012; Panagopoulos, Chavdoula and Margaritis 2010; Panagopoulos and Margaritis 2010; Panagopoulos, Chavdoula, Karabarbounis et al. 2007; Panagopoulos, Chavdoula, Nezis et al. 2007; Panagopoulos, Karabarbounis and Margaritis 2004; Panagopoulos, Karabarbounis and Margaritis 2002).

Panagopoulos has recently summarized his own results from many experiments and over 10 years of research (Panagopoulos 2017). Dimitris Panagopoulos 2019 investigated the effect of a GSM transmitting mobile phone on development of Drosophila ovaries and found a significantly increased number of DNA strand breaks compared to the non-irradiated control. In addition, 36 minutes of GSM exposure (at 19 V/m = 380 mW/m^2) were shown to be significantly more harmful than 120 hours of exposure to a 2 mT low frequency magnetic field (Fig. 12. Helmholtz coil, similar to the LF-EMF experiments described above).

Quoting from Saliev et al. 2019 regarding Panagopoulos 2011: “The difference of effects on reproductive capacity of insects from modulated and non-modulated EMF was examined by Panagopoulos. Experimental data showed that exposure to non-modulated GSM 900 MHz signal led to a decrease in the insect’s reproduction ability, while the modulated GSM 900 MHz signal caused a decrease in reproduction. It was clearly demonstrated that the modulated GSM signal (‘speaking’ mode) had a more significant impact on oogenesis of insects. In addition, the bio-effects from GSM-900 MHz and GSM-1800 MHz signals were studied and compared using the same biological model. A fall in reproductive capacity was detected for both types of GSM radiation. The work of Panagopoulos concurs with other reports on the influence of radiation from mobile phone on reproductive functions and embryogenesis.”

Worth mentioning are the experiments in Panagopoulos, Chavdoula and Margaritis 2010, where maximum toxicity was found at a distance of 0 cm and 30 cm from a GSM mobile phone (and significantly lower toxicity in the area in between). Panagopoulos and Margaritis 2010 attribute this to an “intensity window”, as earlier researchers have done (Salford et al. 2008). In Drosophila, this bioactive window appears to be at an intensity of about 100 mW/m2 (6 V/m), which corresponds to a distance of about 30 meters from a GSM mobile phone mast.

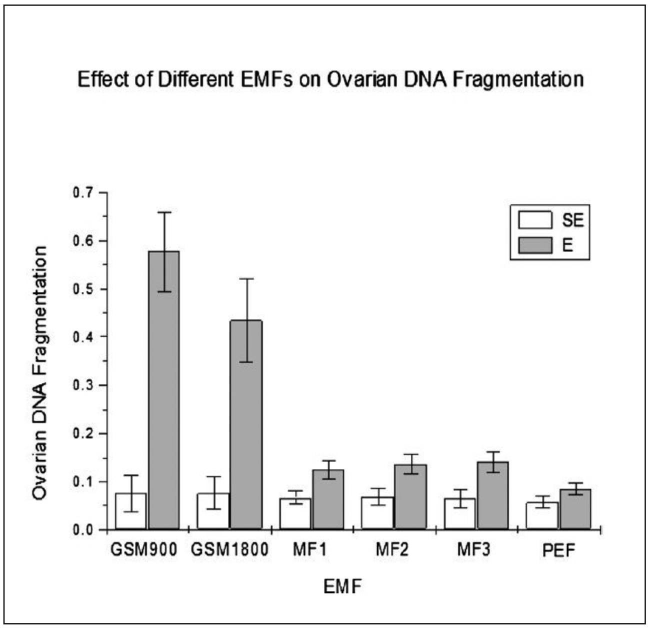

Figure 12: Impact of GSM and low-frequency electromagnetic fields on the DNA strand break rate in Drosophila ovaries (MF1 = 0.1 mT, MF2 = 1 mT, MF3 = 2 mT). Controls (SE) compared to exposed ovaries (E).
Source: Dimitris J Panagopoulos 2019.

3.2.2 Manta 2017, 2014

A study conducted by Margaritis and Manta (Margaritis et al. 2014), the result of 280 experiments, shows an increase in reactive oxygen species (ROS) in the ovaries of Drosophila after exposure to radiofrequency fields. Included were GSM mobile phone, DECT base and handset, Wi-Fi router, Bluetooth, baby phone, microwave oven, 900 MHz unmodulated (oscilloscope) and FM radio. The GSM mobile phone and DECT proved to be particularly harmful, but all other artificial EMFs tested were also slightly harmful in the sense that they led to reduced fertility and increased cell death in the ovaries.

Manta et al. 2017 builds on the 2014 study and has specifically studied free radical production and the genetic profile (gene induction). 168 genes were differentially expressed after irradiation by GSM mobile phone (270 mW/m^2 = 10 V/m during 30 min), 15 of which were down-regulated, including the cryptochrome gene. A number of genes of the antioxidative cycle and genes associated with repair mechanisms were expressed more strongly.

3.2.3 Singh 2020

Singh et al. 2020 irradiated Drosophila during 5 days with a 2400 MHz horn antenna, and found significant differences in brain morphology. Computer-assisted automatic classification of microscopic images of the brain achieved an accuracy of 94.66 % in correctly assigning the images (irradiated or control), although no clear differences were visible to the naked eye (under the microscope).

3.2.4 Lopatina 2019

Lopatina et al. 2019 studied the sensory and memory function of honeybees under irradiation with a Wi-Fi router. Five groups of 18 bees were used, two of which were exposed to a Wi-Fi router (estimated at 50 mW/m^2, for 24 h) and three of which served as controls. The response of the fixed bees to the presentation of a flavored sugar solution was recorded, as well as the formation of a conditioned reflex (proboscis extension reflex) and the retention of this reflex in long-term memory. Significant differences were observed between irradiated and non-irradiated groups in terms of response to presented food (disturbed), short-term memory (significantly deteriorated) and long-term memory (slightly improved). The whole experiment was repeated one year later, with the same results.

