



Radiofrequency electromagnetic fields reduce bumble bee visitation to flowers[☆]

Manuel Treder^{a,*}, Michael Glück^a, Sam J. England^b, Kirsten S. Traynor^a

^a State Institute of Bee Research, University of Hohenheim, Erna-Hruschka-Weg 6, 70599, Stuttgart, Germany

^b Department of Evolutionary Morphology, Museum für Naturkunde – Leibniz Institute for Evolution and Biodiversity Science, Invalidenstraße 43, 10115, Berlin, Germany

ARTICLE INFO

Keywords:

Electromagnetic radiation
RF-EMF exposure
Wild bees
Bumble bees
Apis mellifera
Flower visitation

ABSTRACT

Radiofrequency electromagnetic fields (RF-EMF) are an integral part of our daily lives and we may struggle to imagine life without them, using them to transmit and stream data for television, the internet, or cell phones. Debates circulate on whether this anthropogenic radiation may be an additional stress factor for pollinators, potentially disrupting important habitats and refugia, especially in highly developed areas. Could these anthropogenic fields interfere with foraging pollinators, influence their foraging behavior or reduce the attractiveness of entire habitats? Current data on sublethal impacts is sparse. We tested the effects of realistic 2.4 and 5.8 GHz radiation on flower visitation rates of different pollinators over two years in a blinded study using a standardized radiation source and a novel study design. Documenting 2882 pollinators, we found no effect of this radiation on honey bee visitation rates on *Salvia* and *Lavandula* plants. However, we found a significant reduction in the number of bumble bee visits per observation when the plants were subjected to RF-EMF exposure, highlighting the need for in-depth and long-term studies to elucidate the underlying mechanisms of this effect.

1. Introduction

Today, electromagnetic fields are an integral part of our daily lives as we often depend on them for access to the internet, television and cell phone communication (Federal Office for Radiation Protection, 2024). These fields are especially common in heavily developed areas (International Telecommunication Union, 2021), where insects are exposed to them. They could encounter these fields in two ways: if their nests are located in exposed areas, or if they pass through such fields while foraging for nutritional resources or nesting materials. How do these radiation fields affect insects and especially wild pollinators, such as bees, many of which are in decline (Hallmann et al., 2017) and therefore threatened? This emerging area of research into the impacts of radiofrequency electromagnetic fields (RF-EMF) on pollinators has experienced a recent surge in publications (Thill et al., 2023). We previously showed the negative effects of electromagnetic fields (EMF) on the homing success of honey bees in an experimental study (Treder et al., 2023), while others have demonstrated impacts on the development of queen pupae (Odemer and Odemer, 2019), on aggression (Shepherd et al., 2019), on the learning capacity (Shepherd et al., 2018)

of honey bees, and damage to DNA during the developmental stages (Vilić et al., 2017). There is currently a lack of robust data on how human made electromagnetic fields influence pollinator behavior (Vanbergen et al., 2019). Most experiments involving pollinators have been conducted with honey bees (Thill et al., 2023) as wild pollinators are more difficult to assess in experiments. Despite the difficulties of working with unmanaged pollinators, the abundance of pollinators is highly dependent on landscape (Bottero et al., 2023) and weather factors (McCall and Primack, 1992; Treder et al., 2024). Therefore, it is difficult to derive robust data and effects from correlative studies, as they have limited ability to adequately control for these confounding factors. This is why an experimental setup comparing areas of low and high RF-EMF exposure is preferable to an observational one.

To help fill this knowledge gap, we asked whether exposure to the ubiquitous frequencies of the 2.4 and 5.8 GHz band (both commonly used for Wi-Fi) could influence the flower visitation rates of pollinators to plants and thus their foraging behavior. If this radiation causes disturbances or negative effects, it could make exposed areas in cities less attractive to bees and thus may represent a disruptive factor impacting pollinators in highly developed areas. For our experiment, we used a

[☆] This paper has been recommended for acceptance by Pavlos Kassomenos.

* Corresponding author.

E-mail address: Manuel.Treder@uni-hohenheim.de (M. Treder).

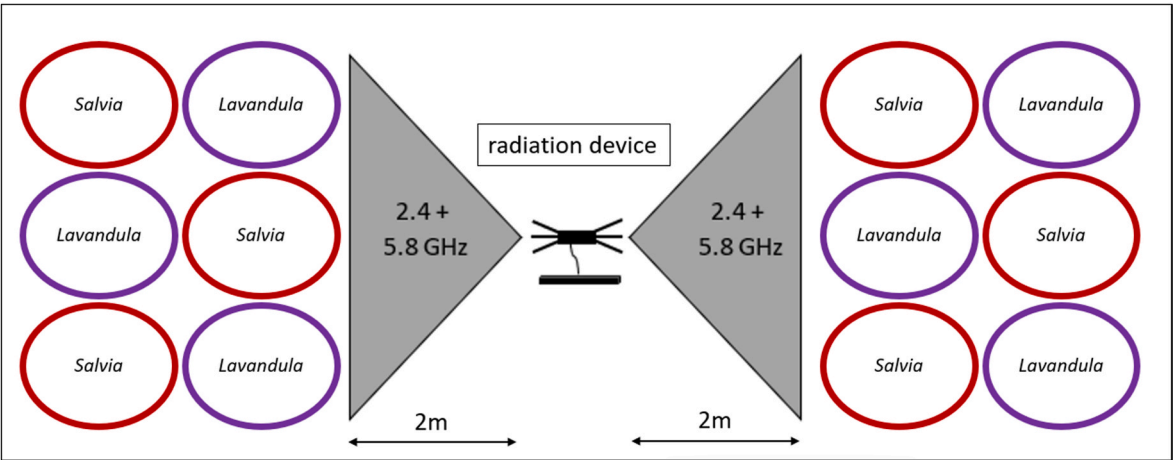


Fig. 1. Experimental setup of the flowerpots (*Lavandula*/*Salvia*). Each flowerpot, represented by an oval, contained three plants of either *Lavandula* or *Salvia*.

