Land-Based Wind Energy Stimuli and Wildlife Sensory Environments

Summary

- Wind energy introduces novel sensory cues, including visual, acoustic, thermal, mechanical, electrical, and physical stimuli, that interact with animal perceptual systems.
- While many of these stimuli are minimal or not ecologically relevant, some could interfere with animal behavior and others may be imperceptible to animals, potentially creating unrecognized risks.
- Wildlife impacts may occur through multiple pathways such as the masking of natural signals, distraction from important tasks, or maladaptive attraction to misleading cues.
- A sensory ecology framework can improve research and management by informing interventions through species-specific perception.

Introduction

Land-based wind turbines and the associated energy infrastructure alter the sensory environments in which they are built, introducing novel visual, acoustic, thermal, mechanical, electrical, and physical cues into habitats to which animals are finely tuned. These stimuli vary in their detectability and relevance across species. While responsible development aims to minimize the levels of stimuli, renewable energy technologies can still interact with the perceptual world of many animals. If anthropogenic stimuli are detectable by a certain species, they act as sensory pollutants (Jonasson et al. 2024). Sensory pollution refers to any human-caused change to the sensory environment that disrupts how animals detect, assess, and/or respond to information (Smith et al. 2021). Such stimuli can mask important cues, distract attention, or mislead behavior in ways that may be detrimental (Dominoni et al. 2020).

However, detectability does not inherently determine whether a stimulus is harmful. Not all stimuli produced by wind turbines are even perceivable by all organisms. Some detectable cues may have neutral or even beneficial effects. Conversely, undetectable cues may still create risk, such as collision, because the individual cannot perceive and respond to them appropriately. Understanding potential impacts begins with determining whether a given stimulus falls within an animal's sensory range and evaluating whether it alters behavior in a positive, negative, or neutral way. In cases where an undetectable stimulus is associated with risk, mitigation may involve intentionally increasing detectability to allow an organism more time to respond (Smith et al. 2021).

Sensory stimuli produced by wind turbines can interact with animal perception in species-specific ways and can be grouped into broad categories of sound, light and vision, odor, and physical, electrical, and geophysical disturbance. It is essential to understand animal perceptual systems and if and how these stimuli are perceived by groups highly impacted by wind energy, such as raptors and bats, to assess impacts and design of ecologically relevant minimization approaches. A sensory ecology framework is a valuable tool for informing the adaptive management of wind energy effects on wildlife.

Stimuli Emitted by Wind Turbines and Associated Infrastructure

The stimuli discussed below vary greatly in both magnitude and temporal and spatial extent. Many may be irrelevant to most species, may not alter behavior, or may not be associated with risk. Many stimuli can be reduced or eliminated with appropriate design, maintenance, or mitigation measures.

Sound

Wind turbines produce sound through both mechanical and aerodynamic pathways. Mechanical sound is created by the moving components of a wind turbine such as the gear box, generator, and bearings. This type of sound can be decreased through design, high-quality construction, and regular maintenance. Aerodynamic sound is created by wind passing the wind turbine blades and increases with the speed of the rotor. It is further influenced by atmospheric turbulence, wind direction, and wind speed. Aerodynamic sound is the most significant source of noise generation but can be reduced through optimizing blade design (Teff-Seker et al. 2022).

Primer on Sound

Sound is described by its magnitude (loudness) and frequency.

- Sound intensity at the source can be expressed as either sound power, which is measured in watts (total acoustic energy emitted at the source), or sound pressure level, which is measured at a distance from the source (the sound pressure level decreases with distance from the source) and is reported in decibels (dB).
- Sound pressure level in decibels is measured on a logarithmic scale, which is referenced to the threshold of human hearing. This definition sets the threshold of human hearing at a sound pressure level of zero decibels. Noise measurements in the ocean are not comparable to measurements in air, because a different threshold is used as a reference for the measurements.
- Frequency, measured in hertz (Hz), describes the pitch of a sound and is categorized as infrasound (1–20 Hz), low frequency (20–200 Hz), and ultrasound (>20,000 Hz). Most humans can hear in the range of 20 to 20,000 Hz (Rogers et al. 2006).

A utility-scale wind turbine on land typically produces a sound pressure level of about 35–45 decibels (dB) at a distance of 300 meters, which is similar in magnitude to an air conditioner (50 dB) or refrigerator (40 dB) during normal use within a home (Office of Energy Efficiency and Renewable Energy n.d.). A jet engine at a distance of 100 meters produces a sound pressure level of about 110 dB, which is about 10 dB below the threshold of pain for humans. Wind turbines produce sound primarily in the audible low to mid-range frequency, although they also generate some low-frequency infrasound, which is more often felt rather than heard.

