Review

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Biological effects of electromagnetic fields on insects: a systematic review and meta-analysis

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Abstract: Worldwide, insects are declining at an alarming rate. Among other causes, the use of pesticides and modern agricultural practices play a major role in this. Cumulative effects of multiple low-dose toxins and the distribution of toxicants in nature have only started to be investigated in a methodical way. Existing research indicates another factor of anthropogenic origin that could have subtle harmful effects: the increasingly frequent use of electromagnetic fields (EMF) from man-made technologies. This systematic review summarizes the results of studies investigating the toxicity of electromagnetic fields in insects. The main objective of this review is to weigh the evidence regarding detrimental effects on insects from the increasing technological infrastructure, with a particular focus on power lines and the cellular network. The next generation of mobile communication technologies, 5G, is being deployed – without having been tested in respect of potential toxic effects. With humanity's quest for pervasiveness of technology, even modest effects of electromagnetic fields on organisms could eventually reach a saturation level that can no longer be ignored. An overview of reported effects and biological mechanisms of exposure to electromagnetic fields, which addresses new findings in cell biology, is included. Biological effects of non-thermal EMF on insects are clearly proven in the laboratory, but only partly in the field, thus the wider ecological implications are still unknown. There is a need for more field studies, but extrapolating from the laboratory, as is common practice in ecotoxicology, already warrants increasing the threat level of environmental EMF impact on insects.

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Introduction

Insects are an integral part of all ecosystems. It is estimated that over 80 % of flowering plants require pollinators [1]. In the absence of pollinating insects, around one-third of all wild plant species would produce no seeds at all, and half would experience an 80 % reduction in fertility [2]. Pollinators contribute to the productivity of most agricultural crops, and their lack could only be compensated by costly substitutes [3]. In addition, insects contribute to seed dispersal, nutrient cycling, decomposition of detritus and constitute an essential stage in food chains [4]. Many amphibian, reptile and bird species rely on insects for their diet, at least during critical periods of growth [5, 6]. The loss of pollinators could increase human global deaths yearly by about 1.4 million, which corresponds to a 2.7 % increase [7, 8].

The decline of insects began several decades ago and is caused by a multitude of factors with cumulative effects [9–11]. The main causes are the use of pesticides and the destruction, degradation, or fragmentation of natural habitats, and to a lesser extent, invasive species, climate change and overexploitation [12]. Pollutants whose occurrence in nature has drastically increased in recent decades are also likely implicated: endocrine disruptors, heavy metals and electromagnetic fields [13–15]. Agrochemicals have synergistic toxic effects: two pesticides, each administered at a dose that kills 10 % of test animals, can kill up to 90 % when administered simultaneously [16].

This systematic review following PRISMA guidelines [17] addresses the effects of low- and high-frequency electromagnetic fields on insects. Electromagnetic fields (EMF) are non-quantum fields produced by moving electrical charges, that exert forces on any charged object in their vicinity. They consist of two distinct but inseparable field components (electric and magnetic) perpendicular to each other, as described in Maxwell's equations [18]. Natural EM radiation (EMR), e.g. sunlight and resonances within the atmosphere caused by lightning discharge (Schumann resonances), differ from man-made EMFs. Anthropogenic EMFs are coherent, polarized and stronger than natural ones [19]. A distinction is made between extremely low frequency electromagnetic fields (LF-EMFs), mainly high-voltage power line and mains current with 50- or 60-Hz frequency, and “radiofrequency”, i.e. high frequency EMFs (HF-EMFs), e.g. WiFi and mobile telephony, but also Radar, mostly in the range of a few GHz [20]. Technically, the currently commonplace HF-EMFs of anthropogenic origin fall into the categories of ultra or super high frequencies, i.e. microwaves (300 MHz–300 GHz), but will here be denoted as HF [20]. HF-EMFs propagate in a wave-like manner, as radiation (i.e. far-field behavior), but LF-EMFs from power lines are better described as bound to these power lines (i.e. near-field behavior). Technological HF-EMFs are in general pulsed or pulse-modulated, meaning that the carrier frequency (a sine wave) is emitted, cut-off and re-emitted many times per second. Typical values are 10 Hz (WiFi), 100 Hz (DECT), 217 Hz (GSM) up to 1,000 Hz and above (4G and 5G). The widespread use of newer technologies that use HF-EMFs, i.e. WiFi and cell phones, started from *ca* 1990 on. In general, a distinction is made between thermal and non-thermal effects of HF-EMFs. The thermal effect is based on direct heating of tissue (as in a microwave oven), and is biologically relevant for an increase of more than 1 °C. Below the intensities where tissue heating is substantial, several non-thermal effects have been described, e.g. parametric resonance and microwave hearing in humans (Frey effect) [21, 22]. Recent findings from cell biology point towards the implication of multiple mechanisms or pathways to explain the experimentally observed biological effects of EMF, as discussed below.

Ephaptic coupling and perception of EMF through ion channels for synchronization of neuronal activity

Animals have stable rhythms in their brains, measurable by electroencephalogram (EEG) or electrodes, for example. For honeybees and locusts, a main frequency of 18 Hz or 20 Hz was observed, and 20–30 Hz in *Drosophila* fruit flies [23–25]. Parametric resonance describes the change of the human or animal EEG observed upon exposure to pulsed EMFs [26, 27]. EMFs pulsed at brain frequencies cause considerably stronger effects than continuous, non-pulsed EMF. This is likely a by-product of the mode of operation of voltage-gated ion channels (VGICs) responsible for relaying nerve impulses, and therefore might affect all animals and plants [22, 28]. VGICs, e.g. Na^+, K^+, Ca^{2+} channels, as well as the N-methyl-D-aspartate (NMDA) receptor, are sensitive to non-thermal (i.e. very low) endogenous EMF strengths. The perception of surrounding EMF arising from neuronal activity can lead to coupling of nerve fibers as a result of local electric fields [29–31]. This so-called “ephaptic coupling” influences the synchronization and timing of action potential firing in neurons, and appears to play an active role in the heart, hippocampus, cerebellum and olfactory or antennal nerves [30, 32, 33, 34, 35]. VGICs have been shown to respond to LF-EMF [36–39].

The activation of voltage-gated sodium or potassium channels or NMDA receptors indirectly leads to increased activation of synaptic voltage-gated calcium channels (VGCC) and release of calcium [40]. Calcium is an important secondary messenger in all organisms, and elevated levels of calcium have a stimulating effect, e.g., on the respiratory chain and muscle [41, 42]. An overactivation of calcium-dependent neurotransmission leads to the production of reactive oxygen species (ROS) such as peroxynitrite, i.e. to oxidative stress. Chronic oxidative stress has a toxic effect on organisms, e.g., by blocking the respiratory chain, damaging mitochondria, misactivating the immune system and increasing the mutation rate [43, 44].