radiation source specifically developed for such experiments (Treder et al., 2023) to test the short-term effects of RF-EMF on the flower visitation rates of different pollinators on pollinator-attractive plants over a two year period. Using this radiation source that generates a consistent, definable and realistic electromagnetic field, flowerpots containing *Salvia* and *Lavandula* plant species were either exposed or not exposed in a 4-day rhythm during the 2023 and 2024 seasons. In this fully blinded experimental study, all flower-visitors were recorded on 92 observation days and relevant environmental factors like temperature or solar irradiance were continuously recorded during these observation timepoints. With more than 1300 recorded flower pot observations and 2882 recorded pollinators, this study provides a systematic investigation of the actual effects of radiofrequency electromagnetic fields (RF-EMF) on wild pollinator flower visitation.

2. Materials & methods

2.1. Experimental setup & RF-EMF exposure

The experiment was conducted from June to September 2023 and from May to September 2024 at the State Institute of Bee Research, University of Hohenheim, Germany. The aim was to investigate the specific short-term effects of electromagnetic fields (EMF) on the visitation rates and foraging behavior of pollinator individuals, rather than on the plants themselves. This means that, although the electromagnetic treatment (EMF) is applied to the plants, we created an experiment that investigated the direct effects on the pollinator visitation. Nevertheless, we required pollinator-attractive plant species to attract pollinators and allow us to quantify the effect of EMF exposure on their foraging behavior. Therefore, a total of 12 flowerpots were each planted with three individual plants, 6 with *Lavandula angustifolia* (N = 18) and 6 with *Salvia* species (N = 18), for a total of 36 observed plants. In order to ensure a defined irradiation of the flowerpots with their pollinator-attractive blossoms, the pots were placed on two separate sides

(north/south) at the optimal angle (0° and 180°) and distance (2 m) to the radiation source (Fig. 1), following the methods of Treder et al. (2023).

We used the identical technical system described in detail in Treder et al. (2023): The system was developed by experts at the Communications Engineering Lab (CEL) at the Karlsruhe Institute of Technology (KIT). It uses Software Defined Radio (SDR) technology to simulate realistic Wi-Fi radiation at 2.450 and 5.805 GHz (simultaneously; Table 1). Our radiation source is, in principle, technically equivalent to commercially used Wi-Fi devices (IEEE802.11a standard), but does not try to establish communication. The ability to adjust the percentage of emission time is an essential feature of experimental setups like ours. To control the transmission intensity, the percentage of time during which Wi-Fi packets are sent (duty cycle) and the duration of the period (ms) over which the duty cycle applies can be set. The total output power, packet rate, and radiation direction was consistent and quantifiable and a duty cycle of 100 % over a period of 100 ms was chosen (simulation of a heavily loaded access point). We recorded the chosen parameter setting and, consequently, the intensity of the radiation exposure over the entire experimental duration in both years.

As the focus of this study was the short-term impact of electromagnetic radiation on pollinator visitation rates, it was inappropriate to place unexposed flowerpots (controls) in close proximity to irradiated ones or alternately irradiate the separate sides of the technical setup. Pollinators move freely through the environment and under such a set-up they would be exposed to radiation on their flight path to the control plants. Control sites at greater distances are not comparable, given the high variability in pollinator visitation rates from site to site (e.g. in our experiment significant differences exist between the two sides of flowerpots; see Table 2). We thus sought to isolate the effect of EMF through a new experimental design involving repeated exposure and control trials conducted at close temporal intervals over time. By frequently alternating between short exposure and non-exposure periods every four days (Fig. 2; except for two periods with longer intervals), this design

Table 1
Equivalent Isotropic Radiated Power (EIRP), free space loss, electric field strength and magnetic field strength in relation to the used frequencies.

Frequency	EIRP (on each side)	Free space loss (α) at a distance of 2 m	Electric field strength at a distance of 2 m	Magnetic field strength at a distance of 2 m
2.450 GHz	22.5 dBm = 177.83 mW	α _{2.450 GHz} = 46.25 dB	1.16 V/m	3.06 mA/m
5.805 GHz	10.0 dBm = 10 mW	α _{5.805 GHz} = 53.74 dB	0.27 V/m	0.73 mA/m

