




PERSPECTIVE

Limitations of acoustic monitoring at wind turbines to evaluate fatality risk of bats

Christian C. VOIGT*  *Department of Evolutionary Ecology, Leibniz Institute for Zoo and Wildlife Research, Alfred-Kowalke-Str. 17, 10315 Berlin, Germany. Email: voigt@izw-berlin.de*

Danilo RUSSO  *Wildlife Research Unit, Dipartimento di Agraria, Università degli Studi di Napoli Federico II, Portici, Italy and School of Biological Sciences, University of Bristol, Bristol Life Sciences Building, 24 Tyndall Avenue, Bristol BS8 1TQ, UK. Email: danrusso@unina.it*

Volker RUNKEL *Bundesverband für Fledermauskunde Deutschland e.V., Schmidtstedter Str. 30a, 99084 Erfurt, Germany. Email: vrunkel@me.com*

Holger R. GOERLITZ  *Acoustic and Functional Ecology, Max Planck Institute for Ornithology, Eberhard-Gwinner-Strasse, 82319 Seewiesen, Germany. Email: hgoerlitz@orn.mpg.de*

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*Correspondence

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ABSTRACT

Wind turbines (WTs) frequently kill bats worldwide. During environmental impact assessments, consultant ecologists often use automated ultrasonic detectors (AUDs) to estimate the activity and identity of bats in the zone of highest mortality risk at WTs in order to formulate mitigation schemes, such as increased curtailment speeds to prevent casualties. While acknowledging the potential of acoustic monitoring, we evaluate the limitations of AUDs for monitoring bats at WTs and highlight directions for future research. We show that geometric attenuation and atmospheric attenuation of ultrasonic echolocation calls, in conjunction with limited sensitivity of ultrasonic microphones, severely constrain detection distances of bats at WTs. Taking into account the acoustic shadow produced by the nacelle, AUDs cover only approximately 23% of the risk zone for a bat calling at 20 kHz and 4% for a bat calling at 40 kHz, assuming a 60 m blade length. This percentage will further decrease with increasing blade lengths in modern WTs. Additionally, the directionality of echolocation calls and the dynamic flight behaviour of bats constrain the detectability of bats. If a call can be detected, the low interspecific and high intraspecific variation of echolocation call characteristics may impair species identification, limiting the power to predict population-level effects of fatalities. We conclude that technical, physical, and biological factors severely constrain acoustic monitoring in its current form. We suggest the use of several AUDs, installed at complementary sites at WTs, and the testing of other techniques, such as radar, cameras, and thermal imaging, to inform stakeholders on the mortality risk of bats at WTs.

INTRODUCTION

Wind energy production is booming globally in an effort to reduce CO₂ emission and mitigate global climate change (GWEC 2020). However, energy production from wind is not environmentally neutral, since large areas are required for establishing and operating wind turbines (WTs)

and because large numbers of birds and bats are killed by WTs (Northrup & Wittemyer 2013, Voigt et al. 2015). This green–green dilemma, i.e. the conflict between the environmental goals of protecting both biodiversity and global climate, is yet unsolved (Voigt 2016). The highest number of fatal incidents for vertebrates at WTs has been observed for bats. Based on the available record

of documented human-induced fatalities, WT's appear to be the most frequently observed anthropogenic cause of multiple mortality events for bats worldwide (O'Shea et al. 2016).

In many, albeit not all, countries, environmental impact assessments are mandatory during the first year(s) following WT construction to assess the likelihood that bats get killed at WT's. Legal requirements are, for example, based on national and European law (Habitat Directive 92/32/CEE, Annexes II and IV), on the Endangered Species Act in the USA (1973) and on the UN Convention on Migratory Species of Wild Animals (CMS convention dated Bonn 1979 and London 1991). Past studies showed that pre-construction surveys and ground-based monitoring schemes are inadequate to reveal the acoustic activity and thus mortality risk of bats at WT's (Hein et al. 2013, Lintott et al. 2016, Solick et al. 2020). Therefore, consultant ecologists often use automated ultrasonic detectors (AUDs) placed at the bottom of the nacelle (housing) of WT's (called nacelle monitoring) to estimate the mortality risk of bats at the operating WT (Brinkmann et al. 2011, Korner-Nievergelt et al. 2013). AUDs record echolocation calls automatically following a trigger and store the files for subsequent analysis, such as identifying species and quantifying their activity. These data are then used to identify the environmental conditions, such as season, time of day, ambient temperature, and wind speed, at which bats are most active. Knowing critical environmental conditions allows the formulation of mitigation schemes to reduce bat mortality risk at operating WT's. Since bats are less active with increasing wind speeds (e.g. Martin et al. 2017), the most effective mitigation scheme is to increase the cut-in speed, i.e.