3.2.5 Odemer 2019

Odemer and Odemer 2019 studied the development of honey bee queens in the presence of a transmitting GSM mobile phone in the hive (about 2.2 V/m or 13 mW/m^2). The development of larvae to queens was significantly impaired (40% decrease after 14 days of exposure) compared to control. However, other development parameters remained the same between irradiated and non-irradiated queens and their colonies.

3.2.6 Vilić 2017

In Vilić et al. 2017 honey bee larvae were exposed to 900 MHz radiation for 2 hours, unmodulated (4 field strengths) and modulated (80 % 1 kHz, 217 Hz). DNA damage was significantly increased with modulated but not with unmodulated radiation. However, TBARS (“thiobarbituric acid reactive substance”), an indicator of lipid peroxidation and oxidative stress, was significantly reduced in all irradiated groups – indicating reduced oxidative stress. The authors summarize the results of other, similar studies, with about one third showing an increase, one third a decrease and the remaining studies finding constant or variable oxidation parameters. The conclusion is that the effects of radiofrequency EMF are complex and depend on the type of animal studied (e. g. insect, earthworm, rat), the developmental stage (e. g. egg, larva, adult) and the duration of exposure.

3.2.7 Taye 2017

Taye et al. 2017 used a total of 20 beehives placed at 5 different distances from a mobile phone tower (100, 200, 300, 500 and 1000 meters), observed during 6 months, at very low radiation intensities (20 – 80 µW/m^2). Quoting Taye: “The flight activity and returning ability of worker honey bees were maximum in colonies placed at 500 m and minimum at 100 m from the tower.”

3.2.8 Favre 2017, 2011

In Favre 2017 the weak local GSM signal (1 µW/m^2) was detected, amplified and then projected onto a nearby beehive, using a directional antenna. The amplified signal had a power intensity in the range of 80 – 100 µW/m^2 (0.17 to 0.19 V/m) directly in front of the transmitting antenna and about 1 to 2.5 µW/m^2 (0.02 to 0.03 V/m) in the front of the hive (inside). Favre’s bees responded with the (acoustically recorded) whistle sound – a signal associated with danger or displacement of the hive – within 1 hour after the start of GSM irradiation and this was tested 5 times.

In the pilot study Favre 2011, a GSM mobile phone was placed directly in the beehive instead of the GSM repeater – here too the whistle sound was the reaction of the bees. This experiment was repeated twelve times, each time with different beehives.

3.3 High-frequency electromagnetic fields: Older Studies

3.3.1 Lázaro 2016

Lázaro et al. 2016 used pan traps at certain distances (50, 100, 200, 400 m) around five mobile phone masts on the Greek island Limnos and five towers on Lesvos. From 17000 collected insects, 3700 wild bees, 800 wasps and 7000 beetles the following tendencies were observed: Avoidance of high EMF levels for beetles and wasps, but attraction to wild bees (more wild bees trapped near antennas) – with a clearer tendency of attraction for ground-nesting wild bees as opposed to above-ground nesting wild bees. Power densities ranged from 0.1 V/m = 26 µW/m2 to 0.7 V/m = 1300 µW/m^2.

3.3.2 Geronikolou 2014

Geronikolou et al. 2014 compared the effect of 900 MHz (mobile phone) and 1900 MHz (DECT handset) irradiation on Drosophila eggs (100 minutes in the near field). A significant decrease in fertility (i. e. number of laid eggs) was observed.

3.3.3 Chavdoula 2010

Drosophila were subjected to a GSM mobile phone in call mode for 6 minutes per day. Quoting Panagopoulos, Chavdoula and Margaritis 2010: “Intermittent exposures with 10-min intervals between exposure sessions proved to be almost equally effective as continuous exposure of the same total duration, whereas longer intervals between the exposures seemed to allow the organism the time required to recover and partly overcome the above-mentioned effects of the GSM exposure.”

3.3.4 Cammaerts 2014, 2013, 2012

Cammaerts, De Doncker, et al. 2012; Cammaerts, Rachidi, et al. 2013 and Cammaerts and Johansson 2014 describe three experiments on ants in the laboratory that reveal avoidance of EMF, disturbance of memory, orientation and movement. Cammaerts recommends repeating a similar setup with bees.

3.3.5 Kumar 2011 – 2013

Kumar, Sangwan, and Badotra 2011 investigated the effect of mobile phone exposure on different biomolecules in adult worker honeybees. Ten honeybees were taken from each comb and irradiated in a small cage with two mobile phones in talk mode. The exposure duration was 10, 20 or 40 minutes. The concentration of different biomolecules increased significantly.

Kumar 2012 and Kumar, Rana and Kalia 2013 investigated the effect of mobile phone exposure on different biomolecules in the seminal fluid (2012) and hemolymph (2013) of honeybee drones (same setup as the previous experiment, exposure duration 30 minutes). Seminal fluid: the concentration of carbohydrates, proteins and lipids increased compared to the control and the activity of various enzymes was reduced. Hemolymph: the concentration of various biomolecules increased under the influence of EMF, e. g. from 1.65 mg/ml to 2.75 mg/ml for carbohydrates, 3.74 mg/ml to 4.85 mg/ml for proteins and from 0.325 mg/ml to 1.33 mg/ml for lipids.

3.3.6 Stever & Kuhn 2006, 2005

In the pilot study Stever, Kuhn et al. 2006, Stever and Kuhn investigated the effects of DECT base stations (at 2.5 mW average power, or about 1.4 mW/m^2) on the sense of orientation of individual honey bees and the development of bee colonies. Eight out of sixteen hives were exposed to DECT base stations for 11 days. The sense of orientation was significantly worse in the irradiated group, as well as the development of the hives. Stever, Kimmel et al. 2006 repeated the experiment and studied again the sense of orientation (duration until return, number of returners) with the same setup and could confirm the disturbing effect of DECT.