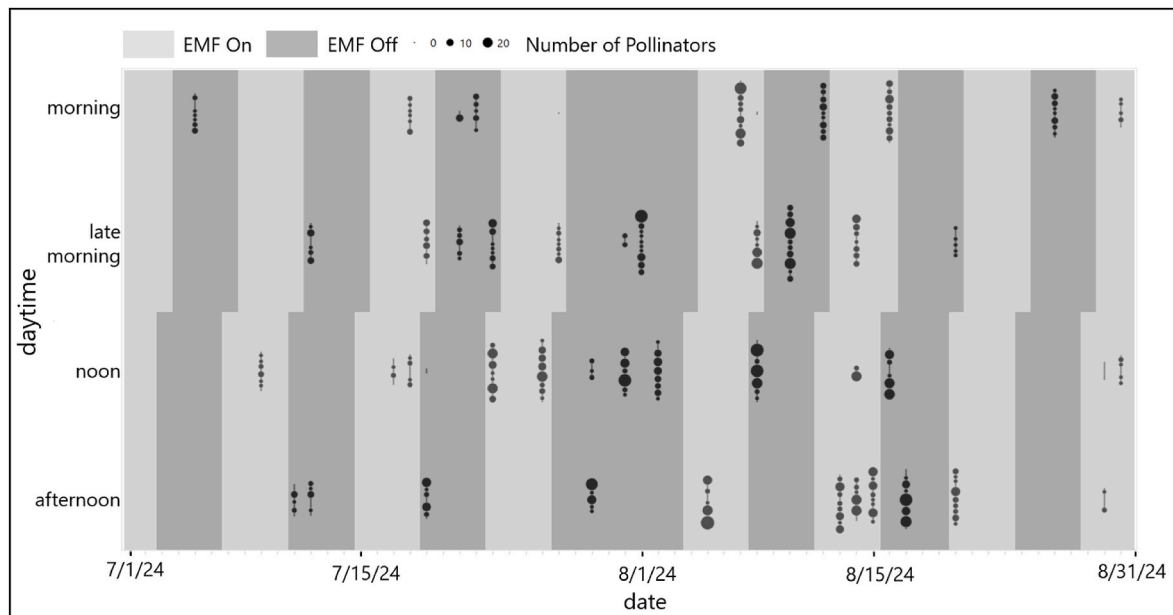


Fig. 2. Timeline of EMF exposure periods (on/off), observation dates, and number of pollinator visitations, shown as an example for the period from 1 July to 31 August 2024. Each dot represents a flowerpot observation, positioned by date and daytime (e.g., noon, afternoon). The size of points reflects the number of pollinators recorded per flowerpot observation (5 min). EMF exposure periods are indicated in the background shading (light gray = EMF on, dark gray = EMF off).

controls for confounding factors such as natural temporal variation. This switching occurred throughout the entire testing periods of the two years, resulting in a total of 21 time phases with EMF exposure and 23 without EMF exposure. To address the temporal and environmental effects even more precisely, we made several flower visitation observations within a single day, switching between exposed and unexposed settings. Key weather parameters were also recorded during the observations on the different days, to control for important day-dependent and confounding environmental factors over time (see 2.2).

2.2. Data collection

To determine the effects on the flower visitation rates of different pollinators, the insects were recorded on 92 days distributed from June to September 2023 and from May to September 2024 between 8:00 a.m. and 6:00 p.m. in the absence of precipitation and at temperatures between 15 and 35.5 °C. On each observation day, every flowerpot was observed as soon as it had at least one open flower. All plants in each pot were observed together. A total of 1307 flowerpot observations were made, with the order of the flowerpot observations randomly re-ordered at each individual observation window. All visiting pollinators were counted for exactly 5 min per flowerpot, following the methods of Marquardt et al. (2021) and Treder et al. (2024), only counting pollinators that were actively collecting pollen and/or nectar or were in contact with the reproductive parts of the flower. All counted flower-visitors were divided into the following groups: honey bees (*Apis mellifera*), bumble bees (*Bombus* spp.), other wild bees (not including *Bombus*), butterflies (Lepidoptera), hover flies (Diptera, Syrphidae) and all other pollinators (e.g. non-syrphid flies, wasps or beetles). If a pollinator left the flowerpot and potentially returned, it was recorded as a new visit, because repeated visits could not be reliably distinguished.

As the number of flowers, the temperature, the intensity of solar irradiance, the time of the day or the time of year can strongly influence pollinator foraging (Treder et al., 2024), these factors were always recorded during the observations. An ALMEMO® 2890-9 (Ahlsborn, Holzkirchen, Germany) data logger was used to record weather intervals of at least 1 min, recording temperature (°C) and global solar irradiance (W/m²) along with the exact time and date of the observation. The number of flowers per plant was recorded by counting the single flowers of *Salvia* as individual units, while the inflorescences of the *Lavandula* plants were also treated as single units. To avoid interfering with radiation fields, the observers turned off their smartphones and other technical devices or set them to airplane mode during the observations.

2.3. Statistical analysis

The flower visitation rates were analyzed using generalized linear mixed models (GLMM). The GLMMs used a negative binomial distribution, which is appropriate for the observed count data. To test the effects on the different pollinator groups, different dependent variables were selected, such as the number of total pollinators, honey bees, bumble bees, and other wild bees. We focused our analyses on these four categories, because they contain the largest number of recorded insects and thus allow us to conduct appropriate model estimations and draw robust conclusions.

2.3.1. Main models

Specifications of the models were kept identical, with plant name, number of flowers, the interaction effect between plant name and the number of flowers, temperature, and EMF radiation (off/on) as fixed factors. Since there are only two levels for the year (2023/2024) and sides (north/south), these were also considered fixed factors. Solar

irradiance was excluded as a fixed effect because it had no significant impact on visitation rates. The interaction between the pot number (nested in the years) and the month was included as a random factor to account for the dependency of the observations within flowerpots over time. The estimated variance for the random effect “daytime” was (near) zero. Therefore, this effect was not included in the final model. To account for the possible year-specific variation in the effect of EMF, we first included the random interaction between EMF (off/on) and year in the model. The estimated variance component was also (near) zero, indicating no substantial EMF effect variation between years. Consequently, this term was excluded from the final model. Including this interaction effect would also result in an overly conservative analyses, rendering such ecological experiments uninterpretable and severely limiting the detection of weaker effects. In contrast, excluding the variance component from the model results in a greater number of degrees of freedom (DFDen) for testing the independent variable “EMF”, enhancing the model’s ability to detect potential effects. Nonetheless, our prior comparisons of appropriate models and statistical approaches, together with our assessment of the data and the assumption of independence between potential EMF effects across observations (see Discussion), support the suitability of the main model. At the same time, we fundamentally acknowledge the limitations and statistical challenges inherent in such complex ecological experiments and data.

Random effect variance estimates of the interaction of “EMF x pot number”, “EMF x sides of the setup”, or “EMF x daytime” were also estimated (near) zero.

2.3.2. Additional conservative models

Nevertheless, to ensure a rigorous and comprehensive statistical comparison, we also fitted a more conservative model that included all fixed factors identically as before. In this model, however, the interaction of trial and EMF was specified as a random effect in addition to the interaction between the pot number (nested in the years) and the month. A trial is always defined as a period of time, that contains consecutive phases with and without exposure. Consequently, this model considers only a very small number of degrees of freedom (DFDen) for the EMF factor, potentially leading to an underestimation of its effect.