Geomagnetic storms caused by solar flares have been shown to cause stress in animals, a fact well documented in fish and *Daphnia*, migratory birds, and honeybees [45–47]. During solar flares impacting the Earth, the distance of the ionosphere to the ground changes, which in turn changes the Schumann resonances [48]. It may be that the perception of the stable frequencies of the Schumann resonances (7.83 Hz, 14 Hz, 20 Hz) was a key step in evolutionary history that enabled stable biorhythms [49, 50]. The rat heart responds to very weak magnetic fields in the range of the first Schumann resonance (7.6–8 Hz) [51]. This may be mediated by VGCCs and sarco/endoplasmic reticulum Ca^{2+}-pumps (SERCAs), since specific blockers abolish the effect [52]. This is in accordance with theoretical calculations by Panagopoulos and Balmori, and may be the way animals perceive upcoming earthquakes, since earthquakes are preceded by geomagnetic field and ionospheric perturbations [53, 54]. The hypothesis that VGCCs are the main conduit by which biological effects of EMFs are produced is based on observations that EMFs cause calcium release (leading to oxidative stress), that calcium channel blockers protect from adverse effects as well as on theoretical grounds [55, 56].

Magnetic sense

A magnetic sense has been described in most insect orders, e.g. in butterflies, beetles, flies, ants and bees, termites and cockroaches [57–61]. It has not yet been conclusively elucidated, and there are at least two mechanisms for perceiving the geomagnetic field: cryptochrome and magnetite, both found in vertebrates and insects [62, 63]. Also, some fish and insects (e.g. the electric eel and the hornet) have specialized organs or cells for sensing electric fields [64].

Cryptochrome

Cryptochrome (CRY), a molecule from the blue light receptor family, regulates the circadian rhythm in insects. In addition, cryptochrome is magnetosensitive once it has been activated by high-energy light via the radical pair mechanism [65]. CRY is found in the eyes and brains of most insects and vertebrates, where it acts as a molecular clock (see [66]). Using cryptochrome mutant *Drosophila*, Fedele et al. showed that cryptochrome is necessary for light- and EMF-induced delay of circadian rhythmicity [67]. Fogle et al. showed that CRY, by the intermediary of free radicals (ROS), opens the voltage-gated potassium channel Kvβ in the pacemaker neurons of *Drosophila*, leading to an increased action potential firing rate [36].

Sherrard et al. examined free radical production in *Drosophila* [68]. PEMF (“pulsed electromagnetic field”) devices are coils with medical applications, e.g. faster healing of wounds or bone fractures [40]. Wild-type *Drosophila* showed an aversion response and ROS formation after irradiation with a 10 Hz PEMF. This was not the case in mutant CRY-deficient *Drosophila*. An effect in the wild type was found only when blue or white light was present, since insect cryptochrome requires high-energy blue photons for its activation. In contrast, *Pyrrhocoris* firebugs seem to possess a mechanism to keep Cryptochrome in the activated state for more than a day after exposure to light, and it remains to be seen how comparable various insect orders are in this respect [69]. Using cell cultures of the owl butterfly, it was shown, that CRY is necessary for free radical formation when treated with PEMF coils, and this may apply to all LF-EMF sources [68]. Activation of cryptochrome by EMF, proven and largely elucidated in birds and insects, leads to opening of VGCCs in the clock neurons in *Drosophila* (Figure S1). Since these neurons regulate cell division throughout the body, this implies a cancer-promoting effect, which has been shown *in vitro* [70–72].

Magnetite

All insects possess cryptochromes in their eyes and brain. Ocular cryptochromes only function as magnetosensors under blue light (red light in the case of birds). Insects that are active in the dark seem to use a magnetite-based magnetic sense instead; this has been experimentally confirmed in bees, ants and termites [60, 73, 74]. In honeybees, changes in the size of magnetite crystals cause a release of calcium [75]. Termites and cockroaches use a combination of CRY and magnetite for their orientation – CRY during the day, magnetite at night or in the dark [76–79].

Previous reviews whose references were included in this review

Cucurachi’s review: “Insects are a useful target system for the study of HF-EMF due to their limited size, short life cycle and the possibility to easily detect developmental errors [80].”

Balmori’s review: Balmori mentions that insects have long been shown to respond to (non-thermal) electromagnetic radiation in the microwave range, since this was first described 50 years ago by Carpenter and Livstone [81, 82]. Pulsed microwave radiation from cell phones or WiFi disrupts the development of *Drosophila* fruit flies and leads to reduced fecundity and increased mutation rate; these effects have been documented by several research groups [83–85].

Levitt et al.’s review: Levitt et al. is a three-part review of EMF effects on flora and fauna [86]. Part two discusses the effects of EMFs on animals and lists 140 references dealing with insects. Quote: “Many behavioral aspects in biology are thought to be synchronized with both the Earth’s natural fields and Schumann resonances. But now, for the first time in evolutionary history, we have covered the Earth’s surface with a blanket of artificial energy fields without knowing what the consequences might be.”

EKLIPSE Report and Vanbergen et al. review: A detailed report was written at the request of the English NGO “Bug-Life” [87, 88]. 39 studies were evaluated according to ecological aspects, 26 of which were additionally evaluated according to technical aspects. Vanbergen et al., contributors to the EKLIPSE report, evaluated the risk to pollinating insects only, thus excluding most EMF studies in insects [89]. The authors emphasize the proven harmfulness of “artificial light at night”, and claim, that the only clearly proven effect of man-made electromagnetic radiation to date is disruption of orientation [90–92]. This is a mere opinion of the authors not supported by science, as discussed below.

Methods

Literature search

A literature search was performed on the EMF-Portal database [93], using the following search terms: "insect drosophila bee apis pollinator ant termite locust cockroach" (separated by "Or"). The references of the reviews listed above were extracted and integrated into a common bibliography. A Google Scholar and Pubmed Central Search of the years 2012–2022 was made separately, using the following search terms: one of each: "insect; drosophila; bee; apis; pollinator; ant; termite; locust; cockroach" and all the following (separated by "Or"): "EMR; EMF; electromagnetic field; electromagnetic radiation; electromagnetic; high frequency; HF; low frequency; LF; WiFi".

Methodology for selection of studies

The titles and abstracts of all entries were read and entries not in English nor German, or not related to the topic, were excluded. Then, full-text articles were viewed, and only those describing experiments with EMF on insects, not older than 1980, and considering non-thermal effects, were kept. Studies were categorized as non-thermal based on provided tissue temperature measurements, or on the declared power densities used in experiments, if they were below ICNIRP limits [94]. Some of the magnetic sense studies were used for the introduction, but were not used for further analysis.

Quality assessment

Studies underwent quality assessment before being included in the review. The review criteria checklist published by the Task Force of Academic Medicine and the GEA-RIME Committee was used for this purpose, as adapted by Bertagna et al. [55, 95]. All studies relevant to the topic were reviewed by the lead author for quality using 13 prespecified criteria, and those meeting at least 11 of the 13 criteria were retained [55].