3.4 No-effect studies

3.4.1 Miyan 2014

Miyan 2014 used 35 beehives, in 5 exposure groups, in 0 – 800 m distance from a mobile phone mast. No differences between the exposure groups were found for all measured parameters, e. g. honey production, pollen collection, reproduction, hive size, etc. A power density of 0.423 V/m was measured directly at the mobile phone tower (475 µW/m^2), all other values were below 0.01 V/m (25 µW/m^2), which are very low values that are hardly found in Europe. The maximum value at 0 m was also below the threshold value where experts suspect a harmful effect, i. e. 1000 – 100000 µW/m^2 (Cucurachi et al. 2013; Panagopoulos and Margaritis 2010).

3.4.2 Hoofwijk 2013

In 2011, an experiment of the group around Tjeerd Blacquiere (Hoofwijk and Blacquiere 2013) investigated indicators for the toxicity of mobile phone masts to honey bees. The experimental set-up consisted of 20 hives housed in two separate enclosures. 10 hives were shielded with metal mesh, 10 were exposed to the radiation of the nearby mobile phone mast. All experiments were performed double-blind. The test site with the two dwellings is located 230 m away from a mobile phone mast, in direct view. The GSM 900 MHz intensity on site, outside the dwellings, was on average 0.5 V/m or about 660 µW/m^2.

The authors summarize the results of the experiment as such: “Our investigations show that colonies from the exposed and the control group had a comparable developmental success from the egg via the larva to the adult bee, comparable orientation skills, a comparable performance in their adult phase, comparable morphometric and physiological parameters at hatching, a comparable longevity, a comparable development at colony level (production or bread and young bees), but differed in winter survival in the sense that more non-exposed than exposed colonies survived.”

Winter survival rate: 3 out of 10 for exposed hives, 9 out of 10 for non-exposed (shielded). According to the authors, the nested setup of shielded and exposed hives being housed in two separate “houses” of 10 colonies does not permit for a clear statistical description of the outcome, and this experiment should be repeated with at least 30 exposed and 30 shielded hives, housed separately each or in small groups, to reduce the possibility of a parasite infecting an entire house, as the exposed hives in the above experiment had high infection rates with Varroa mites.

4. Overview of research and state of knowledge at the beginning of 2020

Overview of the study situation:

High-frequency EMF: effect found in 56 of 64 experiments in 46 of 55 studies

Low-frequency EMF: effect found in 26 of 29 studies

The effect found was in most cases harmful, in rare cases neutral. In one study (Makarov and Khmelinskii 2016) it could be shown that both negative and positive effects can be achieved by changing the parameters of a 3D LF-EMF.

General considerations and recommendations for the future:
One experimental finding supporting the hypothesis of activation of VGCC – or other voltage-gated channels – is that damage from EMF occurs only after prolonged exposure to radiation from one direction. A randomly rotating (“chaotic”) magnetic field can be used to neutralize the toxicity of simultaneous irradiation with EMF (Lai and Singh 2005; Litovitz et al. 1994). In practice, one would therefore expect a stronger harmfulness of EMF in plants than in moving animals, which has also been generally confirmed experimentally (Halgamuge, Yak and Eberhardt 2015; Halgamuge 2016). In insects, the harmful influence should be stronger in the early stages of development (egg, larva, pupa) than in adults - signs of this were found e. g. by Odemer and Odemer 2019.

There is considerable evidence of many medical applications of EMFs waiting to be used (Markov 2007; Pilla 2013). Even if current wireless EMF technologies are generally – dose-dependently – toxic, existing research suggests that it should be easy to significantly improve the biocompatibility of wireless technologies (Lai 2004; Pilla 2006). Since, at least as far as the largely elucidated mechanism of cryptochrome activation is concerned, the presence of blue (or white) light seems necessary for adverse effects of EMF in insects, the massive use of artificial street lighting should be reconsidered – and if necessary, light sources with less blue content should be used (e.g., LEDs with a "warm" instead of "cold" spectrum). For all insects that use magnetite for their magnetic sense, e.g. all hymenopterans – bees, wasps, ants – harmful effects of EMF are to be expected even in the absence of (artificial) light.

Starting at which field strengths are toxic effects expected to occur in insects, or have been proven to occur in experiments? Panagopoulos, Chavdoula and Margaritis 2010 has detected a bioactive window at a distance of 20–30 cm from GSM mobile phones, which corresponds to a power density of 100 mW/m^2, or about 6 V/m – where significant toxic effects have been observed in Drosophila already after short-term exposure (10 minutes), and these results have meanwhile been replicated several times (Chavdoula 2010, Margaritis 2014, Geronikolou 2014). If this is generally true for insects, the limit for toxic effects would be 100 times below the current ICNIRP limits (10 W/m^2 or 61 V/m, see Non-Ionizing Radiation Protection et al. 2020), which only protect against thermal effects. For chronic exposure, negative effects might be expected at a power density 10 times lower – i.e. 10 mW/m^2 – but here the state of knowledge is still uncertain.

At the moment (anno 2020), power densities in the environment are generally still far below 10 or 100 mW/m^2 (i.e. 2 or 6 V/m). A recent study has measured values of 0.17–0.53 V/m RMS in the field (0.1–0.8 mW/m^2 – Thielens, Greco et al. 2020). The author of this review has measured values up to a maximum of 10 mW/m^2 RMS (2.5 V/m) in his master's thesis, but only in the immediate vicinity (30–50 m) of LTE/GSM masts. Measurements in urban hotspots (UK, Ofcom 2020) found a maximum of 150 mW/m^2 (1.5 % of the ICNIRP limit) and an average of 25 mW/m^2 (as sum of all RF emissions in the frequency range 0.3–6 GHz).

