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Bat Visual Systems and Wind Energy

Introduction

Anthropogenic changes to the landscape can introduce novel stimuli to the environment that can increase risk for animals, whether or not the animals detect the stimuli. When animals detect anthropogenic stimuli, these stimuli may act as sensory pollutants—human-caused change to the environment that interferes with how animals detect, assess, and/or respond to information—that can mask important natural cues; divert attention away from important natural cues; mislead animals by resembling natural cues, resulting in maladaptive behavioral responses; or even result in animal disorientation (Van Doren et al. 2017; Dominoni et al. 2020). Anthropogenic stimuli outside the range of an animal's perception (e.g., outside of visual or auditory range) go undetected and may result in animals being exposed to risk without being capable of assessing or responding appropriately (Smith et al. 2021).

Certain species of bats are disproportionately killed by collisions with wind turbines compared to other taxa. Observational studies document bats approaching, circling, and/or lingering near wind turbines for extended periods, suggesting that they are attracted to wind turbines (Horn et al. 2008; Goldenberg et al. 2021). Although there are several hypotheses for why bats might be attracted to wind turbines or wind farms (Cryan and Barclay 2009), the mechanism(s) of attraction is currently unknown. Attraction may result from maladaptive responses (or non-responses) to wind turbine visual stimuli. Bats can visually detect tree-sized objects at distances exceeding 2 kilometers under favorable low-light conditions, far beyond the range of echolocation (<100 meters) (Boonman et al. 2013). The necessity of vision for long-distance navigation by bats was recognized in the 1960s (Griffin 1970). Bats use visual cues such as landmarks (Tsoar et al. 2011; Williams et al. 1966), sunset (Lindecke et al. 2019), and post-sunset glow (Holland et al. 2010; Buchler and Childs 1982) to orient themselves, and their vision can detect objects as small as simulated stars (Childs and Buchler 1981).

Visual stimuli may be driving bat attraction to wind turbines, but competing hypotheses differ in identifying the mechanism. Proposed drivers include wind turbine silhouettes, wind turbine surface reflectance, wind turbine aviation lighting, or some other yet-unknown visual cues. The "attraction to silhouettes" hypothesis (more commonly referred to as the "tall trees" hypothesis) suggests that wind turbine silhouettes resemble tall trees that some species of bats approach because they perceive them as a valuable resource for foraging, roosting, and/or mating. Another hypothesis is that bats are attracted to wind turbines because of their surface reflectance because of the sensitivity of bat vision to dim light (Gutierrez et al. 2018) and the high reflectivity of wind turbine surfaces. Ambient light reflected off white or light gray wind turbine surfaces may be perceived as the direction of the open sky, eliciting an innate "move towards the light" response that is adaptive in bats for exiting roosts (Chase 1981, 1983; Mistry and McCracken 1990). Finally, the attraction to lighting hypothesis suggests that aviation lighting, blinking red lights required on all turbines, masks natural orientation cues such as post-sunset glow or misleads bats into maladaptive orientation decisions (Lindecke et al. 2019).

Silver-haired bat. *Photo from Kristin Jonasson*

It is critical to understand which stimuli are driving attraction and at what distance the stimuli are detected by bats. To enhance existing, or develop new minimization solutions, we must understand how bats perceive their environment, particularly the visual characteristics of wind turbines. Here, we briefly describe what we know about bat visual systems, how wind turbine visual stimuli may interact with bat visual systems, and what next steps we might take to fill knowledge gaps and identify effective mortality minimization solutions.

Bat Visual Systems

Glossary of Terms

Bat Visual System Component	Description
Visual acuity	The ability to resolve static spatial detail. Visual acuity dictates what details can and cannot be resolved in a given scene. Sometimes called the minimum resolvable acuity, it measures the smallest detail that can be interpreted by the visual system.
Cycles per degree	The number of pairs of black and white stripes that animals can discern within a visual angle of one degree.
Minimum resolvable angle	The angular width of the narrowest black/white line pair that can be discerned.
Contrast sensitivity	The ability to distinguish an object from its background based on luminance differences; a function of visual acuity.
Temporal resolution	The ability to track movement in a scene.
Luminance	An indicator of how bright a surface appears. Luminance levels indicate how much light could be detected by the eye looking at a particular surface from a particular angle of view.