Data extraction and processing

All studies included in the review were evaluated and data was recorded (by the lead author) in one spreadsheet each for HF- and LF-EMF. The data format of the Oceania Radiofrequency Scientific Advisory Association (ORSAA) database was used to record both the EMF sources used, field strengths and duration of experiments, as well as biological findings [96]. Supplementary columns for effect size (as percent change compared to control) and direction of effect (detrimental, beneficial, uncertain, none) were added. Direction of effect was determined based on the judgment of the respective study authors, or on common sense understanding of biology (such as increased mortality or occurrence of mutations being detrimental), or on corollary variables that the study authors had measured. E.g., increased oxidative stress was usually classified as "uncertain", unless co-occurring reduced reproductive capacity or DNA damage was also observed, in which case it was classified as "detrimental". When possible, extracted data were compared with values already recorded in the ORSAA database. Exposure times were converted to hours, and field strengths or power densities to V/m, when possible, using the formulas listed in the Appendix. Estimates of effect size were obtained and normalized by converting percentage changes to ratios of means (ROM), and inverting the ratio of means in case of a diminution. Thus, a decrease of 50 % was counted as a ROM of 0.5, and the inverse of this, 2, was noted as the effect size estimate. In this way, positive toxicity measures, such as increased DNA damage in the ovaries, could be compared to negative changes, like reduced reproductive capacity [97]. Effect sizes of experiments finding beneficial outcomes were inverted, so that all detrimental outcomes would have a ROM>1, and all beneficial outcomes a ROM<1. Observed bioeffects were classified into the following categories: reduced reproductive capacity (damage to egg or sperm cells, reduced number of eggs laid or offspring), developmental effects (delayed or accelerated larval development, occurrence of mutations), DNA damage, altered DNA or DNA transcription, altered enzyme activity or metabolism, oxidative stress, altered behavior (speed of locomotion, reaction speed, orientation, response to pheromones), impaired memory, other. Disturbance of sense of direction or orientation was included in "altered behavior" [89]. Data was plotted in RStudio.

Data synthesis and statistical analysis

A minority of studies did have complete statistical information needed for meta-analysis, and it was possible to infer standard errors from p values for a wider number of studies (R package "dmetar"). Experiments that provided an effect size but were declared as "not statistically significant" or "no effect" were assigned a p value of 0.5. A meta-analysis was performed for all HF-EMF studies that found reproductive effects in *Drosophila*, this being the subgroup with the highest number of studies. Also, for the devices most often used in studies, it was possible to derive estimates of pooled effect sizes by meta-analysis, using the R packages "meta" and "bayesmeta" [98, 99]. RStudio was used for data synthesis, analysis and plots.

Results

The literature search in EMF-Portal yielded 413 results. The bibliographies of previous reviews and the literature search in Pubmed and Google Scholar together yielded 291 studies. After removing duplicates, a total of 587 entries resulted, which were treated as follows and as described in the PRISMA flowchart (Figure 1).

Selection of studies

One hundred and thirty studies relating experiments with EMF in insects, published after 1980, underwent quality appraisal. Three HF studies that are computer simulations were treated separately [100–102]. These studies are prospective in nature, and did not provide data points for the graphs, but did provide information on impacts to be expected in the future. 11 studies were excluded because of qualitative deficiencies (lacking EMF measurements, bad experimental procedure, inadequate design of experiments,

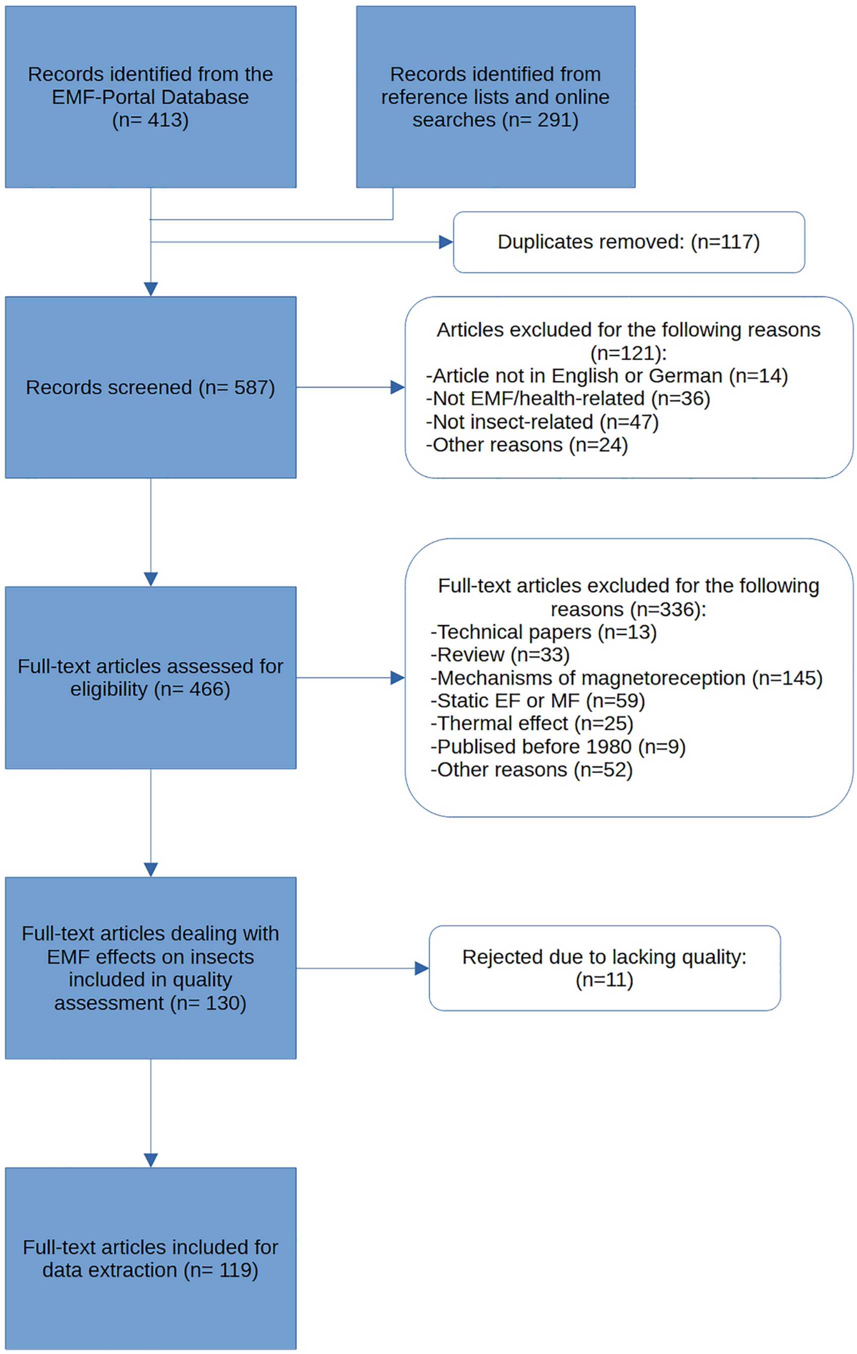

Figure 1: PRISMA flow diagram for selection of studies.

poor data handling or lack of reporting of statistical analyses) (cf. Supplementary Tables 1 and 2). 119 studies (64 LF studies, 55 HF studies) involving experiments with EMF in insects were subjected to data extraction and included in summary tables (cf. Supplementary Tables 3–6).