In Belgium, Italy, Switzerland, Russia, and China, the maximum permissible exposures (installation limits) for the general population are 6 V/m (100 mW/m^2) or less (3 V/m in Luxembourg) in the mobile telephony/Wi-Fi range, while Germany, the USA, and many other countries adhere to the ICNIRP limits, which are set at 41 V/m (4000 mW/m^2) for 900 MHz, or at 61 V/m (10 W/m^2) for 2 GHz and above (funkstrahlung.ch 2017; Woelfle 2003; Non-Ionizing Radiation Protection et al. 2020).

Thirty-six (36) of the 64 radiofrequency experiments in this review used a field strength of less than 6 V/m (100 mW/m^2), and 30 experiments (83 %) nevertheless found clear indications of or statistically significant adverse effects, roughly starting from 3 V/m, i.e. even below the particularly low installation limits found only in some countries. The installation limit is measured where people can stay for long periods of time, i.e. streets, city squares, homes, etc.

According to Thielens, Bell, et al. 2018, the absorption of artificial EMFs in insects remains relatively constant, even at much higher frequencies than those generally used today (e.g. 60 GHz). The wavelengths of 5G are very close to the body length of various insects, which leads to resonant absorption (see Fig. 13). 5G will be gradually expanded, into progressively higher frequencies. As the power loss due to scattering, reflection, and the lower penetration force of higher frequencies becomes increasingly greater, the radiated power of base stations would also have to be increased to ensure that wireless connections in homes and vehicles function comfortably. According to Xu et al. 2017, the power of a single 5G station (in the 15 GHz band) should be about 10 W/m^2 at 1 m distance, or 100 mW/m^2 at 10 m distance.

After Thors et al. 2017 calculations, 5G antennas would, in the worst case, only emit 15 % of their theoretical maximum power and would have the advantage – compared to the current infrastructure (1G–4G) – that the radiation intensity would be reduced to virtually zero in the absence of users (e.g. at night).

According to measurements by Ofcom, 5G base stations (in the UK) currently only have power levels of up to 3.8 mW/m^2, and on average only 0.59 mW/m^2, in urban hotspots (Ofcom 2020). However, since the infrastructure is still very rudimentary and the number of users small, these figures may be many times higher in the future, especially since with 5G, the antenna power is directly dependent on the number of channels used, i.e. the end users. Recent measurements at 5G pilot projects in France found higher values, e.g. about 6 V/m (100 mW/m^2) at a distance of 150 meters, at maximum antenna power, and about 3.5 V/m (32 mW/m^2) at the end device in case of a 10 gigabyte download (Anfr 2020). However, this is only a rough estimate, since the new "beam-forming" technique precisely focuses the radiation from typically 64 individual antennas per 5G station onto devices (small aperture, i.e. beam angle) and at the same time each base station transmits toward many devices separately ("massive MIMO").

It is planned to install one base station every 250 meters (or less) in the urban sector, with a distinction being made between so-called "small cells" and ordinary base stations. If this were to be implemented, a considerable portion of the air region typical for insects, in urban areas, would possibly be saturated with power levels around 100 mW/m^2 at some point. Switzerland, Italy and a few Eastern European countries are probably within the safe range with a 6 V/m installation limit – but elsewhere in Europe the 5G expansion threatens to lead to a significant increase in EMF emissions.

In view of the current research situation, the author of this review must warn against such an approach, as harmful effects on insects would be unavoidable. In addition, 5G-radiation is probably – at least for insects – more bioactive than e.g. 4G-emissions of the same field strength, because of the very "dense" signal characteristics (Panagopoulos 2011).

However, the currently available information and assessments on 5G are quite controversial and contradictory, ranging from “completely unproblematic”, with reference to a significantly reduced radiation exposure compared to current technology (Chiaraviglio et al. 2018; Matalatala et al. 2018) – although recent measurements do not or only to a limited extent confirm this (Anfr 2020; Ofcom 2020) – up to apocalyptic warnings of serious effects (Kostoff et al. 2020; Hardell and Nydberg 2017). Until the truth emerges, the development of the expansion should be closely monitored and toxicological tests should be started immediately to quickly identify and quantify any harmful effects so that realistic protective guidelines can be issued. Toxic effects to insects might occur at radiation levels that are safe for humans, particularly in the higher frequency bands (see Figure 13). This author refers to the so-called precautionary principle, which is detailed in Article 191 of the Treaty on the Functioning of the European Union.

Conclusions: Research indicates that EMF could have a serious impact on the vitality of insect populations. 72 of the 83 studies analysed found an effect. Negative effects that were described in studies include: disturbance of the sense of orientation, reduced reproductive capacity and fertility, lethargy, changes in flight dynamics, in the success of foraging, in reaction speeds, escape behaviour, disturbance of circadian rhythms, blocking of the respiratory chain and damage to mitochondria, misactivation of the immune system, increased number of DNA strand breaks. Some mechanisms of action leading to these damages are identified. EMF affect the metabolism, among other things affecting voltage-controlled calcium channels, e.g. in neurotransmission and in muscle tissue, which can lead to an overactivation of signal transduction and of the respiratory chain with production of free oxygen radicals and consequently to oxidative cell stress.

In some experiments, it was found that despite low levels of exposure to transmitters, harmful effects occurred after several months. Field strengths 100 times below the ICNIRP limits could already have effects. Harmful effects for insects might occur at radiation intensities that are harmless to humans – especially in the higher frequency bands (see Fig. 13). Until the truth is known, the development of the expansion should be closely monitored and toxicological tests should be started immediately to quickly identify and quantify any harmful effects so that realistic protective guidelines can be established. Against the background of the rapid decline of insects and the further expansion of high-frequency electromagnetic field sources, there is not only an urgent need for further research, but also in particular, on interactions with other harmful noxious agents such as pesticides. When planning the expansion of mobile networks, insect habitats should be protected from high-intensity EMF exposure already now. This author refers here to the so-called precautionary principle, which is anchored in Article 191 of the Treaty on the Functioning of the European Union.