Photoreceptor Composition and Spectral Sensitivity

Bats have limited color vision and extend their visual sensitivity into the UV spectrum (Figure 1; Kelber and Roth 2006; Zhao et al. 2009). Bats are dichromatic, which means their eyes have two types of cones with peak sensitivity at different wavelengths of light: one around 500 nanometers (green) and one at 360–400 nanometers (ultraviolet [UV]). Sensitivity to UV light in particular means that bats may perceive visual features of wind turbines that are invisible to humans, such as UV reflectance from wind turbine surface coatings. Despite having color vision, rods are the dominant photoreceptors in bat retinae and account for greater than 97% of photoreceptor density (Kim et al. 2008). Rods allow bats to maintain visual sensitivity and motion detection in dim light but come at the cost of reduced spatial resolution and color discrimination (Jones et al. 2013).

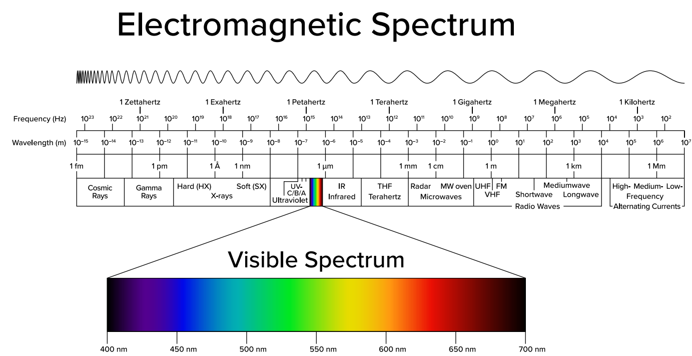

Figure 1. The electromagnetic spectrum. The two types of cones that bats possess peak at 500 nanometers (green) and between 360 and 400 nanometers (violet to ultraviolet). *Image from Getty Images 2152966948*

Visual Acuity and Contrast Sensitivity

Visual acuity, defined as the ability to resolve static spatial details, is typically lower in bats than for mammals that are active during the day. For example, humans have visual acuities approximately 10–20 times greater than bats, giving humans the ability to see finer details (Eklöf et al. 2014). One measure of acuity is cycles per degree, with more cycles per degree indicating better acuity and finer detail resolution. Using equations from Boonman et al. (2013), Jonasson et al. (2024) considered the maximum distance that Nathusius's pipistrelle (*Pipistrellus nathusii*) and Daubenton's bat (*Myotis daubentonii*) could visually perceive a wind turbine. They estimated that under ideal environmental conditions, the two species could detect a wind turbine silhouette 20 and 4 kilometers away, respectively.

Contrast sensitivity is the ability to distinguish an object from its background based on differences in brightness and depends on an organism's visual acuity. Collecting data on how the contrast sensitivity changes as a function of visual acuity is critical for understanding how bats visually perceive the world (e.g., at what distances and resolution a bat can see an object), but currently there are no known studies that have investigated bat contrast sensitivity.

Temporal Resolution

Temporal resolution, or the ability to perceive motion, is another important visual parameter. Bats' visual systems are rod-dominated, tuned to detect movement in low light, but, like other nocturnal mammals, bats may only be capable of visually detecting relatively slow to moderate motion (Horsten et al. 1962). Because they are nocturnal, bats may have less than half the temporal resolution of mammals adapted to detecting motion during the day (Horsten et al. 1962; Ward and Doerflein 1971). There are currently no published studies providing direct, species-specific measurements of the temporal resolution for insectivorous bats.