Mechanical sounds are primarily low frequency (below about 500 Hz). Aerodynamic blade sound is at higher frequencies, from a few hundred hertz up to several kilohertz, and is generally the main source of sounds humans hear from modern wind turbines (Liu 2017). Construction activities and associated increased road traffic are also anthropogenic contributors to the soundscape.

Light and Vision

Structure and Silhouette

Wind turbine towers are tall, vertical structures on the landscape that often stand in stark visual contrast to the surrounding environment. Their size and form can create prominent silhouettes in what are often relatively featureless

A wind turbine in silhouette against the rising sun at King Plains Wind Farm in Oklahoma. *Photo by Bryan Bechtold, National Laboratory of the Rockies (NLR) 84177* landscapes (e.g., agricultural fields, sagebrush plains). These silhouettes can alter the horizon line and introduce novel visual markers into the landscape. In 2022, the average nacelle height for land-based wind turbines in the United States was 100 meters (Wiser et al. 2024). Wind turbine heights continue to increase with advancing technology (Lantz et al. 2019).

Lighting and Illumination

To meet Federal Aviation Administration (FAA) safety requirements, some wind turbines are equipped with aviation obstruction lights to alert pilots to the presence of the tall structures. Wind farm turbines have omnidirectional red flashing obstruction lights (FAA L-864) high on the nacelle synchronized to flash simultaneously. The lights flash about 30 times per minute with an intensity of 2,000 candelas. One candela is approximately the brightness of a single candle. The lights are primarily placed on the nacelles of turbines around the perimeter of the wind farm and must be visible from all horizontal directions. Some facilities use Aircraft Detection Lighting Systems, which use radar to keep the lights off unless an aircraft is detected nearby to reduce overall light pollution while maintaining safety (FAA 2020).

Color, Reflectivity, and Contrast

Per FAA guidelines, wind turbines are typically painted white or light gray to maximize daytime visibility for pilots and aviation safety (FAA 2020). The exact visibility of these structures depends on wind turbine size, placement, distance, ambient illumination level, and atmospheric conditions.

Light pollution at a wind energy facility is not just the addition of new light sources; human-made structures can also modify light fields by reflecting ambient sunlight or moonlight. High-albedo (white) surfaces reflect more light than dark ones. This phenomenon is well documented for horizontal surfaces at night. For example, fresh snow increases levels of light pollution, and models have linked urban surface albedo with increased night sky brightness (Jechow and Hölker 2019; Wallner and Kocifaj 2019). By this same mechanism, large, glossy white wind turbine surfaces could potentially increase brightness locally, particularly at night. Many wind turbines are painted the light-gray color RAL 7035, which reflects around 58% of light (RAL denotes a standardized industrial color index [Siemens AG 2011]). White finishes (often RAL 9010) reflect more light, closer to 85%. Most wind turbine surfaces are semigloss. The finish of the coatings impacts how the light is reflected; matte surfaces scatter light more diffusely while semigloss surfaces add a modest specular highlight that can produce glints of light when viewed at certain angles. Glint is a short reflection of light off of a smooth surface. On wind turbines, glint may occur when the viewing angle lines up

Wind turbine against a cloudy sky at the National Laboratory of the Rockies' Flatirons Campus. *Photo by Gregory Cooper, NLR 96680*

Primer on Polarization

Polarization describes the orientation of light waves. Most light waves vibrate in a mix of many directions, but when light reflects off a surface it can become organized such that the waves line up, which is called polarized light. Direct sunlight is only weakly polarized. Moonlight is sunlight reflected off the moon and becomes modestly polarized depending on the moon phase. Moonlight becomes further polarized as it enters Earth's atmosphere. This double polarization means moonlight can create night-sky polarization patterns similar to daytime light polarization, which is caused by sunlight interacting with air molecules as it passes through the atmosphere (Gál et al. 2021).

Wind turbine against a blue sky. *Photo by Gregory Cooper, NLR 90315*

with the sun or moon. Wet wind turbines or turbines with a semigloss coating may reflect light in a way that makes small amounts of polarized light, which could change the local polarization patterns.

Contrast is the difference in brightness or color between a feature and its background. A white wind turbine contrasts more with a blue sky than a gray sky of the same overall brightness (Bishop 2019). The contrast of a scene is dynamic; the same white wind turbine can appear lighter than a blue sky at midday but can create a dark silhouette against the brighter sky at dawn or dusk. Haze or clouds lower contrast and reduce visibility. The night sky is generally a low-contrast environment. Under a bright moon, reflected moonlight can raise the brightness of wind turbines and increase their visual prominence.