F-tests were used to test the effects of the fixed factors. All statistical analyses and result graphs were done in JMP Pro 18 (SAS Institute, Cary, USA).

3. Results

We recorded a total of 2882 flower-visitors, with 50.3 % of all flower visitations from honey bees ($n = 1450$), followed by 32.4 % from bumble bees ($n = 935$) during the two years of the study. Wild bees ($n = 234$) excluding *Bombus*, 8.1 %, hover flies ($n = 195$, 6.8 %), other pollinators ($n = 50$, 1.7 %), and butterflies ($n = 18$, 0.6 %) were much less common on our plants. Overall, due to the weather and normal annual fluctuations, we were able to record significantly more flower-visitors in 2023 with 1734 (60.2 %) than in 2024 with 1148 (39.8 %) (F-ratio = 30.672, $df = 1$, $p < 0.001$). Both selected plant genera (*Lavandula* and *Salvia*) were very attractive to flower-visitors and had long flowering periods throughout the two seasons. However, the *Lavandula* was visited significantly more often than the *Salvia* (F-ratio = 53.896, $df = 1$, $p < 0.001$; Fig. 3). While honey bees visited the *Lavandula* substantially more frequently, bumble bees and other wild bees showed a visitation preference for the *Salvia*.

The aim of this work was to investigate the effects of the tested EMF radiation on pollinator visitation. For the pollinators in total, a significant negative effect of EMF on flower visitation was found in the main model (GLMM, EMF[off-on]: 0.15, $p = 0.0099$). A closer look at the data shows that this effect is particularly evident for the group of bumble bees (GLMM, EMF[off-on]: 0.25, $p = 0.0029$), which were found significantly more often (increased by 28 %) on the flowers when the plants were not irradiated (Fig. 4, Table 2). In contrast, this effect was not found for the group of honey bees (GLMM, EMF[off-on]: $p > 0.05$) or other wild bees (excluding *Bombus*; GLMM, EMF[off-on]: $p > 0.05$). When the very conservative models were used, the effect could not be detected for the pollinator groups examined (GLMM, EMF [off-on]: $p > 0.05$). However, the direction of the effect remains the same.

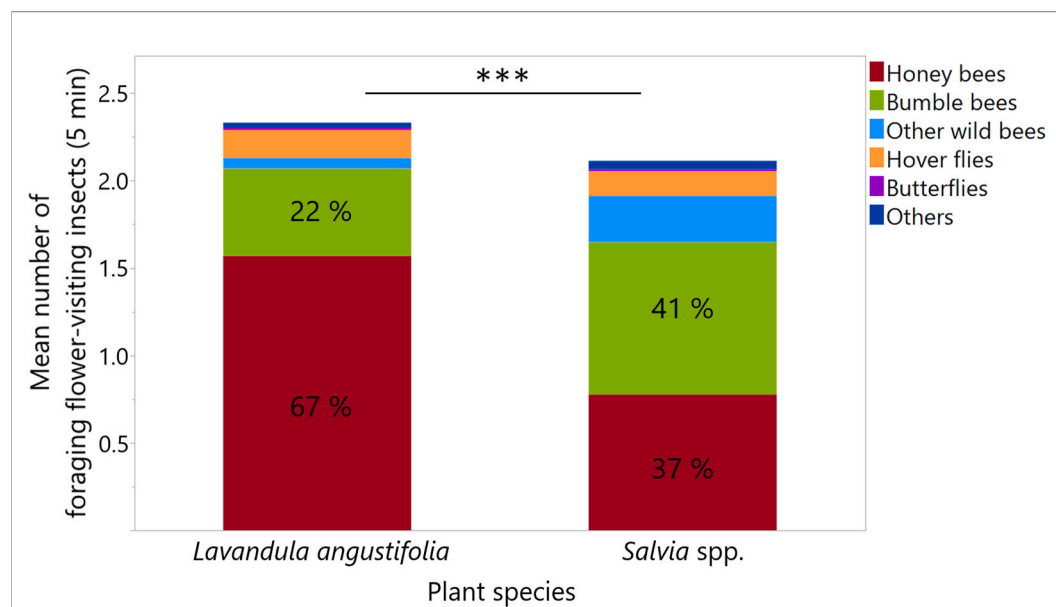


Fig. 3. Mean number of flower-visitors of the different pollinator groups (total pollinators: $n=2882$) on the plant species used. The plant species differ significantly in their total pollinator visitation rate (GLMM, *** $p < 0.001$).

