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CONSERVATION

Disruptive effects of brief radiofrequency noise exposure on migratory bat navigation

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How anthropogenic electromagnetic noise can affect living systems is a poorly understood impact of an increasingly urbanized natural environment, especially when occurring in a sublethal manner. In this study, we investigated impacts of weak-broadband radiofrequency (RF) fields on animal behavior. We exposed migratory soprano pipistrelle bats (*Pipistrellus pygmaeus*) to 0.01- to 300-megahertz RF fields and then tested their orientation later in the night. Whereas control bats oriented normally, bats exposed to RF noise exhibited random departure flight orientation, suggesting disruptive effects lasting beyond immediate exposure. These findings suggest that electromagnetic pollution has the potential to have a greater effect on animal behavior than previously assumed.

The ongoing expansion of anthropogenic electromagnetic fields, such as those emitted from household electronics and radio antennas, raises questions of potentially adverse effects on human health around the world (*1*). Human protection from so-called electrosmog is subject to medical research and covered by the Guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) adopted by the World Health Organization (*2*, *3*). Yet there remains a demand for research on the consequences of electromagnetic fields for biodiversity. In particular, the ecological consequences of anthropogenic electromagnetic noise for wildlife moving through human-dominated landscapes, such as seasonal migrants, are virtually unknown (*4*–*6*). To date, investigations into such effects have been mostly concentrated on migratory songbirds. In passerines, it has been demonstrated that their light-dependent magnetic compass is disrupted by low-intensity, weak-broadband signals in the 50-to-85-MHz range, which is more prevalent in urban environments than in rural areas but is also produced by infrastructure such as radio towers and power lines (*7*–*11*). Notably, these effects are seen at exposure levels below current ICNIRP reference levels for the general public (*2*, *3*). In bird magnetoreception research, the disruption of orientation only when presented with specific radiofrequencies (RFs) has been argued to be diagnostic of a magnetosensitive cryptochrome (CRY4) (*8*, *10*, *12*). However, the focus on birds leaves a critical knowledge gap regarding sensitivity in other organisms for which magnetoreception might be based on a different sensory mechanism (*13*–*16*). For example, it is not clear that any mammal has an analog to CRY4 (*17*) nor a similar magnetic compass based on the principle of radical pair formation (*10*, *18*), which is sensitive to RF fields. One study reported that constant RF sweeps (0.9 to 5 MHz) alter nest-building orientation in wood mice, *Apodemus sylvaticus* (*19*). However, nonspecific cognitive (*20*, *21*) or stress (*22*, *23*) impairments after experimental electromagnetic field treatments, such as those seen in rats or honeybees, cannot be ruled out. It is therefore important to understand whether, and how, wild mammals respond to electromagnetic exposure that is considered safe for humans by the ICNIRP guidelines. Effects of artificial electromagnetic fields on both humans and animals have so far been investigated primarily under immediate exposure (*7*, *24*), and it remains to be established whether exposure could cause any behavioral carryover effects after the noise has ceased or the source is left behind.

Bats are an ideal mammalian comparative model for such research because they share many similarities to small night-migrating songbirds in terms of the distances they move (*25*) and the ecological challenges they face (*26*). Bats have been shown to detect the Earth's magnetic field (*27*), although it remains unclear how they sense it and how they use it to orientate in flight in comparison with birds. Recently however, we found soprano pipistrelle bats, *Pipistrellus pygmaeus*, to be sensitive to the angle of magnetic inclination (*28*), a characteristic feature of the magnetic compass sense in birds (*29*).

Soprano pipistrelles migrating toward their wintering grounds are known to calibrate environmental cues at sunset for navigation later at night (*28*, *30*). We took advantage of this behavior to test whether electromagnetic exposure leads to long-term disruption of the bats' natural orientation by exposing them to low-intensity 0- to 300-MHz RF constant broadband noise with a peak between 0 and 10 MHz (Fig. 1) and releasing them later the same night in three diagnostic tests based on theoretically predicted time dependence of radical pair-based magnetoreception.

We compared our data from bat release trials during four migration seasons with occasional orientation observations of freely moving bats, as well as birds, at the site. This was to check that the orientation of bats recorded in the release trials matched with the patterns of movement being observed along the shore at the research station. Bidirectional or northerly movements of bats have been occasionally observed along the shore, and this has been reflected in the bat orientation measured in the circular release box (*28*, *31*, *32*).