Landscape Alteration and Habitat Modification

The broader footprint of wind energy development such as roads and transmission lines can visually alter the natural patterns of the landscape. These human-made features can fragment previously homogenous viewsheds and create visual patterns or edges that vary distinctly from the surrounding area.

Movement Cues, Flicker, and Shadow

The rotation of wind turbine blades introduces movement in the visual environment. Moving blades create temporal contrast that naturally draws attention. Motion blur can occur when an object moves faster than an eye can resolve the movement, making the object appear streaked and/or semi-transparent. This can reduce edge contrast and make the object less visible. Motion blur is more likely at higher rotor tip speeds, against uniform backgrounds, and at close range.

Under certain sun angles, the wind turbine blades can cast long, moving shadows on the nearby ground. This shadow flicker happens when the sun, wind turbine, and viewing angle are aligned. The effect is most pronounced when the sun is strong and low on the horizon. In any given location, shadow flicker typically occurs only in a very short window of time, as the sun's position changes throughout the year. The effect is also diminished by cloud, haze, vegetation, and distance.

Odor

Direct odor emissions from wind turbines are limited. However, changes in atmospheric mixing caused by wind turbine wakes can alter how scents are dispersed across the landscape, thereby potentially affecting the spatial distribution of natural odor cues (Svensson et al. 2014).

Physical, Electrical, and Geophysical Disturbance

Wind energy can introduce localized physical and geophysical changes to the natural environment. Wind turbine operation produces mechanical and electrical heat, although optimized design and cooling systems usually minimize this heat waste (Xydis et al. 2015). Turbulence mixing caused by wind turbine wakes can alter microclimates through changes to humidity as well as changes in air, surface, and soil temperatures (Miller and Keith 2018). Nighttime warming of up to 1°C–2°C has been observed in some wake zones (Rajewski et al. 2013; Smith et al. 2013). Vegetation greenness can also increase or decrease within the wake zone depending on site-specific factors (Diffendorfer et al. 2022).

Electricity generation and transmission can generate electromagnetic fields (EMFs) in addition to the EMFs that exist naturally in the environment. These physical and geophysical changes are generally small in magnitude and spatial extent.

Species Sensory Perception

Improving management and conservation strategies for wildlife requires understanding how species perceive their surroundings. Yet this can be difficult to disentangle from a human-centered lens, as humans naturally filter the world through their own sensory systems. Many measurement units are based on human perception; for example, light is often described in lumens, which is a unit inherently tied to the human visual spectrum. It can therefore be difficult to consider the magnitude or extent of stimuli in ways that are independent of human biology.

Some sensory abilities are beyond human perception. While there are some concerns about the impacts of EMFs on human health, some species directly rely on these cues for navigation or spatial orientation (Mouritsen 2018). Bats can echolocate ultrasound that is undetectable to humans, and many birds and insects can see into the ultraviolet spectrum that is beyond the wavelengths humans can visualize. Some animals have specialized photoreceptors that allow them to detect polarized light; certain species of insects and bats incorporate information from polarized skylight into celestial compasses for navigation (El Jundi et al. 2014; Holland et al. 2010).

Mexican free-tailed bats flying at dusk in Texas. *Photo from Getty Images 128144201*

Even when humans and other species can detect the same type of stimulus, the way it is perceived can differ greatly. For example, vision in a certain species may be especially sensitive to parts of the light spectrum and less sensitive to others. As a result, some colors of light can appear much brighter to individuals of that species than to humans, even if the total physical brightness is the same (Longcore 2023). Another difference in visual perception is temporal resolution, which refers to how quickly a visual system can sample and process change over time. High temporal resolution means an animal can detect fast-moving objects or rapid changes in light intensity and pattern. Critical flicker frequency (CFF), the threshold frequency at which a flickering light is perceived as continuous, is a common way to quantify temporal resolution (Potier et al. 2020). A light designed to flash at intervals to reduce light pollution may still appear continuous to some species if they have a low CFF, meaning such an intervention may fail to alter the intended behavioral response or produce the expected ecological outcome (Lafitte et al. 2022).

Primer on Sensory Systems

Audition: Detection of acoustic vibrations through air or water.

Vision: Perception of electromagnetic radiation within the light spectrum. Some species have specialized photoreceptors that can detect polarized light.

Olfaction: Detection of volatile chemical compounds via olfactory receptors.

Somatosensory: Detection of physical and environmental cues, including thermoreception (detection of heat or cold), mechanoreception (detection of vibration and pressure), and magnetoreception (detection of Earth's magnetic fields).

Sensory ecology is the study of how organisms acquire, process, and respond to information in their environment through their sensory system.