Trends

One hundred and eighty five papers (including reviews) on the effects of EMF on insects, and 145 studies on insect magnetic sensing, have been published since 1980 (Figure 2). Trends indicate a slight increase of interest in the subject, but there is probably a lack of awareness for biological effects of EMF in general, since it is not a part of most university curricula and requires knowledge in multiple fields. In addition, the field of bioelectromagnetics is underfinanced and considered controversial.

The majority of the studies were conducted with *Drosophila* fruit flies or honey bees (Figure 3A). Generally, cell phones, coil systems or signal generators were used

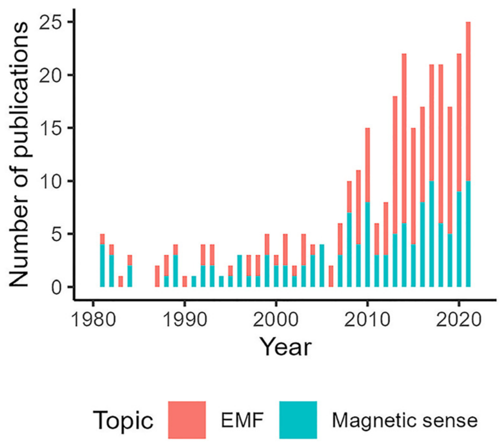

Figure 2: Number of publications on insects per year by topic.

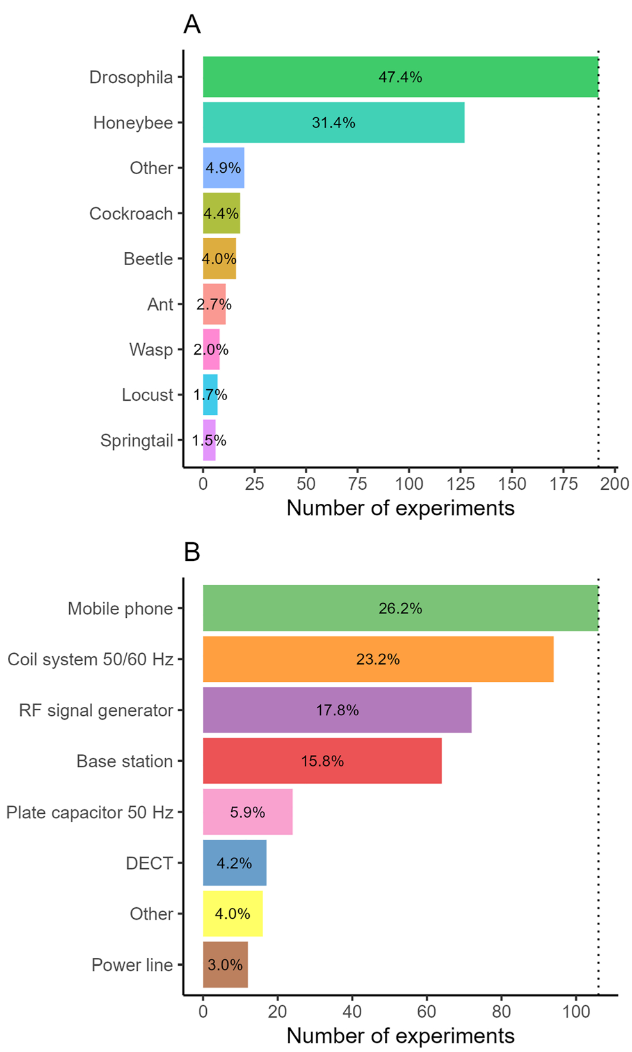

Figure 3: Number and percentage of published experimental findings by insect species or group (A) and EMF sources (B) used in experiments.

(Figure 3B). Helmholtz coils are wire coils powered by line current, and emit 50 Hz low-frequency EMF. In 70 % of studies using a coil system, Helmholtz coils were used. Nevertheless, a minority of studies used Merritt coils, solenoids or single electromagnetic coils: all these studies were grouped under the category "coil system". Signal generators are, in the simplest case, oscilloscopes configured to produce high-frequency signals, with similar signal characteristics as wireless communications systems (WiFi, cellular 1G to 5G, etc.). The signal is usually fed to a horn antenna to radiate HF-EMF.

In the HF-EMF studies, radiation intensities (or electric field strengths) ranged from 0.00005 to 38,200 mW/m^2, respectively 0.0043–120 V/m (Figure 4). The duration of exposure of the insects ranged from 30 s to 8.5 months. 64 % of experiments indicated an effect size, 51 % of experiments also indicated a p-value, while 23 % furthermore indicated standard deviations or standard errors (SEs). By deriving SEs from p-values, 53 % of experiments, or 39 % of studies could be included in the meta-analysis. Almost none of the included studies are randomized controlled trials (RCT). However, a 2014 meta-analysis comparing RCTs with observational-only studies concludes that such studies are as good as RCTs at finding and gauging real-world effects [103].

Estimates of effect size of toxicity

Regarding the toxicity of various EMF sources (Figure 5), the HF devices cordless phone (DECT), cell phone, and signal generator appear to be similarly toxic. Base stations seemed to be less harmful than cell phones, although both use the same technology. This discrepancy is probably due to the fact that studies on cell phones usually are laboratory studies in a controlled environment at relatively high field strengths, whereas the studies on base stations are field experiments, usually at much lower field strengths or with exposure duration too short to find long-term effects. The field strength of the signal from the cellular towers was in the range of 0.56 V/m on average (median value 0.32 V/m), whereas the field strength from cell phones was 18.7 V/m on average (median value 16.2 V/m) (Figure 4). Converted into power densities (median values), the quantitative difference is easier to grasp. Cellular tower: 0.27 mW/m^2; cell phone: 695 mW/m^2. Current typical field strengths of cellular towers (used in experiments) are less harmful than those of cell phones, DECT and WiFi. The current experimental evidence from base station studies should not be interpreted in the way that effects are weak *per se*, but that in general the