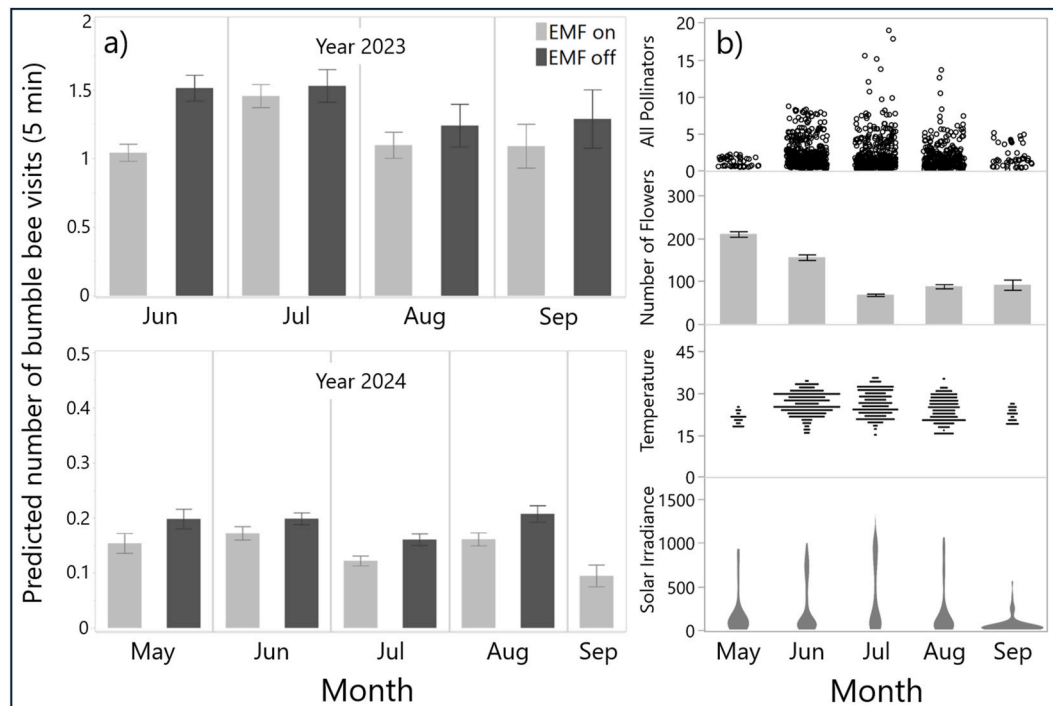


Fig. 4. EMF effect and other factors. a) Predicted number of bumble bee flower visits per observation window (based on the GLMM, main model) $\pm$ SE by month and year depending on the status of EMF irradiation (off vs. on) and b) the total number of all pollinators (GLMM, predicted), the mean number of the flowers $\pm$ SE, the temperature ($^{\circ}\text{C}$) values, and the solar irradiance (W/m^2) values per observation window by sampling month.

Table 2

Results of the GLMM (negative binomial (log), main model) for the flower visits of total pollinators, bumble bees, and honey bees. The table reports the estimates and p-values of the tested coefficients.

Pollinator Group	Coefficients	Estimate and p-value
Total	Intercept	-0.84 ($p = 0.0005$)
	EMF [off-on]	0.15 ($p = 0.0099$)
	Year [2023-2024]	0.80 ($p < 0.0001$)
	Side of the setup [north-south]	-1.05 ($p < 0.0001$)
	Temperature	0.06 ($p < 0.0001$)
	Plant name [Lavandula-Salvia]	1.60 ($p < 0.0001$)
	Number of flowers	0.00 ($p = 0.1635$)
	Plant name x Number of flowers	0.02 ($p < 0.0001$)
	Intercept	-2.24 ($p < 0.0001$)
Bombus	EMF [off-on]	0.25 ($p = 0.0029$)
	Year [2023-2024]	2.14 ($p < 0.0001$)
	Side of the setup [north-south]	-1.02 ($p < 0.0001$)
	Temperature	0.03 ($p < 0.0024$)
	Plant name [Lavandula-Salvia]	0.42 ($p = 0.2035$)
	Number of flowers	0.00 ($p = 0.5593$)
	Plant name x Number of flowers	0.01 ($p < 0.0001$)
	Intercept	-3.50 ($p < 0.0001$)
	EMF [off-on]	0.15 ($p = 0.1151$)
Apis mellifera	Year [2023-2024]	0.27 ($p = 0.2605$)
	Side of the setup [north-south]	-0.96 ($p < 0.0001$)
	Temperature	0.11 ($p < 0.0001$)
	Plant name [Lavandula-Salvia]	2.76 ($p < 0.0001$)
	Number of flowers	0.00 ($p = 0.0011$)
	Plant name x Number of flowers	0.03 ($p < 0.0001$)

4. Discussion

The use of electromagnetic fields to transmit information (Federal Office for Radiation Protection, 2024) is of enormous importance to humans and to technological progress. However, as the use of these fields increases (Neubauer et al., 2007), we must understand what

potential impacts they have on insects, especially on pollinators. Using a precise radiation source that produces a defined and realistic radiation in the range of 2.4 and 5.8 GHz (used by wireless devices, e.g. those with Wi-Fi or Bluetooth), we wanted to investigate the possible effects on flower-visiting insects.

Urban areas are important habitats for a variety of pollinators, including wild bees (Baldock et al., 2015; Wenzel et al., 2020), but this is exactly where communication technology and electromagnetic fields are heavily used (Joseph et al., 2012). To reproduce and rear offspring, but also to feed themselves, pollinators such as wild bees must forage on appropriate food resources for carbohydrate-rich nectar and protein-rich pollen (Westrich, 1996). Factors that interfere with this foraging behavior could negatively affect the foraging success of pollinators, for example by increasing foraging effort or reducing the attractiveness of plantings. In the case of EMF, it is conceivable that highly exposed areas could become less attractive to pollinators, which would increase their foraging distance and travel to find suitable non-irradiated food resources. We thus investigated the effects of EMF on foraging on highly attractive pollinator plants, *Lavandula angustifolia* and *Salvia* spp., by switching exposure in a 4-day rhythm between irradiated and not irradiated and documenting pollinator visitation rates over two separate test years. Beyond the technical difficulties, such experiments pose numerous methodological challenges. Particular attention must be paid to the elimination of confounding and environmental effects, the possibility to detect weak effects, and the definition of an appropriate unit of replication. Our experimental approach outlines a suitable design for detecting the weak effects of EMF on flower visitation rates of pollinators. This requires a large sample size and measurements taken over days and months to control for environmental variability. Currently it is not feasible to conduct such studies with their complex technical setups on a large scale across multiple sites. For research questions that require an analysis of treatment effects over time, it may be better to repeatedly