Pathways Of Sensory Impact on Wildlife Behavior

If a stimulus is detectable, it can influence behavior in different ways. These behavioral changes are what potentially make it a sensory pollutant. Dominoni et al. (2020) describe three main pathways through which sensory pollutants alter behavioral and physiological responses: masking, distraction, and misleading.

Masking occurs when an organism's ability to detect or distinguish a natural cue is decreased because a sensory pollutant overlaps in intensity or spectrum with that cue. Masking only involves one sensory modality and happens when the pollutant is similar to the target signal and begins to mask it. For example, traffic noise can overlap in frequency and drown out bird songs, disrupting communication between individuals and lowering breeding success (Halfwerk et al. 2001). Field studies of bats show that traffic noise can mask echolocation, leading some bat species to avoid roadsides (Bonsen et al. 2015).

Distraction is when a sensory pollutant competes for an animal's attention and diverts focus away from an important task. In this case, the pollutant does not need to match the modality of the intended task. For example, loud anthropogenic noise can draw a predator's attention away from hunting and reduce success (Mason et al. 2016). Experimental work with pallid bats (*Antrozous pallidus*) found that noise reduced foraging success even when it did not overlap acoustically with prey cues, demonstrating how different types of anthropogenic noise can interfere with attention and hunting efficiency (Allen et al. 2021). Relatedly, songbirds exposed to high background noise allowed closer approaches from predators before flying away (Petrelli et al. 2017).

Misleading occurs when a sensory pollutant is mistaken as a natural cue or signal, prompting an inappropriate or maladaptive response. If misleading results in reduced survival or reproduction, it can create an ecological trap. For example, some fledgling seabirds on their first nocturnal flights may mistake artificial lights at night for celestial cues, leading to large fallout grounding events (Rodríguez et al. 2017). Migratory bats may be drawn to light-colored, highly reflective surfaces at close range, potentially mistaking them for areas of open sky (Jonasson et al. 2025).

Unlike the behavioral pathways described above, which involve perceivable stimuli, some anthropogenic stimuli are not detectable at all by the individual. If an individual is unable to perceive a stimulus at the appropriate scale or intensity to assess risk, it can lead to negative lethal or nonlethal consequences (Smith et al. 2021). In such cases, imperceptible anthropogenic stimuli disrupt the sensory cues animals rely on to evaluate threats in their environment and to respond accordingly. For example, birds collide with windows because they are unable to see the glass (Loss et al. 2014), and flying foxes may become entangled in barbed wire if the strands are imperceptible in dim light (Jacomassa et al. 2017).

Some animals can adapt to sensory pollutants. For instance, some birds and frogs are able to shift the vocalization of their calls to reduce masking by other anthropogenic noise (Patricelli and Blickley 2006; Higham et al. 2021). Others may even benefit from sensory pollutants; noise indirectly increases reproductive success in urban-adapted bird species as a result of reduced predation risk (Francis et al. 2009).

Knowledge Gaps and Areas for Future Research

- Investigate sensory systems of species impacted by wind energy to better understand species-specific perception of wind turbine stimuli.
- Assess species-specific responses to different sensory pollutants to identify conditions and reasons for increased risk.
- Identify potentially harmful sensory pollutants and design intervention methods that are biologically and mechanistically practical.
- Examine interactions between multiple sensory pollutants, because stimuli often co-occur in natural environments and may have stronger or more complex interaction effects than single-modality sensory inputs (Dominoni et al. 2020; Halfwerk 2011).

Conclusion

The way in which an organism experiences the world around it underscores why sensory ecology is critical to adaptive management of wind-wildlife interactions (Fernández-Juricic 2016). Identifying sensory pollutants and the mechanisms that drive maladaptive responses provides a pathway to interventions that reduce ecological traps and risk to species (Robertson and Blumstein 2019). New tools such as rendering software that translate photographs and videos into animal vision now allow researchers to approximate how species perceive their environment (van den Berg et al. 2020).

Effective management must also account for conflicting sensory needs across species. For example, interventions that make wind turbines safer for birds, such as painting designs on blades to increase visibility to reduce bird collision (May et al. 2020), could potentially increase attraction for bats depending on the sensory modality and mechanism involved with attraction. Each intervention should therefore be evaluated for non-target effects to ensure that measures benefiting one group do not inadvertently increase risks for another.

Ultimately, aligning interventions with the sensory world of animals offers the most promising path toward mitigation strategies that are both biologically meaningful and effective.

Authors

Laura Dempsey, National Laboratory of the Rockies

Jeff Clerc, National Laboratory of the Rockies

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Aviation lights on wind turbines. *Photo from Getty Images 1310993533*

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NATIONAL LABORATORY OF THE ROCKIES

15013 Denver West Parkway
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303-275-3000 • www.nlr.gov

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