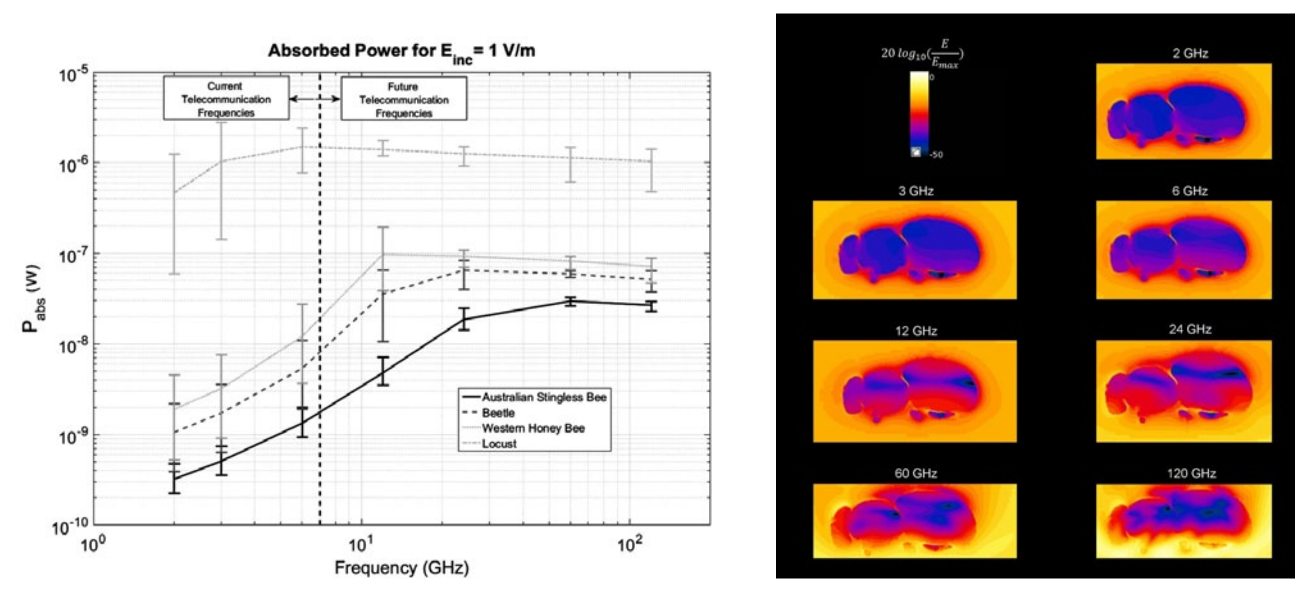

Figure 13: Energy absorption by insects at increasing microwave frequencies. Source: Thielens, Bell, et al. 2018.

5. Appendix

5.1 List of abbreviations

5G	The fifth generation of mobile communications technology
EEG	Electroencephalogram
EMF	Electromagnetic fields
GHz	Gigahertz (1 GHz corresponds to 1.000 MHz)
ICNIRP	The International Commission on Non-Ionizing Radiation Protection
NMDA	N-methyl-D-aspartate receptor, an ionotropic glutamate receptor
MIMO	“Multiple input multiple output”
RMS	“root mean square”, the square mean
ROS	“reactive oxygen species”, free radicals
VGCC	“voltage-gated calcium channel”, voltage-gated calcium channel
W/m^2	watts per square meter, a measure of radiated power density

5.2 Calculations

The SI unit for expressing the strength of an electromagnetic field is volts per meter [V/m], and this is also the general unit of measurement for electric fields. It can be used to calculate the average (RMS) power density or radiation intensity in watts per square meter [W/m^2] in the case of electromagnetic fields, which is also used in solar cell technology. For all radiofrequency studies included here, all given values of field strength were converted into V/m if they were described in a different unit.

The following formulas were used (Woelfle 2003; Poynting-Vector):

$$S = \frac{E^2}{Z_0} \quad \text{oder auch:} \quad E = \sqrt{S \times Z_0}$$

where E is the electric field strength [V/m]

S the power density [W/m^2]

Z_0 the wave impedance [377 Ohm]

For electromagnetic waves, electric field strength is linked to magnetic field strength, according to:

$$B = E/c$$

with B the magnetic field in Tesla,

E the electric field in volts per meter and

c the speed of light (3 × 10^{8}m/s)

(derived from the Ampère-Faraday law, or directly from the Poynting-Vector)

In the near-field, i.e. below one wavelength (e.g. < 30 cm for GSM900), the electric and magnetic fields are present as a vortex field. Averaged over many measurements, however, the proportionality of electric and magnetic field strength is maintained here as well.

The SAR value, short for “Specific Absorption Rate”, expresses how much energy is actually absorbed by irradiated tissue, and therefore depends on the tissue type (or generally on the material), and was estimated here to be

$$\text{SAR} = \frac{(E \times 1{,}19)^2}{1.000} \text{ W/kg}$$

according to Panagopoulos, Johansson, and Carlo 2013; Sagioglou et al. 2014.