observe the same experimental unit across different trials, rather than to observe different units only a few times at multiple sites. This raises the question of the unit of replication. Such studies on the effects of EMF on flower visitation aimed to measure the effects on pollinators and their visitation rates, not on the plants themselves. The composition of pollinators varies from day to day, and each observational period involves a distinct group of individuals, each of which may respond differently and independently to EMF exposure. These biological replicates are thus mostly independent of each other, as it is highly unlikely we would measure the interaction of the same individual pollinators with the (EMF) treatment more than once during the very short observation periods each day. This is also supported by the fact that flower-visitor communities change over the season (Schmack and Egerer, 2023). Moreover, the treatment applied to pollinators on a given day does not influence the interaction between EMF and other pollinators on subsequent days. Such carry-over effects, which could induce relevant dependencies between observations, might be expected, for instance, if the treatment were to permanently and significantly alter the plants reward system or physiology. However, this is unlikely due to the study design with deliberately chosen short alternating exposure phases and the continuous supply of new flowers. Additionally, it is controlled for by the within-day structure of several observations under exposure and non-exposure. Earlier studies that assessed direct treatment effects on pollinator visitation (of factors such as wind or electric fields) treated pollinator observations collected on different days at the same sites or plots as somewhat independent (Hennessy et al., 2021; Mallinson et al., 2025). These methodological aspects and their statistical interpretation, as well as how conservatively they should be addressed, are crucial considerations for future research on the effects of EMF on pollinator visitation in ecological contexts.

Although we found no effect on the visitation frequency of honey bees, we found that bumble bees reduce their visits when plants were irradiated. This suggests that bumble bees may avoid plants in urban areas, if those plants are exposed to widely used Wi-Fi frequencies. Such avoidance reduces the availability of food resources and may force them to switch to other sources of nectar and pollen, which could require greater foraging efforts and thus additional nutritional stress for these pollinators. Simultaneously, this may also negatively affect the plants by reducing the rates at which they are pollinated.

The current literature on the impacts of EMF on pollinator behavior is sparse, and to date there appear to be no other papers on floral visitation rates by wild bees and bumble bees. A correlative study on honey bees using extant power lines and towers for energy transmission or cell phone infrastructure showed a significant decrease in honey bee floral visits to California poppies. They compared foraging rates between exposed and unexposed sites on three days (Molina-Montenegro et al., 2023). As stated above, correlative studies are difficult to interpret conclusively, as many other factors such as temperature and location strongly influence pollinator behavior. Studies using other model organisms, frequencies, and intensities are not directly comparable, so comparisons are limited.

Whilst our study shows an impact of EMF exposure on flower visitation rates by bumble bees, the exact mechanism behind this effect is not yet clear. However, based on the sensory modalities afforded to bees, it is possible to generate some hypotheses. EMFs comprise a magnetic field component and an electric field component, and therefore the senses of magnetoreception and electroreception are prime candidates for future mechanistic exploration. Bees are capable of both magnetoreception (Hsu and Li, 1994; Lindauer and Martin, 1968; Wajnberg et al., 2010) and electroreception (Clarke et al., 2013; England and Robert, 2022; Sutton et al., 2016). Magnetoreception is thought to be used by honey bees for orientation during the waggle dance and navigation when foraging (Collett and Baron, 1994; Lindauer and Martin, 1968; Schmitt and Esch, 1993; Wajnberg et al., 2010), and behavioral and anatomical evidence point to its navigational use by bumble bees also (Chittka et al., 1999; Jandacka et al., 2015), though this remains to

be explicitly tested. The use of magnetoreception by bees for navigation may explain the previous finding that the homing ability of honey bees is significantly hindered after long-term exposure to RF-EMFs (Treder et al., 2023), but the negative effects of RF-EMF exposure on bumble bee flower visitation rates described here cannot be directly explained by this. Electroreception, on the other hand, has been shown to allow bumble bees to detect the static electric field around flowers, and use this information to make foraging decisions, with the strength and structure of the floral electric field possibly indicating flower identity and recent visitation (thus potentially diminished nectar) (Clarke et al., 2013; Clarke et al., 2017; England and Robert, 2022; Sutton et al., 2016). It is conceivable therefore that such bee-flower electrical interactions are being interfered with by RF-EMF exposure. Electroreception is also known in honey bees, but so far only in the context of receiving the waggle dance communication (Greggers et al., 2013). Recent research has shown that the static electric fields emitted by powerlines also may reduce floral visitation by honey bees (Mallinson et al., 2025). However, if disruption of electroreception during foraging is the mechanism by which RF-EMFs are influencing pollinator visitation behavior, and if bumble bees rely more directly and strongly on this, it may explain our finding that only the visitation number of bumble bees decline significantly under RF-EMF exposure. Beyond this, electroreception in air, and electrostatic forces more generally, are beginning to be understood as a major ecological driver (England and Robert, 2022), having an influence in the detection of predators by caterpillars (England and Robert, 2024b), hummingbirds by flower mites (García-Robledo et al., 2025), and storms by spiders (Morley and Robert, 2018) as well as the attraction of parasites by their hosts (England et al., 2023) and pollen by flower visitors (Badger et al., 2015; Clarke et al., 2017; England and Robert, 2024a). Whether RF-EMF exposure may also negatively impact these other ecological interactions warrants urgent investigation. However, it is very important to note that whilst interference with the senses of magnetoreception and/or electroreception could be the mechanism by which RF-EMF hinder floral visitation rates, the specific mechanism by which this could occur is not immediately obvious. Although RF-EMFs are indeed comprised of magnetic and electric fields, the frequency of these fields is on the order of millions of Hz. This is in stark contrast to the largely static electric and magnetic fields that bees are known to be able to detect. It is therefore more likely that bees do not directly detect these higher-frequency EMFs and become disturbed by them, but that the EMFs influence their sensory systems indirectly. For example, they may change or alter the electromagnetic conditions of the bees' bodies or environment, perhaps rendering magnetoreception or electroreception unreliable or dysfunctional, though this remains to be tested explicitly.