We hypothesized that if migratory bats have a radical pair-based magnetic sense that is calibrated at sunset, they would be disturbed by the presence of weak-broadband signals at sunset when they calibrate their orientation system. Likewise, exposure to signals during orientation

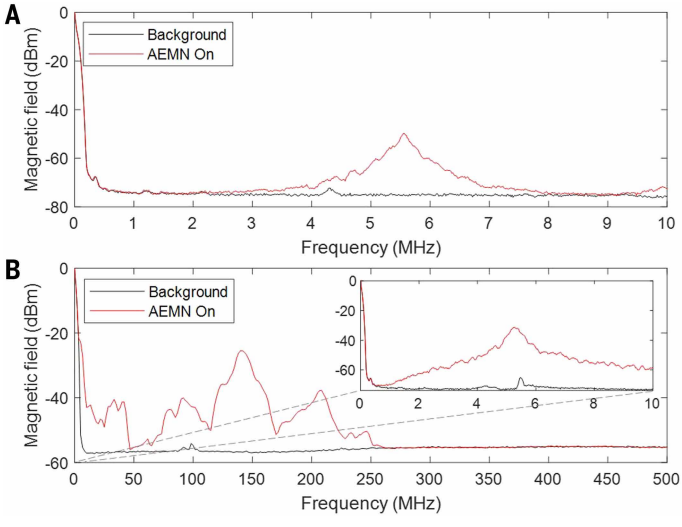


Fig. 1. Weak-broadband RFs add urban spectrum characteristics to the electromagnetic background noise found at the Baltic Sea coast. Traces show the magnetic component of the artificially generated electromagnetic noise (AEMN; red) compared with the background magnetic field (black). The field produced at the experimental site (**A**) elevated the magnetic field strength within a range that is common for anthropogenic environments. The spectrum is also shown between 0 and 500 MHz, measured in the laboratory (**B**). The inset in (B) highlights the same frequency band shown in (A), demonstrating that peak intensities at the field site closely match those seen in the laboratory.

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behavior at takeoff would disturb the bats in the use of a naturally calibrated magnetic compass. By contrast, exposure during the postsunset period, after an undisturbed period of calibration, would not affect them any further if they were not also exposed during takeoff. Consequently, we expected bats in the sunset and takeoff groups to have an impaired sense of orientation and to take off in random directions later at night. Conversely, we predicted that bats of the postsunset group would orient in a direction similar to that of the control animals on the basis of their unaltered access to environmental cues during the critical period at sunset and during takeoff later at night.

Orientation of controls

At our Baltic Sea coast site, our treatments elevated the local RF spectrum toward an urban-like profile compared with ambient electromagnetic background noise, which was relatively low (Fig. 1). In the first year of our study, bats of the control group took off in a northern direction (Fig. 2B); in years two, three, and four, the mean heading direction was southeast, southwest, and south, respectively (Figs. 2C, 3B, and 4A).

Exposure during the sunset calibration period

In both seasons, bats that watched the natural sunset under exposure later took off in random directions with their heading distributions not different from a uniform circular distribution (Fig. 2, D and E, and table S1).

Exposure after the sunset calibration period

A further experiment, in which bats were exposed only after the sunset period, was required to determine whether the disruptive effect seen in the previous years was caused by interference in the calibration of the magnetic compass. In this follow-on experiment, in contrast to our hypothesis, bats did not show oriented takeoff behavior after experiencing sunset under natural geomagnetic field conditions, followed by 30-min exposure, and then being released within 2 to 6 hours after the exposure ended, all within the same night (postsunset; Fig. 3C). Their headings were indistinguishable from a uniform distribution (see also table S1), in contrast to the control that resembled a symmetric modified unimodal distribution.

Exposure at night during migratory takeoff

Bats of the control that watched the natural sunset took off in a southern direction (Fig. 4A), whereas bats that were exposed at release took off in random directions with their heading distributions not different from a uniform circular distribution (Fig. 4B).

We observed a marked difference between the combined control and treatment groups across all years of the study (Mann-Whitney U test = 12.17, $P = 0.002$; concentration test $P = 0.01$; bootstrap $P = 0.01$; fig. S4), revealing a consistent and overall disorienting treatment effect on bats regardless of the timing of exposure.