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Tables

V/m	mW/m^2	nT	SAR [W/kg]
0.00	0.00	0.00	0.00
0.10	0.03	0.33	0.00
0.20	0.11	0.67	0.00
0.30	0.24	1.00	0.00
0.40	0.42	1.33	0.00
0.50	0.66	1.67	0.00
0.60	0.95	2.00	0.00
0.70	1.30	2.33	0.00
0.80	1.70	2.67	0.00
0.90	2.15	3.00	0.00
1.00	2.65	3.34	0.00
1.20	3.82	4.00	0.00
1.40	5.20	4.67	0.00
1.60	6.79	5.34	0.00
1.80	8.59	6.00	0.00
2.00	10.61	6.67	0.01
2.20	12.84	7.34	0.01
2.40	15.28	8.01	0.01
2.70	19.34	9.01	0.01
3.00	23.87	10.01	0.01
4.00	42.44	13.34	0.02
5.00	66.31	16.68	0.04
6.00	95.49	20.01	0.05
7.00	129.97	23.35	0.07
8.00	169.76	26.68	0.09
9.00	214.85	30.02	0.11
10.00	265.25	33.36	0.14
15.00	596.82	50.03	0.32
20.00	1061.01	66.71	0.57
25.00	1657.82	83.39	0.89
30.00	2387.27	100.07	1.27
35.00	3249.34	116.74	1.73
40.00	4244.03	133.42	2.27
45.00	5371.35	150.10	2.87
50.00	6631.30	166.78	3.54
55.00	8023.87	183.46	4.28
60.00	9549.07	200.13	5.10
70.00	12997.35	233.49	6.94
80.00	16976.13	266.84	9.06
90.00	21485.41	300.20	11.47
100.00	26525.20	333.56	14.16

Table 1: Conversion of high-frequency EMF field strengths

Author	Year	Insect	EMF	Title
Wyszkowska	2019	Honeybee	Helmholtz coil	Electromagnetic fields and colony collapse disorder of the honeybee.
Todorovic	2019	Cockroach	Helmholtz coil	Long-term exposure of cockroach Blaptica dubia (Insecta: Blaberidae) nymphs ...
Shepherd	2019	Honeybee	Helmholtz coil	Increased aggression and reduced aversive learning in honey bees exposed to ...
Panagopoulos	2019	Drosophila	Helmholtz coil	Comparing DNA damage induced by mobile telephony and other types of man-...
Erdoğan	2019	Honeybee	Electric fence	Determination of the effect of electric fence system on productivity and behav...
Erdoğan	2019	Honeybee	Helmholtz coil	Effect of Electromagnetic Field (EMF) and Electric Field (EF) on Some Behavio...
Sherrard	2018	Drosophila	PEMF	Low-intensity electromagnetic fields induce human cryptochrome to modulate in...
Shepherd	2018	Honeybee	Helmholtz coil	Extremely low frequency electromagnetic fields impair the cognitive and motor...
Shepherd	2018	Honeybee	Helmholtz coil	The effects of extremely low frequency electromagnetic fields on insects...
Maliszewska	2018	Cockroach	Helmholtz coil	Electromagnetic field exposure (50 Hz) impairs response to noxious heat in ...
Zmejkoski	2016	Drosophila	Helmholtz coil	Different responses of Drosophila subobscura isofemale lines to extremely low...
Zhang	2016	Drosophila	Helmholtz coil	Coupling mechanism of electromagnetic field and thermal stress on Drosophila ...
Zagirnyak	2016	Drosophila	Electric motor	Experimental research of electromechanical and biological systems compatibility...
Wyszkowska	2016	Locust	Helmholtz coil	Exposure to extremely low frequency electromagnetic fields alters the behavio...
Makarov	2016	Drosophila	3d-LF EMF cell	External control of the Drosophila melanogaster egg to imago development peri...
Todorovic	2015	Beetle	Helmholtz coil	Effects of two different waveforms of ELF MF on bioelectrical activity of ant...
Patenkovic	2015	Drosophila	Helmholtz coil	The impact of extremely low frequency electromagnetic field (50 Hz, 0.25 mT) ...
Jankowska	2015	Cockroach	Helmholtz coil	Exposure to 50 Hz electromagnetic field changes the efficiency of the scorpion...
Fedele	2014	Drosophila	Helmholtz coil	Genetic analysis of circadian responses to low frequency electromagnetic field...
Li	2013	Drosophila	Helmholtz coil	Gene expression and reproductive abilities of male Drosophila melanogaster ...
Dimitrijevic	2013	Drosophila	Helmholtz coil	Temporal pattern of Drosophila subobscura locomotor activity after exposure ...
Tipping	1999	Drosophila	Helmholtz coil	Observations on the effects of low frequency electromagnetic fields on cellul...
Korall	1988	Honeybee	Helmholtz coil	Bursts of magnetic fields induce jumps of misdirection in bees by a mechanism...
Bindokas	1988	Honeybee	765 kV	Mechanism of biological effects observed in honey bees (Apis mellifera, L.) h...
Walters	1987	Drosophila	Helmholtz coil	Test for the effects of 60-Hz magnetic fields on fecundity and development in...
Altmann	1987	Honeybee	2 kV-line	Thermographie der Honigbienen-Wintertraube unter Einfluss von Hochspannung...
Ramirez	1983	Drosophila	Helmholtz coil	Oviposition and development of Drosophila modified by magnetic fields...
Greenberg	1981	Honeybee	765 kV	Response of honey bees, Apis mellifera L, to high-voltage transmission lines...
Wellenstein	1973	Honeybee	220 kV	Der Einfluss von Hochspannungsleitungen auf Bienenvölker (Apis mellifica L...

Table 2: List of low-frequency studies (LF)

Author	Year	Insect	EMF	Title
Thielens	2020	Honeybee	Simulation	Radio-Frequency Electromagnetic Field Exposure of Western Honey Bees...
Singh	2020	Drosophila	Signal generator	A novel pilot study of automatic identification of EMF radiation effect on ...
Panagopoulos	2019	Drosophila	cell phone	Comparing DNA damage induced by mobile telephony and other types of man-...
Odemer	2019	Honeybee	cell phone	Effects of radiofrequency electromagnetic radiation (RF-EMF) on honey bee ...
Lopatina	2019	Honeybee	Wi-Fi router	Effect of Non-Ionizing Electromagnetic Radiation on Behavior of the Honeybee ...
Jungwirth	2019	Honeybee	Signal generator	The Effect of Electromagnetic Fields Produced by Wi-Fi Routers on the Magnetite ...
Bartos	2019	Cockroach	Signal generator	Weak radiofrequency fields affect the insect circadian clock...
Zubrzak	2018	Honeybee	Signal generator	Thermal and acoustic changes in bee colony due to exposure to microwave ...
Thielens	2018	various	Simulation	Exposure of Insects to Radio-Frequency Electromagnetic Fields from 2 to 120 GHz...
Mikhaylova	2018	Flies	Signal generator	Determining the electromagnetic field parameters to kill flies at livestock ...
Vilic	2017	Honeybee	Signal generator	Effects of short-term exposure to mobile phone radiofrequency (900 MHz) on ...
Vargova	2017	Tick	Signal generator	Ticks and radio-frequency signals: behavioural response of ticks ...