In our work, we found that electromagnetic fields can indeed influence foraging bumble bees and reduce their flower visitation rates. Urban areas are important habitats for pollinators and the electromagnetic fields will continue to play a large and important role in the human environment. Therefore, future studies are necessary and should also aim to elucidate the precise biophysical mechanisms by which RF-EMFs could impact the sensory ecology of these bees and other pollinators, so that we can derive practical, realistic protection measures, e.g. in the form of exposure-reducing measures or the adjustment of radiation frequencies.

CRedit authorship contribution statement

Manuel Treder: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael Glück:** Writing – review & editing, Methodology, Investigation, Data curation. **Sam J. England:** Writing – review & editing, Writing – original draft. **Kirsten S. Traynor:** Writing – review & editing, Visualization, Validation, Supervision, Resources.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. Open Access funding enabled and organized by Project DEAL.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used generative AI or AI-assisted technologies (DeepL/ChatGPT) on a limited basis for translation and to improve the readability and language. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Marcus Müller, Laurent Schmalen and David Winter from the Communications Engineering Lab (CEL) at the Karlsruhe Institute of Technology for developing and providing the technical equipment. We would also like to thank the colleagues at the State Horticultural College and Research Institute (LVG) Heidelberg for providing the plants. Additionally, we would like to thank Filippo Capezone of the Biostatistics Unit at the Institute of Crop Science, University of Hohenheim for his detailed statistical advice. Many thanks also to all the employees of the State Institute of Bee Research, Hohenheim, Germany, who were involved in this experiment, especially to Mareike Wagner, Carmen Wagner and Yoshua Titus, who did much of the data collection.

Data availability

Data will be made available on request.