Visual Perception of Wind Turbines

Bats can detect objects at greater distances with their visual systems than with other sensory systems like echolocation, highlighting the importance of vision for detecting wind, perceiving, and approaching wind turbines. The ability to detect wind turbines visually means that bats may be attracted to these structures well before they can gather detailed information about them through echolocation or other senses. White reflective wind turbines stand out in the otherwise low-contrast night sky. Additionally, any UV light reflected may make them appear brighter and more strongly contrasted to bats because this wavelength is within their visual sensitivity. Higher contrast might make turbines more visually obvious in the landscape, increasing the distance at which bats can detect them and potentially enhancing their attractiveness to bats. Additionally, the typical semigloss coatings of most wind turbines may sometimes create glints, brief sparkles of reflected light that occur under certain lighting conditions, adding another source of visual salience to bats.

The relatively low visual acuity of bats has important implications for how they perceive wind turbines at different distances. At close range, bats may be able to discern general features of wind turbines, such as the tower and nacelle, but may not be able to resolve finer details like individual blade edges. At greater distances, wind turbines may be perceived primarily as silhouettes or general shapes against the background. The exact distance at which a bat can detect a wind turbine remains unclear because it depends on a more detailed understanding of bat visual systems and how they perform under a range of complex environmental conditions.

Time lapse photo of a spinning wind turbine. *Photo by Dennis Schroeder, National Laboratory of the Rockies (NLR) 39968*

Bats are thought to perceive brighter areas in their visual field as the direction of the open sky, which may result in bats mistaking wind turbines for unobstructed airspace (Jonasson et al. 2025). Thermal video recordings of bats closely approaching wind turbine surfaces (<5 meters), sometimes repeatedly, resembles behaviors described in early studies on the use of vision by bats (Horn et al. 2008; Cryan et al. 2014; Goldenberg et al. 2021). For example, Davis and Barbour (1965) found that bats in a dark flight arena with lit windows persistently attempted to fly through the lit window despite repeated contact with the glass pane. Further, blindfolded bats did not exhibit the same light orientation response, indicating that this behavior is mediated through vision and that in certain situations bats prioritize vision over other sensory modalities at close range. In another example, collisions between wild bats and the dimly lit side of a white trailer demonstrated that reflected metal surfaces can also attract bats (McGuire and Fenton 2010). This positive phototaxis has been documented in various bat species and may represent an innate navigational mechanism that becomes maladaptive in the context of wind turbines.

Wind turbines in moonlight. *Photo by Bryan Bechtold, NLR 84182*

The reflection of moonlight or starlight off wind turbine surfaces may create visual cues that bats interpret as open flyways, leading them into dangerous proximity to moving blades. Jonasson et al. (2025) found that bats flying through a Y-maze were at least twice as likely to fly toward white wind turbine blade sections compared to less reflective black ones. This attraction intensified when one of the Y-maze exits was a dark, empty flyway, with 74% of hoary bats and 97% of silver-haired bats flying toward the white wind turbine blade. These findings suggest that hoary bats and silver-haired bats, two species that make up 44.9% of fatalities at wind energy facilities (Allison and Butryn 2020), may be attracted to wind turbine surfaces when they reflect ambient moonlight and that mortality minimization measures that reduce the reflectivity and contrast of wind turbines could be a valuable avenue for mortality minimization solutions.

Rather than reducing visual cues from wind turbines, some researchers have investigated the value of increasing wind turbine visual cues by illuminating them with dim UV lights. The idea is that if a bat's ability to detect wind turbines is increased, it might recognize that wind turbines are not resource-rich trees and therefore avoid them. Gorresen et al. (2015) showed a small but statistically significant reduction in bat activity near UV-lit trees, but when tested at wind turbines, Cryan et al. (2021) did not observe any change in bat activity between UV-lit and unlit wind turbines.

The ability for bats to perceive the motion of wind turbine blades depends in part on the bats' temporal resolution, the size of the blades, and the speed of blade rotation. While bats can detect slow movement, rapidly spinning blades may not be perceived as discrete objects, especially when bats are close to the blade and in low-contrast conditions. Blade-tip speeds of modern wind turbines can exceed 200 kilometers per hour, which may surpass the motion detection capabilities of bat visual systems under certain conditions as they get closer to the rotor-swept area, creating a situation where the primary hazard—the moving blade—may be difficult for a bat to perceive. An inability to appropriately perceive or assess risk is further supported by video observations of individual bats flying in and out of the rotor-swept area multiple times (Cryan et al. 2014; Goldenberg et al. 2021).