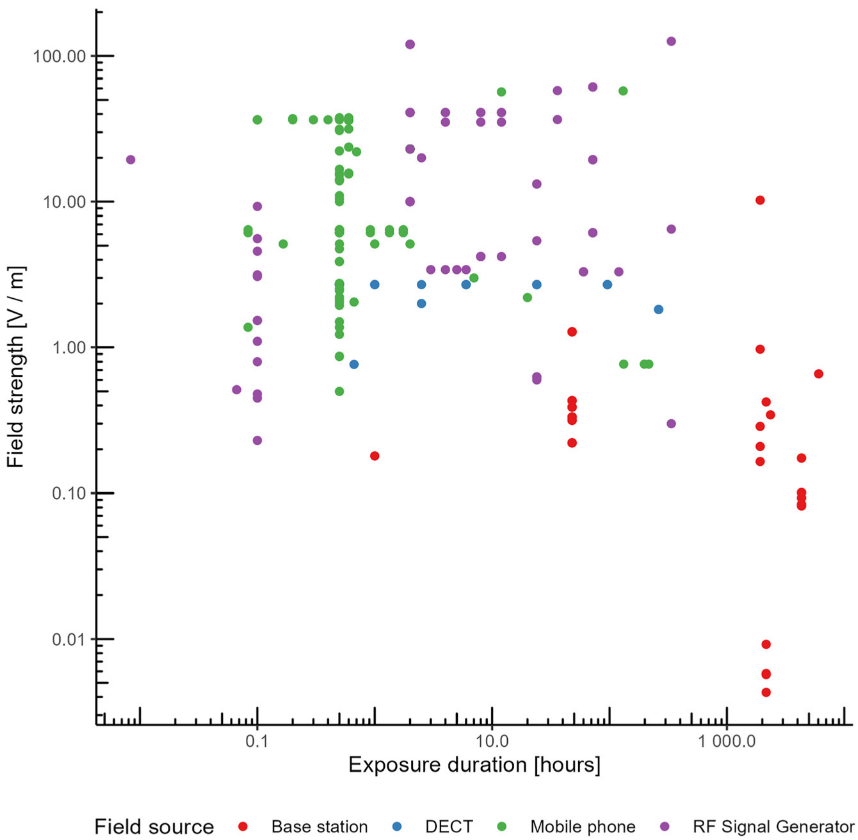

Figure 4: EMF field strength in relation to the duration of exposure (data points from 239 experiments or experimental groups in 48 HF-EMF studies).

experimental setup was such that only relatively weak power densities were tested (typically at 100–500 m from emitter), while insects can be subject to much higher power densities if they get nearer to the antennae. Experiments using cell phones often found detrimental effects within 10 min of irradiation, whereas field experiments at base stations found harmful effects usually after several weeks or months (cf. “Discussion” section). However, some recent human epidemiological studies and field studies in insects, birds and pine trees around cellular towers point to chronic detrimental effects even at current power levels [104–109].

Toxicity estimates derived by meta-analysis number at a ratio of means of about 1.5 for the HF-EMF devices (Supplementary Figures S8, S9, S10, Supplementary Table 1). This estimate includes all types of observed bioeffects that could be unequivocally classified as detrimental or beneficial (Figure 6), and might be interpreted as a 50 % increase in DNA damage or a 33 % reduced reproductive capacity, in the worst case scenario. The toxicity estimate for base stations is about 1.49 (Supplementary Figure S6). This estimate also includes findings that observed avoidance of, or reduced abundance of insects around base stations, and further research is needed to clarify the actual impact of insects avoiding base stations, but behavioral effects should not be underestimated [110]. An estimate based only on direct markers of toxicity (like reduced brood, egg laying etc.) yielded a much lower toxicity of 1.09, corresponding to an 8 % reduction in reproductive capacity (Supplementary Figure S7). The toxicity estimates are statistically highly significant for DECT, mobile phones and the RF signal generators, barely significant for coil systems and nonsignificant for base stations. Forest plots show considerable heterogeneity among studies (I^2 typically>90 %), and wide prediction intervals describing the range of observed effect sizes. This may be due to large differences in measured parameters as well as EMF exposure strength, type and duration. Heterogeneity could also indicate a lacking understanding of underlying mechanisms of action, leading to inadequate experimental designs (with notable exceptions), leading to strong variation among experimental findings.

The results of the meta-analysis for all experiments finding reproductive toxicity in *Drosophila* at over 7 V/m E-field strength (Supplementary Figure S3) are close to those for the cohort of experiments at between 2 and 7 V/m (Supplementary Figure S4): Random effects estimate: 1.40 or 1.44, corresponding to 29–31 % reduced reproductive capacity