References

- Badger, M., Ortega-Jimenez, V.M., Rabenau, L. von, Smiley, A., Dudley, R., 2015. Electrostatic charge on flying hummingbirds and its potential role in pollination. *PLoS One* 10 (9), e0138003.
- Baldock, K.C.R., Goddard, M.A., Hicks, D.M., Kunin, W.E., Mitschunas, N., Osgathorpe, L. M., Potts, S.G., Robertson, K.M., Scott, A.V., Stone, G.N., Vaughan, I.P., Memmott, J., 2015. Where is the UK's pollinator biodiversity? The importance of urban areas for flower-visiting insects. *Proc. R. Soc. A B* 282 (1803), 20142849.
- Bottero, I., Dominik, C., Schweiger, O., Albrecht, M., Attridge, E., Brown, M.J.F., Cini, E., Costa, C., La Rúa, P. de, Miranda, J.R. de, Di Prisco, G., Dzul Uuh, D., Hodge, S., Ivarsson, K., Knauer, A.C., Klein, A.-M., Mänd, M., Martínez-López, V., Medrzycki, P., Pereira-Peixoto, H., Potts, S., Raimets, R., Rundlöf, M., Schwarz, J.M., Senapathi, D., Tamburini, G., Talaván, E.T., Stout, J.C., 2023. Impact of landscape configuration and composition on pollinator communities across different European biogeographic regions. *Front. Ecol. Evol.* 11.
- Chittka, L., Williams, N.M., Rasmussen, H., Thomson, J.D., 1999. Navigation without vision: bumblebee orientation in complete darkness. *Proc. R. Soc. A B* 266 (1414), 45–50.
- Clarke, D., Morley, E., Robert, D., 2017. The bee, the flower, and the electric field: electric ecology and aerial electroreception. *Z. Vergl. Physiol.* 203 (9), 737–748.
- Clarke, D., Whitney, H., Sutton, G., Robert, D., 2013. Detection and learning of floral electric fields by bumblebees. *Science (New York, N.Y.)* 340 (6128), 66–69.
- Collett, T.S., Baron, J., 1994. Biological compasses and the coordinate frame of landmark memories in honeybees. *Nature* 368 (6467), 137–140.
- England, S.J., Lihou, K., Robert, D., 2023. Static electricity passively attracts ticks onto hosts. *Curr. Biol. : CB* 33 (14), 3041–3047.e4.
- England, S.J., Robert, D., 2022. The ecology of electricity and electroreception. *Biol. Rev. Camb. Phil. Soc.* 97 (1), 383–413.
- England, S.J., Robert, D., 2024a. Electrostatic pollination by butterflies and moths. *J. R. Soc., Interface* 21 (216), 20240156.
- England, S.J., Robert, D., 2024b. Prey can detect predators via electroreception in air. *Proc. Natl. Acad. Sci. USA* 121 (23), e2322674121.
- Federal Office for Radiation Protection, 2024. Elektromagnetische felder: was sind elektromagnetische Felder? Bundesamt für Strahlenschutz. https://www.bfs.de/DE/themen/emf/einfuehrung/einfuehrung_node.html. (Accessed 8 July 2024).
- García-Robledo, C., Dierick, D., Manser, K., 2025. Electric transportation and electroreception in hummingbird flower mites. *Proc. Natl. Acad. Sci. USA* 122 (5), e2419214122.
- Greggers, U., Koch, G., Schmidt, V., Dürr, A., Floriou-Servou, A., Piepenbrock, D., Göpfert, M.C., Menzel, R., 2013. Reception and learning of electric fields in bees. *Proc. R. Soc. A B* 280 (1759), 20130528.
- Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T., Goulson, D., Kroon, H. de, 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS One* 12 (10), e0185809.
- Hennessy, G., Harris, C., Pirot, L., Lefter, A., Goulson, D., Ratnieks, F.L., 2021. Wind slows play: increasing wind speed reduces flower visiting rate in honey bees. *Anim. Behav.* 178, 87–93.
- Hsu, C.Y., Li, C.W., 1994. Magnetoreception in honeybees. *Science (New York, N.Y.)* 265 (5168), 95–97.
- International Telecommunication Union, 2021. Facts and Figures: Measuring Digital Development, 2021.
- Jandacka, P., Kasparova, B., Jiraskova, Y., Dedkova, K., Mamulova-Kutlakova, K., Kukutschova, J., 2015. Iron-based granules in body of bumblebees. *Biometals : an international journal on the role of metal ions in biology, biochemistry, and medicine* 28 (1), 89–99.
- Joseph, W., Verloock, L., Goeminne, F., Vermeeren, G., Martens, L., 2012. Assessment of RF exposures from emerging wireless communication technologies in different environments. *Health Phys.* 102 (2), 161–172.
- Lindauer, M., Martin, H., 1968. Die Schwereorientierung der Bienen unter dem Einfluß des Erdmagnetfeldes. *Z. Vergl. Physiol.* 60 (3), 219–243.
- Mallinson, V.J., Woodburn, F.A., O'Reilly, L.J., 2025. Weak anthropogenic electric fields affect honeybee foraging. *iScience*, 112550.
- Marquardt, M., Kienbaum, L., Kretschmer, L.A., Penell, A., Schweikert, K., Ruttensperger, U., Rosenkranz, P., 2021. Evaluation of the importance of ornamental plants for pollinators in urban and suburban areas in Stuttgart, Germany. *Urban Ecosyst.* 24 (4), 811–825.
- McCall, C., Primack, R.B., 1992. Influence of flower characteristics, weather, time of day, and season on insect visitation rates in three plant communities. *Am. J. Bot.* 79 (4), 434–442.
- Molina-Montenegro, M.A., Acuña-Rodríguez, I.S., Ballesteros, G.I., Baldeomar, M., Torres-Díaz, C., Broitman, B.R., Vázquez, D.P., 2023. Electromagnetic fields disrupt the pollination service by honeybees. *Sci. Adv.* 9 (19), eadh1455.
- Morley, E.L., Robert, D., 2018. Electric fields elicit ballooning in spiders. *Curr. Biol. : CB* 28 (14), 2324–2330.e2.
- Neubauer, G., Feychting, M., Hamnerius, Y., Kheifets, L., Kuster, N., Ruiz, I., Schüz, J., Überbacher, R., Wiart, J., Rösli, M., 2007. Feasibility of future epidemiological studies on possible health effects of mobile phone base stations. *Bioelectromagnetics* 28 (3), 224–230.
- Odemer, R., Odemer, F., 2019. Effects of radiofrequency electromagnetic radiation (RF-EMF) on honey bee queen development and mating success. *Sci. Total Environ.* 661, 553–562.
- Schmack, J.M., Egerer, M., 2023. Floral richness and seasonality influences bee and non-bee flower interactions in urban community gardens. *Urban Ecosyst.* 26 (4), 1099–1112.
- Schmitt, D.E., Esch, H.E., 1993. Magnetic orientation of honeybees in the laboratory. *Die Naturwissenschaften* 80 (1), 41–43.
- Shepherd, S., Hollands, G., Godley, V.C., Sharkh, S.M., Jackson, C.W., Newland, P.L., 2019. Increased aggression and reduced aversive learning in honey bees exposed to extremely low frequency electromagnetic fields. *PLoS One* 14 (10), e0223614.
- Shepherd, S., Lima, M.A.P., Oliveira, E.E., Sharkh, S.M., Jackson, C.W., Newland, P.L., 2018. Extremely low frequency electromagnetic fields impair the cognitive and motor abilities of honey bees. *Sci. Rep.* 8 (1), 7932.
- Sutton, G.P., Clarke, D., Morley, E.L., Robert, D., 2016. Mechanosensory hairs in bumblebees (*Bombus terrestris*) detect weak electric fields. *Proc. Natl. Acad. Sci. USA* 113 (26), 7261–7265.
- Thill, A., Cammaerts, M.-C., Balmori, A., 2023. Biological effects of electromagnetic fields on insects: a systematic review and meta-analysis. *Rev. Environ. Health.*
- Treder, M., Joedecke, V., Schweikert, K., Rosenkranz, P., Ruttensperger, U., Traynor, K., 2024. Vertical greening systems serve as effective means to promote pollinators: experimental comparison of vertical and horizontal plantings. *Landsc. Urban Plann.* 243, 104951.
- Treder, M., Müller, M., Fellner, L., Traynor, K., Rosenkranz, P., 2023. Defined exposure of honey bee colonies to simulated radiofrequency electromagnetic fields (RF-EMF): negative effects on the homing ability, but not on brood development or longevity. *Sci. Total Environ.* 896, 165211.
- Vanbergen, A.J., Potts, S.G., Vian, A., Malkemper, E.P., Young, J., Tscheulin, T., 2019. Risk to pollinators from anthropogenic electro-magnetic radiation (EMR): evidence and knowledge gaps. *Sci. Total Environ.* 695, 133833.
- Vilić, M., Tlak Gajger, I., Tucak, P., Štambuk, A., Šrut, M., Klobučar, G., Malarić, K., Žura Žaja, I., Pavelić, A., Manger, M., Tkalec, M., 2017. Effects of short-term exposure to

- mobile phone radiofrequency (900 MHz) on the oxidative response and genotoxicity in honey bee larvae. *J. Apicult. Res.* 56 (4), 430–438.
- Wajnberg, E., Acosta-Avalos, D., Alves, O.C., Oliveira, J.F. de, Srygley, R.B., Esquivel, D. M.S., 2010. Magnetoreception in eusocial insects: an update. *J. R. Soc., Interface* 7 (Suppl. 2), S207–S225 (Suppl 2).
- Westrich, P., 1996. Habitat requirements of central European bees and the problems of partial habitats. In: Matheson, Andrew (Ed.), *The Conservation of Bees*. Linnean Society symposium series. no. 18, pp. 1–16.
- Wenzel, A., Grass, I., Belavadi, V.V., Tschardt, T., 2020. How urbanization is driving pollinator diversity and pollination – a systematic review. *Biol. Conserv.* 241, 108321.