Evidence suggests that aviation lighting may have an attraction effect on certain bat species. Migrating bats increase activity near lighthouses (Cryan and Brown 2007) and meteorological towers equipped with aviation lighting relative to control habitats (Jameson and Willis 2014). At least two bat species are attracted to red lights during migration (Voigt et al. 2018). Aviation lights viewed from a distance on the horizon are vastly different in intensity and directionality from aviation lights viewed within a wind farm. The spectral characteristics of aviation lights, typically centered in the red portion of the spectrum, may be less visible to bats than to humans, given bats' reduced sensitivity to long wavelengths. However, the intensity of these lights may still make them detectable to bats at considerable distances, potentially serving as attractants by masking or misleading navigational cues or by distracting bats who investigate their novelty on the landscape. No study has tested the hypothesis that bats are attracted to wind farms from multiple kilometers away, before they are able to see wind turbine silhouettes. Previous

Aviation lights on wind turbines. *Photo from Getty Images 2251430037* research has focused on the effects of aviation lights within wind farms, where lit wind turbines killed no more bats than unlit ones (Arnett et al. 2008; Bennet and Hale 2014); however, these studies were conducted prior to the development of modern mortality estimators and had low sample sizes. Future investigations of bat and aviation light interactions are warranted.

Knowledge Gaps and Future Research on Bat Visual Systems in the Context of Wind Energy

To gain a deeper understanding of bat visual systems in the context of wind turbines, future research could address the following:

- While it is established that bats can detect large vertical structures and silhouettes at considerable distances because of their sensitivity to contrast and low-light conditions, it is still unclear how the specific size, shape, and increasing height of modern wind turbines affect bats' perception and attraction at various distances. Studies aimed at measuring visual acuity and contrast sensitivity for bat species most affected by wind energy can use behavioral and physiological assays such as the optomotor response (Eklöf et al. 2014) to better understand wind turbine detection distances across different lighting and weather conditions.
- Controlled experiments could be done to test the effects of wind turbine contrast, reflectance, and color and to determine if removing visual stimuli reduces bat attraction. This may lead to collaborations with materials scientists and industrial partners who could be critical in facilitating the development of practical, durable, and cost-effective solutions on a commercial scale.
- The impact of aviation lighting on bat behavior is not fully resolved. Bats are generally less sensitive to longer-wavelength (red) light compared to shorter wavelengths (blue/UV), but some studies suggest that certain species may still perceive and respond to red lights, possibly using them as navigational cues or being attracted to the aggregation of lights on the landscape. However, the exact spectral sensitivity curves for bats and how these lights interact with their visual systems in real-world contexts remain poorly quantified. Further research is needed to understand how different types, intensities, and patterns of aviation lighting affect bat perception, detection distance, and behavior around wind turbines.
- Bats' temporal resolution and motion detection thresholds are not well characterized, making it difficult to predict whether moving blades are perceived as distinct, avoidable objects or as blurred, indistinct hazards, especially under low-light conditions. Studies aimed at quantifying the limits of motion detection in bats will be valuable. Research is needed on the critical flicker fusion frequency in bats to determine their ability to perceive rapidly moving turbine blades.

Conclusion

The drivers of bat attraction to wind turbines remain unknown, but it is likely that wind turbine visual cues play at least some role in increased attraction. The complex interplay between bat visual systems, wind turbine characteristics, and environmental factors creates both challenges and opportunities for developing effective mitigation solutions. While identifying specific visual cues that attract bats to wind turbines and understanding the limitations of bat visual systems are essential, more than one sensory attractant may be responsible for differing attraction effects across species and spatial scales. Effective solutions will likely require that we integrate our understanding of bat visual systems into the larger context of sensory and behavioral ecology to develop holistic strategies that minimize bat mortality with little impact on the wind energy industry.

Authors

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Cover image: Hoary bat. *Photo from Kristin Jonasson*

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