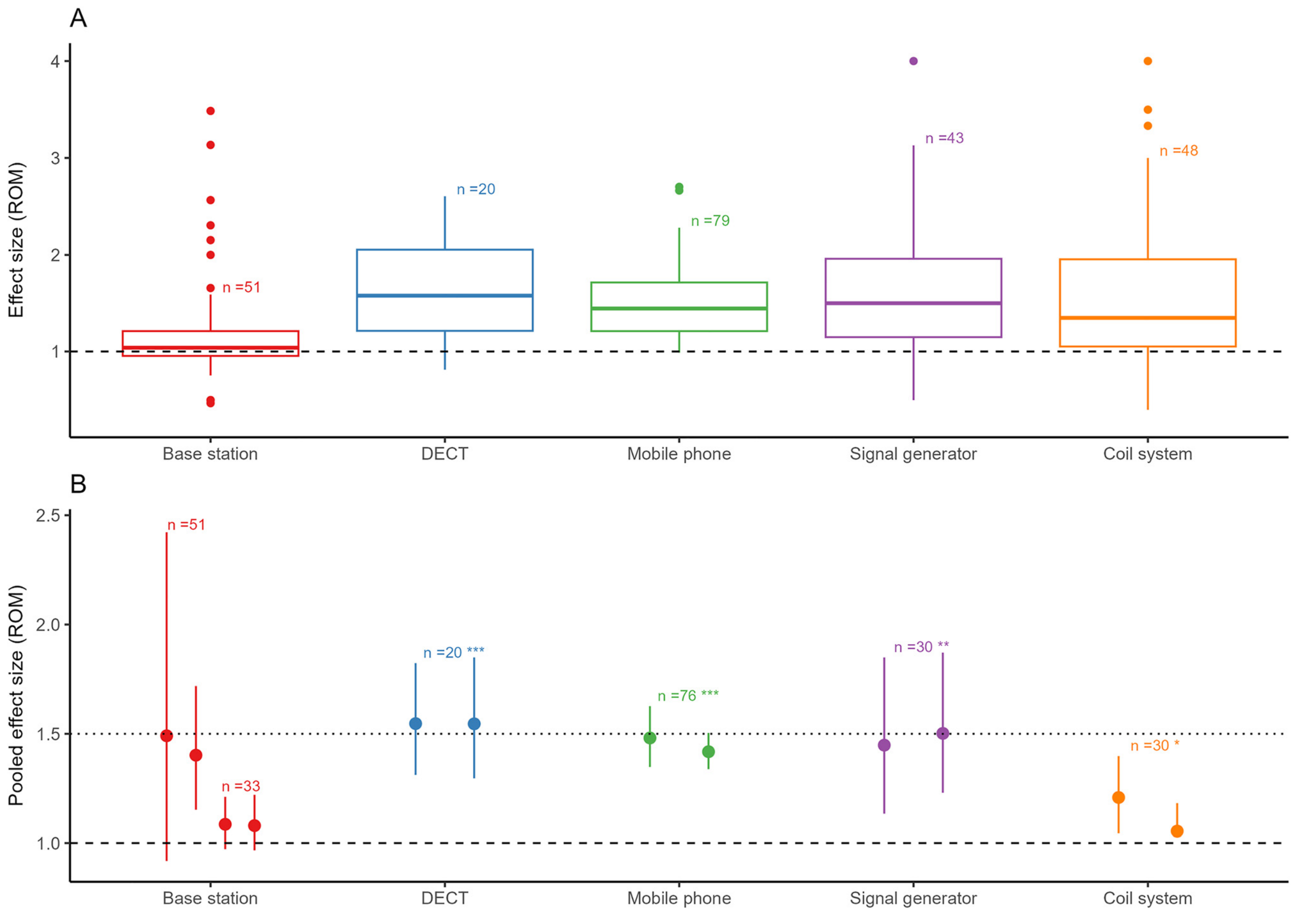

Figure 5: (A) Boxplots (median and quartiles) of effect size found in experiments by EMF type, given as normalized ratio of means (ROM), with indication of the number n of experiments. ROM>1 indicative of detrimental effects. (B) Toxicity estimate derived from meta-analysis, with effect size given as ratio of means with 95 % confidence interval (*p<0.05, **p<0.01 & ***p<0.001). Estimate from "clustered" three-level analysis (R package "meta") besides Bayesian estimate (R package "bayesmeta"), with indication of the number n of experiments the estimate is derived from. For base stations, estimates including all findings of reduced abundance or altered behavior (left) besides estimates based on toxicological findings only (right).

(p=0.01). The meta-analysis for all experiments finding reproductive toxicity at less than 2 V/m (Supplementary Figure S5) indicate a lesser toxicity, with an effects estimate of 1.22, corresponding to a reduction of 18 % in reproductive capacity (p=0.03). Supplementary Tables 1 and 2 list all estimates derived by clustered, three-level meta-analysis and Bayesian meta-analysis respectively.

Summary of study findings

A number of studies on the effect of power lines on honey bees were conducted in the 1970s and 1980s [111–115]. Most later studies used Helmholtz coils or other coil systems in the laboratory, which allows more easily controlling the experimental parameters. Coils produce much stronger magnetic fields, but weaker (induced) electric fields, when compared with HF-EMF sources [116–118].

The frequencies used in HF experiments were distributed as follows: 55 % of the HF experiments used frequencies near 900 MHz, corresponding to the GSM (2G) and LTE (4G) mobile phone standard. 8 % used 1900 MHz (DECT), 7.6 % used 1800 MHz, which corresponds to DCS (2G), and 3.6 % used 3,500 MHz, like low-band 5G.

The biological effects of LF- and HF EMF observed in experiments clearly differed (Figures 5, 6 and 7), which could indicate differing biological targets for LF-EMF coil systems compared to HF-EMFs, and may be due to the fact that coils usually were operated with alternate-current sine-wave, whereas HF-EMF devices used pulsed carrier signals; RF signal generators used a pulsed signal in 21 % of experiments, a 50 kHz frequency-modulated signal in 17 %, and a continuous sine-wave signal in 61 % of experiments. For the HF-EMF, observed effects were mostly detrimental as to their impact (57 %). About one quarter were classified as uncertain effect (such as increased or reduced locomotion).

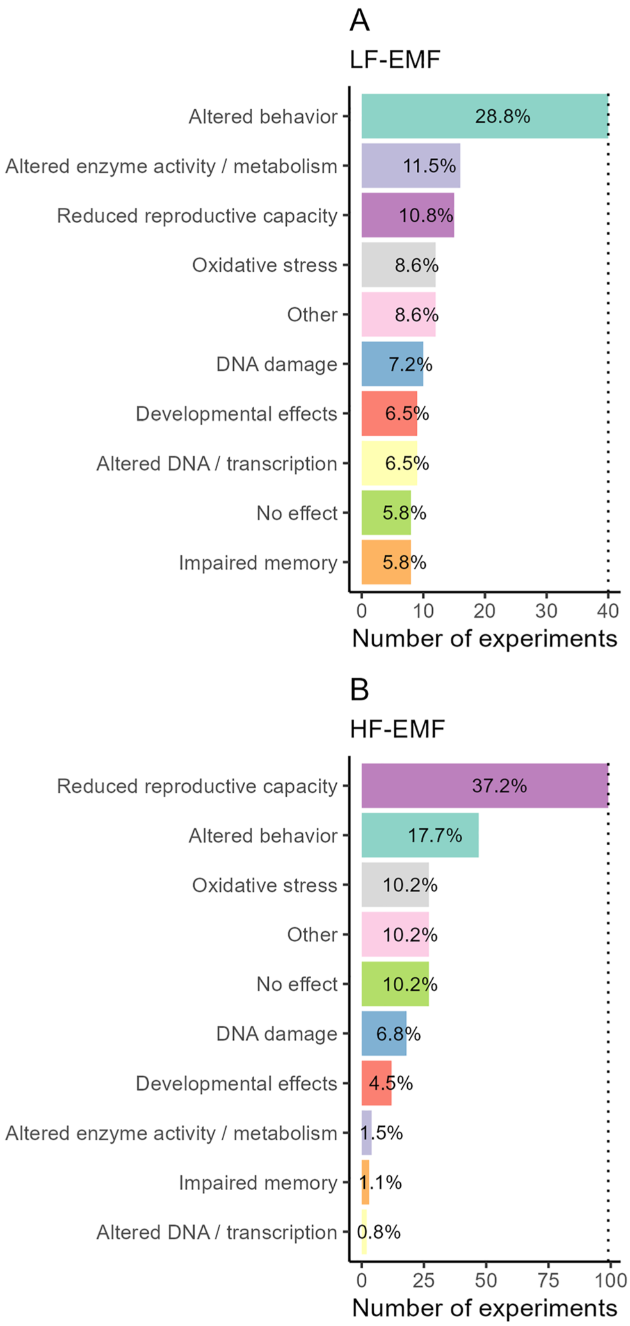

Figure 6: Number and percentage of experiments classified according to bioeffect categories, (A) low-frequency EMF, (B) high-frequency EMF.