Our experiments show that electromagnetic noise exposure disrupts the orientation of bats several hours beyond the exposure period. This raises critical implications and numerous questions. Our results suggest that a carryover effect of weak-broadband RF noise may play a role in movement behavior and navigational decision-making in animals (*4*, *33*). Theory suggests that a light-dependent magnetic compass sense is sensitive to immediate exposure to RF fields (*18*), which is supported by experimental work on birds. A carryover effect is not necessarily predicted owing to the short lifetime of radical pairs forming in the candidate magnetosensitive cryptochrome, but to date no study on the effect of RF fields in birds has attempted to test the effect of exposure in the way that we have (*34*). The fact that orientation is disrupted regardless of whether the exposure was during the crucial calibration period or after suggests that our result is an interaction between the effect on the magnetoreceptor and the behavioral interpretation of the effect subsequently. A previous finding in turtles, which were tested not in a navigational but a magnetic alignment assay, suggested that RF-field exposure either immediately before, during, or both immediately before and during testing could change the way animals interpret magnetic cues (*35*). The carryover effect that we observed here would not be predicted by the current models for how long specific RF fields affect magnetoreception pathways (*9*, *12*, *19*, *35*). Therefore, our discovery highlights the gap between predictions from quantum mechanics and animal behavior.

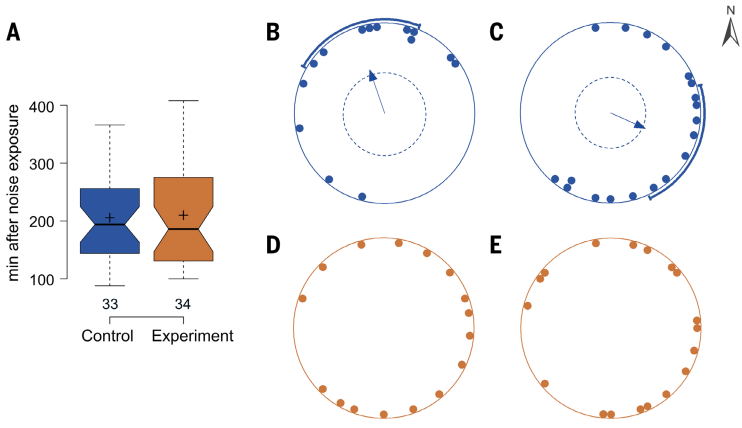


Fig. 2. Artificially produced broadband electromagnetic noise elicits a long-lasting negative effect on the ability of bats to take up a migratory orientation. The first release commenced 80 min after the end of the treatment at sunset (**A**). Median release times were 194 min for the controls and 186 min for the experimental group; the plus signs illustrate the means. The last bat was released 408 min after the treatment. These timings provide the temporal context for the observed orientation patterns in the other panels, where each point indicates the takeoff direction of a bat released in the natural magnetic field, with all other environmental cues obscured. (**B**) Heading direction of controls in our first season was significantly oriented toward north-northwest (mean vector orientation $\mu = 340° \pm 41°$, $P = 0.024$, vector length $r = 0.509$, $Z = 3.623$, $n = 14$; Rayleigh test). (**C**) In the following season with more favorable weather further down the coastline, directional choices of our controls were significantly toward east-southeast ($\mu = 114° \pm 41°$, $P = 0.032$, $r = 0.421$, $Z = 3.78$, $n = 19$). Both headings resembled the migratory behavior observed in freely flying bats in these seasons. (**D** and **E**) By contrast, when exposed to electromagnetic noise during their compass calibration period at sunset, bats of both seasons oriented in random directions; in (D), exposure at sunset 2021: $\mu = 104°$, $P = 0.602$, $r = 0.18$, $Z = 0.52$, $n = 16$; in (E), exposure at sunset 2022: $\mu = 94°$, $P = 0.451$, $r = 0.212$, $Z = 0.811$, $n = 18$. The arrows represent mean vectors with their lengths corresponding to the vector length, r, for significantly oriented groups. Dashed circles indicate the minimum length needed to be found significantly unimodally oriented ($P < 0.05$) according to a Rayleigh test. Solid lines outside of the plots represent the 95% confidence interval limits.

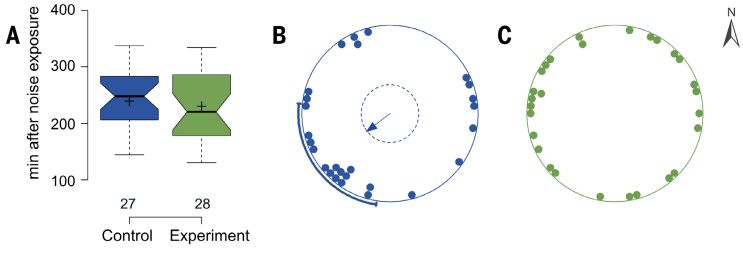


Fig. 3. Weak broadband RF exposure after sunset also disrupts migratory bat orientation after a noise-free sunset calibration period. The first release commenced 130 min after the end of the treatment (**A**). Median release times were 247 min for the controls and 219 min for the experimental group; the plus signs illustrate the means. The last bat was released 336 min after the treatment. (**B**) In contrast to control bats that oriented south-southwest ($233° \pm 44°$, $P = 0.044$, $r = 0.339$, $Z = 3.097$, $n = 27$), (**C**) bats that were released >2 hours after a 30-min electromagnetic noise exposure headed in random directions (exposure postsunset: $\mu = 305°$, $P = 0.531$, $r = 0.151$, $Z = 0.64$, $n = 28$).