Taye	2017	Honeybee	GSM tower	Effect of electromagnetic radiation of cell phone tower on foraging behaviour...
Syalima	2017	Cockroach	cell phone	Mobile phone radiation induces sedation in Periplaneta americana...
Poh	2017	Mosquito	Signal generator	Effects of low-powered RF sweep between 0.01-20 GHz on female Aedes Aegypti ...
Manta	2017	Drosophila	cell phone	Mobile-phone radiation-induced perturbation of gene-expression profiling, ...
Favre	2017	Honeybee	GSM tower	Disturbing Honeybees' Behavior with Electromagnetic Waves: a Methodology...
Lazaro	2016	various	GSM tower	Electromagnetic radiation of mobile telecommunication antennas affects the ...
Fauzi	2016	Drosophila	cell phone	The Effect of EMF Radiation Emitted by Mobile Phone to Insect Population ...
Dyka	2016	Drosophila	Signal generator	Effects of 36.6 GHz and static magnetic field on degree of endoreduplication ...
Darney	2016	Honeybee	Signal generator	Effect of high-frequency radiations on survival of the honeybee (Apis mellifera ...
Patel	2015	Honeybee	GSM tower	Impact of electromagnetic radiations on biology and behaviour of Apis mellifera ...
Dalio	2015	Honeybee	cell phone	Effect of Electromagnetic (cell phone) radiations on Apis mellifera ...
Sagioglou	2014	Drosophila	Signal generator	Apoptotic cell death during Drosophila oogenesis is differentially increased ...
Miyan	2014	Honeybee	GSM tower	Effect of electromagnetic waves on the performance of Apis mellifera ...
Margaritis	2014	Drosophila	Wi-Fi router	Drosophila oogenesis as a bio-marker responding to EMF sources...
Manta	2014	Drosophila	DECT	Reactive oxygen species elevation and recovery in Drosophila bodies and ovaries...
Mall	2014	Honeybee	GSM tower	Effect of electromagnetic radiations on brooding, honey production and foraging...
Geronikolou	2014	Drosophila	DECT	Diverse radiofrequency sensitivity and radiofrequency effects of mobile or ...
El Halabi	2014	Honeybee	GSM tower	The effect of cell phone antennas' radiations on the life cycle of honeybees.
Cammaerts	2014	Ant	Signal generator	Ants can be used as bio-indicators to reveal biological effects of electromag...
Cammaerts	2014	Ant	Signal generator	Effect of Short-Term GSM Radiation at Representative Levels in Society on a B...
Vijver	2013	various	GSM tower	Investigating short-term exposure to electromagnetic fields on reproductive ...
Kumar	2013	Honeybee	cell phone	Biochemical changes in haemolymph of Apis mellifera L. drone under the influence ...
Hoofwijk	2013	Honeybee	GSM tower	Mobiele telefonie en de ontwikkeling van honingbijen.
El Halabi	2013	Honeybee	cell phone	The effect of cell phone radiations on the life cycle of honeybees.
Cammaerts	2013	Ant	Wi-Fi router	Food collection and response to pheromones in an ant species exposed to electro-...
Panagopoulos	2012	Drosophila	cell phone	Effect of microwave exposure on the ovarian development of Drosophila ...
Kumar	2012	Honeybee	cell phone	Influence of cell phone radiations on Apis mellifera semen.
El Kholy	2012	Drosophila	cell phone	Effect of 60 minutes exposure to electromagnetic field on fecundity, learning...
Cammaerts	2012	Ant	Signal generator	GSM 900 MHz radiation inhibits ants association between food ...
Sahib	2011	Honeybee	cell phone	Impact of mobile phones on the density of honeybees.
Kumar	2011	Honeybee	cell phone	Exposure to cell phone radiations produces biochemical changes in worker honey ...
Favre	2011	Honeybee	cell phone	Mobile phone-induced honeybee worker piping.
Sharma	2010	Honeybee	cell phone	Changes in honeybee behaviour and biology under the influence of cellphone ...
Panagopoulos	2010	Drosophila	cell phone	Bioeffects of mobile telephony radiation in relation to its intensity or distance...
Chavdoula	2010	Drosophila	cell phone	Comparison of biological effects between continuous and intermittent exposure...
Lee	2008	Drosophila	Signal generator	Mobile phone electromagnetic radiation activates MAPK signaling and regulates...
Panagopoulos	2007	Drosophila	cell phone	Cell death induced by GSM 900-MHz and DCS 1800-MHz mobile telephony radiation...
Stever	2006	Honeybee	DECT	Verhaltensänderung der Honigbiene Apis mellifera unter elektromagnetischer ...
Atli	2006	Drosophila	Signal generator	The effects of microwave frequency electromagnetic fields on the development ...
Stever	2005	Honeybee	DECT	Verhaltensänderung unter elektromagnetischer Exposition–Pilotstudie 2005...
Panagopoulos	2004	Drosophila	cell phone	Effect of GSM 900-MHz mobile phone radiation on the reproductive capacity of ...
Weisbrot	2003	Drosophila	cell phone	Effects of mobile phone radiation on reproduction and development in Drosophila ...
Westerdahl	1981	Honeybee	Signal generator	Flight, orientation, and homing abilities of honeybees following exposure to ...
Westerdahl	1981	Honeybee	Signal generator	Longevity and food consumption of microwave-treated (2.45 GHz CW) honeybees ...
Carpenter	1971	Beetle	Signal generator	Evidence for nonthermal effects of microwave radiation: Abnormal development ...