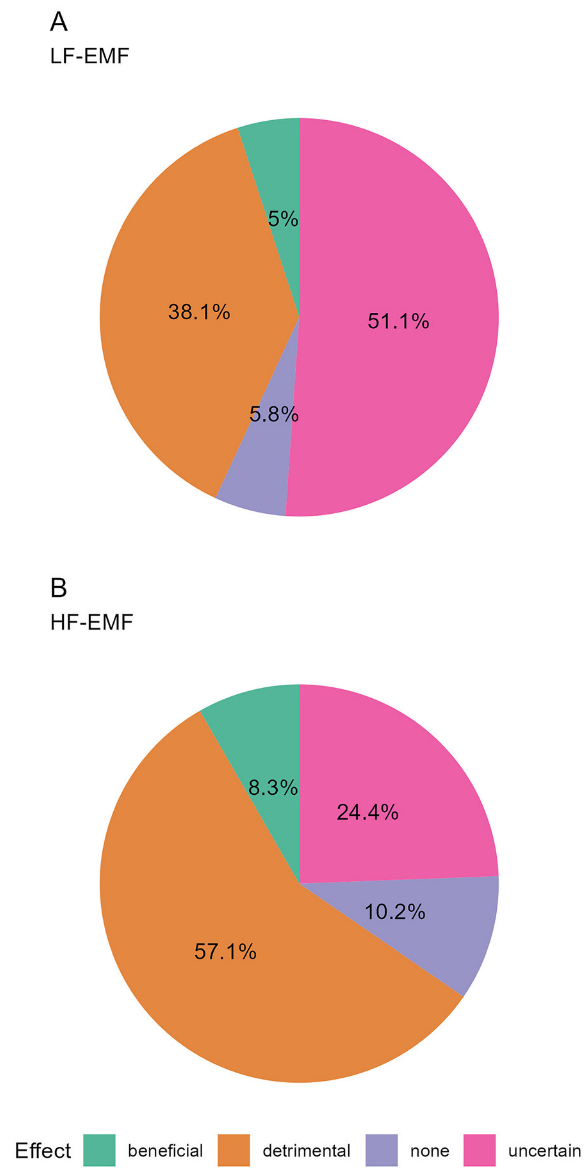

Figure 7: Percentage of experiments finding biological effects of EMF on insects by direction of effect, (A) low-frequency EMF, (B) high-frequency EMF.

For the LF-EMFs (133 experiments), a behavioral effect was observed in 29 % of experiments, in 12 % of experiments, the effect concerned metabolism, and in 11 %, reproductive ability was impaired. For HF-EMFs (238 experiments), the following trends were observed: decreased reproductive capacity in 37 % of experiments, altered behavior (18 %), oxidative stress (10 %), DNA damage (7 %) and impaired development (5 %). In 10 % of experiments, no effect could be found; this higher number than for LF-EMF (6 %) is probably due to the fact that several HF studies were field studies with base stations, at low field strengths, and that it is easier to find significant results in laboratory studies.

Discussion

The vast majority of studies found effects, generally harmful ones. These findings are unlikely to be the result of chance. Sceptics might object that most studies were not randomized controlled trials (but see here [103]). Despite these shortcomings, the existence of consistent results from numerous studies conducted by various research groups using various protocols make an irrefutable case for adverse effects of low-power LF- and HF-EMF on insects [86, 119]. This is further corroborated by a recent report commissioned by the Swiss federal office for the environment (BAFU) [120]. HF-EMF seem to produce stronger and more harmful effects in insects, compared to LF-EMF. It is highly probable that the effects shown in the laboratory also occur under real conditions [110]. A summary and chronicle of individual studies in insects is available in the supplemental materials, and in other reviews [86, 105, 121]. EMF bioeffects have also been shown in plants and all studied animals, as well as in humans [86, 122, 123, 124]. Insects are expected to be affected the most however, since they are already under pressure of multiple threats, less resilient to stressors and pollutants than larger animals, and due to their small size, more vulnerable to increasingly high frequencies used by the mobile phone infrastructure (5G and 6G in the future) [12, 100, 125].

Comparison between the problem of artificial light at night (ALAN) and other electromagnetic fields

Some environmental and biodiversity threats have been gaining interest recently among researchers and policymakers, e.g. anthropogenic noise and artificial light at night [126, 127]. The same has not yet happened concerning electromagnetic pollution, even though its increase in recent years has been exponential [15, 86, 128]. Here, we compare the effects of artificial light at night (ALAN) with those of wireless communications high-frequency electromagnetic fields (HF-EMF). Light has driven the development and organization of biological systems from the molecular level to ecosystem cycles [127]. Also, life evolved in a matrix of relatively weak, natural electromagnetic and geomagnetic fields. ALAN is entirely unprecedented and has been introduced in places, times and at intensities at which it does not naturally occur and with a different spectrum from that of sunlight [127]. Likewise, man-made HF-EMF also have been rapidly introduced worldwide, at intensities far above those occurring naturally. Anthropogenic EMF are polarized, pulsed, modulated and include extremely low frequencies in their pulse-rate, while natural EMF lack these characteristics [128]. Light pollution has been on the rise during the past 100 years, whereas the development of mobile communications started just a few decades ago. HF-EMF have been introduced very quickly worldwide, and levels of exposure have increased by a factor of about 10^{18} compared to natural ambient levels [15]. The physiological and behavioural effects of ALAN and HF-EMF are widely documented, but the extent to which this translates into impacts on populations and ecosystems remains poorly understood [86, 127, 129].

General considerations

Considerable evidence suggests many medical applications of EMF waiting to be developed [130–133]. Although an earlier review cautioned against medical PEMF ("pulsed electromagnetic field"), PEMF devices are now being used with success, although their mechanism of action has only partly been elucidated [134–136]. Nevertheless, this should be secondary in a medical context: if an agent or device is effective for some medical condition, e.g. cancer or viral infection, and if no serious side effects occur, the agent should be used. Conversely, agents or technologies that produce serious adverse effects should not be used. Even if current wireless technologies are generally toxic in a dose-dependent manner, it should be possible to significantly improve their biocompatibility, similarly to what has already been achieved for e.g. computer and TV screens, for example by eliminating "biomimetic" low-frequency pulsing [132, 137, 138, 139]. An experiment on cockroaches suggests that the simultaneous presence of static magnetic fields or LF-EMF together with HF-EMF is more harmful than each separately, as had been shown earlier for birds and theoretically postulated [140–142]. It is so far unclear if EMF are synergistically toxic with pesticides, with some studies indicating synergistic toxicity, but others not [143, 144].

Most studies included in this review that were amenable to meta-analysis come from one very prolific group of scientists from Athens University. A recent study from Italy does however confirm the basic mechanisms for toxicity described and posited by Panagopoulos et al., which is that HF-EMF cause first oxidative stress, leading to defective transposon silencing, causing chromosomal aberrations and DNA damage, which finally causes reduced reproductive capacity [139, 145].

At which field strengths are toxic effects expected to occur in insects?