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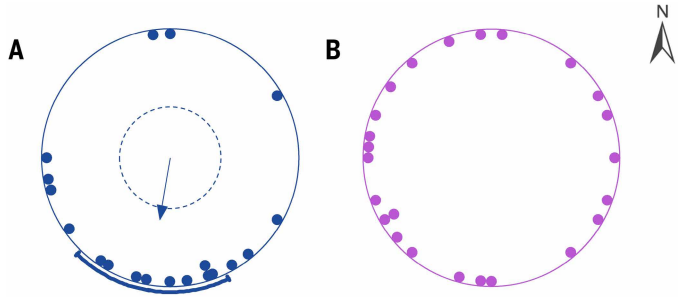


Fig. 4. Artificially produced broadband electromagnetic noise elicits an immediate negative effect on the ability of bats to take up migratory orientation at night. (**A**) Heading direction of controls significantly oriented southward ($\mu = 189° \pm 35°$, $P = 0.009$, $r = 0.487$, $Z = 4.501$, $n = 19$) resembled the migratory behavior observed in freely flying bats at the site. (**B**) By contrast, bats exposed to electromagnetic noise for release oriented in random directions (exposure during takeoff: $\mu = 258°$, $P = 0.461$, $r = 0.181$, $Z = 0.783$, $n = 24$).

The key to understanding these effects on ecological phenomena, such as long-distance animal movements in general, could come from a focus on real-world frequency ranges (*1*). This could help to reveal whether omnipresent electromagnetic pollution contributes to observed disappearances of animal migrations (*36*, *37*). At least for bats, exposure effects are virtually unexplored but could play a role in some phenomena, such as so-called invasions by pipistrelle bats that have been observed in European cities more regularly since the late 20th century (*38*). Because there is a relative lack of knowledge on how mammals sense the magnetic field, it is unclear whether its components differ appreciably from the avian magnetic sense in this regard and whether the same predictions on light-dependent magnetoreception would apply (*17*, *39*). Irrespective of the model animal, it therefore remains to be seen whether electromagnetic exposure–induced carryover effects are functionally linked to magnetoreception. It is also possible that when exposed to both natural (*40*) as well as anthropogenic electromagnetic noise, stress could have affected the bat's cognitive long-term functions, such as attention and memory (*41*), contributing to carryover effects. In this situation, RF field–induced interference to bats' sensory input would cause confusion about the reliability of the geomagnetic field and affect later flight behavior. It should be noted that we tested migratory bats in a cue-deprived flight room, i.e., without further access to other cues such as stars or the natural soundscape. Thus it may be that additional cues in a natural setting mitigate RF-induced disorientation (*42*).

Human-induced electromagnetic spillover into the environment may act as a stressor for wildlife, with effects extending beyond immediate exposure. We show a reproducible carryover effect of anthropogenic electromagnetic noise on bat orientation. Regardless of the specific reason for the observed carryover effect, the potential ecological consequences of the disruption shown here are concerning because current exposure standards pertain exclusively to humans, leaving wildlife vulnerable even within the confines of these guidelines. The widely anticipated increase of electromagnetic pollution as a consequence of urbanization trends and global proliferation of wireless technology may further add to the effects of anthropogenic climate change and land conversion by disrupting migratory movements of wildlife.

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SUPPLEMENTARY MATERIALS

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Materials and Methods; Figs. S1 to S7; Table S1; References (*44*–*49*); Data S1 and S2; Reproducibility Checklist

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Editor's summary

Radiofrequency, or electromagnetic, noise naturally occurs in the atmosphere, but it has increased substantially due to human activities, being produced by electronics, power lines, and even LED lights. The impacts of such noise on wildlife and humans is often debated and is yet to be understood. Lindecke *et al*. looked at the impacts of relatively weak broadband radiofrequency fields on migratory soprano pipistrelle bats and found that it disrupted their orientation even hours after exposure (see the Perspective by Balmori and Balmori-de la Puente). Although the disruptive mechanism of the noise remains to be characterized, these results suggest that the ever-present din of our devices may be having a bigger effect than was previously thought. —Sacha Vignieri

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