Table 3: List of high-frequency studies (HF)

Author	Year	Title
Stoll	2019	Method and device for influencing insects.
Sadeghi	2019	Microwave Application for Controlling Oryzaephilus surinamensis Insects Infes...
Rosi	2019	Emigration Effects Induced by Radio Frequency Treatment to Dates Infested by ...
Souza	2018	Low-cost electronic tagging system for bee monitoring.
Benedetti	2017	Device and respective control method for controlling the activities of a colo...
Panagopoulos	2013	ELF alternating magnetic field decreases reproduction by DNA damage induction...
Schneider	2012	RFID tracking of sublethal effects of two neonicotinoid insecticides on the f...
Al Ghamdi	2012	The effect of static electric fields on Drosophila behaviour.
Tirkel	2011	Effects of Millimetre Wave Exposure on Termite Behavior.
Swedberg	2011	Rfid helps scientists study honeybees' homing behavior.
Schick-Borken	2011	Schülerstudie zur Einwirkung von Wlan Strahlung auf die Entwicklung von Mehl...
Pinpathomrat	2011	Inhibition of Culex quinquefasciatus (Diptera: Culicidae) viability by nanosec...
Hausmann	2011	Auswirkung von Mobilfunkstrahlung auf Hautflügler (Hymenoptera) und Käfer (...
Panagopoulos	2010	The identification of an intensity window on the bioeffects of mobile telephony...
Panagopoulos	2010	The effect of exposure duration on the biological activity of mobile telephony...
Panagopoulos	2008	Mobile telephony radiation effects on living organisms.
Kimmel	2007	Effects of electromagnetic exposition on the behavior of the honeybee (Apis m...
Harst	2007	Can Electromagnetic Exposure Cause a Change in Behaviour? Studying Possible N...
Pan	2004	Apparent biological effect of strong magnetic field on mosquito egg hatching...
Webber	1946	High-frequency electric fields as lethal agents for insects.
Headlee	1931	The differential between the effect of radio waves on insects and on plants...

Table 4: List of excluded studies (poor quality, irrelevant or double publications)

Author	Year	Title
Wan	2019	Geomagnetic field absence reduces adult body weight of a migratory insect by ...
Landler	2018	Cryptochrome: The magnetosensor with a sinister side?
Kong	2018	In-vivo biomagnetic characterisation of the American cockroach
Zhang	2017	Molecular Mechanisms for Electromagnetic Field Biosensing
Nordmann	2017	Unsolved mysteries: Magnetoreception – A sense without a receptor
Lambinet	2017	Honey bees possess a polarity-sensitive magnetoreceptor
Krylov	2017	Biological effects related to geomagnetic activity and possible mechanisms
Clites	2017	Identifying cellular and molecular mechanisms for magnetosensation
Clarke	2017	The bee, the flower, and the electric field: electric ecology and aerial elec...
Wu	2016	Magnetoreception Regulates Male Courtship Activity in Drosophila
Sutton	2016	Mechanosensory hairs in bumble bees (Bombus terrestris) detect weak electric ...
Qin	2016	A magnetic protein biocompass
Liang	2016	Magnetic sensing through the abdomen of the honey bee
Bae	2016	Positive geotactic behaviors induced by geomagnetic field in Drosophila
Wan	2015	Cryptochromes and Hormone Signal Transduction under Near-Zero Magnetic Fields...
Spasic	2015	Effects of the static and ELF magnetic fields on the neuronal population acti...
Shaw	2015	Magnetic particle-mediated magnetoreception
Ferrari	2015	Severe Honey Bee (Apis mellifera) Losses Correlate with Geomagnetic and Proto...
Wan	2014	Bio-effects of near-zero magnetic fields on the growth, development and repro...
Solovyov	2014	Cryptochrome and Magnetic Sensing
Guerra	2014	A magnetic compass aids monarch butterfly migration
Greggers	2013	Reception and learning of electric fields in bees
Clarke	2013	Detection and learning of floral electric fields by bumblebees
Begall	2013	Magnetic alignment in mammals and other animals
Winklhofer	2010	Magnetoreception
Wajnberg	2010	Magnetoreception in eusocial insects: an update
Oliveira	2010	Ant antennae: are they sites for magnetoreception?
Liedvogel	2010	Cryptochromes—a potential magnetoreceptor: what do we know and what do we w...
Yoshii	2009	Cryptochrome mediates light-dependent magnetosensitivity of Drosophila’s circ...
Vacha	2009	Radio frequency magnetic fields disrupt magnetoreception in American cockroac...
Knight	2009	Cockroaches use radical pair mechanism to detect magnetism
Gegear	2008	Cryptochrome mediates light-dependent magnetosensitivity in Drosophila
Hsu	2007	Magnetoreception System in Honeybees (Apis mellifera)
Kirschvink	1997	Measurement of the threshold sensitivity of honeybees to weak, extremely low-...
Kirschvink	1996	Microwave absorption by magnetite
Frier	1996	Magnetic compass cues and visual pattern learning in honeybees
Hsu	1994	Magnetoreception in honeybees
Kirschvink	1991	Is geomagnetic sensitivity real? Replication of the Walker-Bitterman magnetic...
Walker	1989	Short Cummunication: Honeybees can be Trained to Respond to very Small Change...
Kirschvink	1981	The horizontal magnetic dance of the honeybee is compatible with a single-dom...
Gould	1980	Orientation of demagnetized bees
Gould	1978	Bees have magnetic remanence
Becker	1964	Reaktion von Insekten auf Magnetfelder, elektrische Felder und atmospherics
Schneider	1963	Systematische Variationen in der elektrischen, magnetischen und geographisch-...

Table 5: List of magnetic sense studies

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