Looking back at the history of science, it seems that adverse effects have frequently been reported early on, but mostly been ignored – e.g. in the cases of asbestos, lead and cigarettes. It has typically taken decades to understand the mechanisms of toxicity and for the official position to shift. The European Environment Agency EEA has produced several reports on this topic under the title “Late lessons from early warnings” [146, 147].

Thirty-six of the fifty-five HF-EMF studies reported in this review used field strengths lower than 6 V/m (~100 mW/m^2), and 31 of these 36 studies (86 %) nevertheless found statistically significant adverse effects, starting at about 2 V/m and peaking around 6 V/m. This is below the regulatory thresholds established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (41 V/m, or 61 V/m above 2 GHz), and even below the particularly stringent installation limits only found in a handful of countries [94]. (The installation limit is measured where people can stay for long periods of time, i.e. homes, schools, working places and playgrounds for kids.)

Panagopoulos et al. detected a bioactive window at a distance of 20–30 cm from GSM mobile phones, where the power density equaled 100 mW/m^2 (~6 V/m), and where toxic effects in *Drosophila* are already observed after a 1-min exposure. These results have been replicated several times [148–150]. If this is generally true for insects, the limit for toxic effects would be 100 times below the current ICNIRP limit (10 W/m^2 or 61 V/m), which protects only against thermal effects (in humans), and possibly 1,000 times lower than current limits for chronic exposure, i.e. 10 mW/m^2 or 2 V/m (all comparisons based on power densities, i.e. energy per surface area units) [94]. A recent study found significant effects on gene transcription and chromosomal abnormalities using a WiFi signal at 4.8 mW/m^2 or 1.35 V/m in *Drosophila* exposed for 9 days [145]. These findings of biological effects in insects starting at around 2 V/m imply that existing standards would have to be revised and made more stringent, to include nature protection/wild-life concerns.

Current ambient power densities are generally still below 10 or 100 mW/m^2 (i.e. 2 or 6 V/m). A recent study measured values of 0.17–0.53 V/m in the field (0.1–0.8 mW/m^2) [101]. Values mainly in the range of 0.5–1 V/m were found around schools in Crete [151]. Nationwide measurements of the National Observatory of electromagnetic fields (NOEF) in Greece found average values higher than 1 V/m in 55 % of sites, and values greater than 2 V/m in 20 % of measurement sites [152]. A recent review lists power densities ranging from 0.23 V/m in Swiss residential areas to 1.85 V/m in an Australian university neighborhood [86]. In urban hot spots (UK), a maximum of 150 mW/m^2 (7.5 V/m) and an average of 25 mW/m^2 (3.3 V/m) were measured (including WiFi) [153]. The French “Agence nationale des fréquences” (ANFR) found an average of 1.17 V/m at 1,300 5G base stations, and the authors expect a 20 % increase in the next years [154]. In Belgium, Italy, Switzerland, Russia and China, the installation limit is 6 V/m (100 mW/m^2) for mobile telephony base stations, whereas Germany, the UK, the USA and many other countries adhere to the much higher ICNIRP limits [94, 155]. The ICNIRP limits have recently been questioned, since they are based on findings from more than 20 years ago, and their assumptions have been proven false [156]. Furthermore, the ICNIRP limits are designed to protect humans and have not been tested as to their adequacy in protecting wildlife and insects [157].

In the future

The mechanisms of biological effects, apart from the magnetosensitive cryptochrome and HF effects on reproduction, are not yet well understood [65, 139, 145]. The following questions need to be clarified:

- to what extent biological processes triggered by HF- and LF-EMF are comparable;
- to what extent interference effects or synergies take place between Earth’s static magnetic field, man-made LF-EMF and HF-EMF;
- to what extent findings with HF-EMF in the laboratory are transferable to cellular towers, and emerging EMF sources like high-band 5G;
- what are power densities in the natural environment (detailed EMF maps).

Compared to most animals, humans are quite resilient in terms of how much stress or toxins they can withstand before developing clinical symptoms [158]. On the other hand, many pesticides initially considered harmless to humans have subsequently proven harmful, such as DDT, organophosphates, and pyrethroids [159]. Insects are more sensitive to pollutants, including EMFs, than humans [86, 120]. Healthy ecosystems and sustainable agriculture require insects. Although ecological practices and organic agriculture are on the rise in Europe, important measures to protect insect populations, such as banning neonicotinoids and reducing monocultures, are being implemented too slowly [125, 160].

According to Thielens, De Borre et al., the EMF power absorbed by insect bodies (for the same emitted power of 1 V/m) increases by up to a hundredfold for a change in frequency from ~1 GHz (e.g. 4G and low-band 5G) to 10 GHz and higher, e.g. high-band 5G at 26 GHz, hence an increase in negative effects on insects is to be expected, since low-level (non-thermal) effects are still dependent on absorbed power [100–102]. As power losses become greater due to scattering, reflection, and the lower penetration force of higher frequencies, the radiated power of base stations will also have to increase to ensure comfortable wireless connections in homes and vehicles. The 5G expansion is leading to a significant increase in EMF emissions, as suggested by recent measurements [152, 154, 161]. Based on an assessment of the overall study situation on insects, we must warn against a careless deployment of further mobile telephony infrastructure, as harmful effects on insect populations would be likely, especially if interactions with other noxious agents are taken into account (including high-voltage power lines and artificial lighting). This might lead to further declines of already dwindling populations of pollinators, and would thereby entail costs for humanity. It is also possible, and would need further clarification (which could be reached by a few well-planned field studies), that some insect populations are already negatively impacted by the present infrastructure.

The ongoing 5G-deployment should be closely monitored, and toxicological testing for the evaluation of adverse effects should begin immediately, so that protective guidelines can be enacted. Experimental findings should be reported transparently, and granted the political presence necessary to lead to timely response, as there is a tendency for scientific discussion to become polarized into extreme positions, which rarely reflects the truth and causes substantial waste of resources [160]. Toxic effects on insects may occur at radiation levels that are considered safe for humans, particularly in the higher frequency bands. We refer to the so-called precautionary principle, detailed in article 191 of the Treaty on the Functioning of the European Union. Pollinator conservation requires a stronger and broader application of the precautionary principle as currently practiced [125]. Also, the EU precautionary principle implies that legislative action should already be taken if there is a founded suspicion of negative effects.

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Appendix

Calculations

The SI unit for expressing the strength of an electromagnetic field is volts per meter [V/m], and this is also the common unit of measurement for electric fields. It can be used for calculating 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 here included, all given values of field strength were converted into V/m if they were described in a different unit. The following formulas were used [18, 162]:

$$S = \frac{E^2}{Z_0} \text{ or also: } E = \sqrt{S * Z_0}$$

where E is the electric field strength [V/m], S the power density [W/m^2], Z_0 the wave impedance [377 Ω].

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 [162]).

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 (abbreviation 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 according to [100–102].

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