the wind speed at which WT's start to operate and produce energy, during critical environmental conditions (Arnett et al. 2011, Brinkmann et al. 2011, Mantoiu et al. 2020). However, comparing acoustic data with independent methods, such as visual surveys (videography), shows that only about 30 to 50% of the independently documented bat passes are also recorded by AUDs (Cryan et al. 2014, Gorresen et al. 2017, 2019). Further, recent studies suggest that acoustic activity of bats at nacelle height does not necessarily correlate with fatality numbers (Solick et al. 2020, Bach et al. 2020a). Discrepancies between acoustic activity of bats at WT's and fatality numbers are also echoed by consultant ecologists in a recent Internet-based survey (Voigt et al. 2020). We discuss the likely factors that may cause AUDs to miss bat passes in the zone of highest bat mortality at WT's (the risk zone), building on recent findings and critique (e.g. Bach et al. 2020a, b, Runkel 2020, Solick et al. 2020, Voigt et al. 2020).

STEPS AND LIMITATIONS IN ACOUSTIC MONITORING OF BATS AT WIND TURBINES

Several conditions need to be met to allow bats at the turbine nacelle to be recorded and identified using AUDs (Fig. 1). In a first step, the echolocation call has to travel from the sender (the bat) through air to the microphone (Fig. 1). In a second step, the detector needs to distinguish the echolocation call from ambient noise so that an automated recording is triggered. In a last step, the recordings need to be inspected either automatically or manually, recognised as bat calls and, ideally, identified to the species level (Fig. 1). We review and evaluate each step.

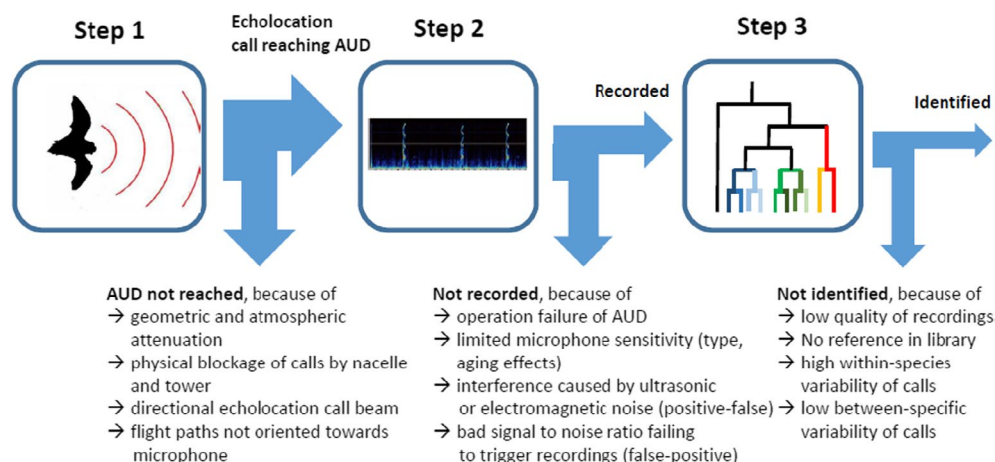


Fig. 1. Scheme describing the major steps and limitations associated with the use of automated ultrasonic detectors (AUDs) at wind turbines for the purpose of environmental impact assessments.

ECHOLOCATION CALL TRAVELS FROM THE BAT TO THE MICROPHONE (STEP 1)

Detection range of automated ultrasonic detectors is limited by geometric and atmospheric attenuation

Echolocation calls propagate through air in a spherical way. AUDs are only capable of detecting those calls that arrive at the microphone above a critical sound pressure level (SPL) and at a sufficiently high signal-to-noise ratio (SNR). Although the peak SPL (peSPL) produced by bats may be relatively high, ranging between about 100 and 110 peSPL re 20 μ Pa measured at 1 m in front of bats, or even higher (Holderied & von Helversen 2003, Surlykke et al. 2009, Goerlitz 2018, Currie et al. 2020), two processes rapidly attenuate SPL while calls travel through air: geometric and atmospheric attenuation (Goerlitz 2018). The spherical propagation of calls causes a halving of call amplitude with each doubling of the distance to the emitting bat, equalling a reduction of SPL by 6 dB (geometric attenuation). Atmospheric attenuation further reduces the SPL, depending strongly on ambient temperature and

humidity and on call frequency (Lawrence & Simmons 1982, Goerlitz 2018). Atmospheric attenuation is stronger for high frequencies (e.g. median across typical bat activity periods in Germany = 0.45 dB/m for 20 kHz, 1.1 dB/m for 40 kHz, and 2.3 dB/m for 80 kHz; Fig. 2). It also depends in a nonlinear way on temperature and relative humidity, and sometimes increases or decreases with increasing temperature and humidity based on prevailing weather conditions and call frequency (Luo et al. 2014, Goerlitz 2018). Notably, atmospheric attenuation reduces the SPL per metre of increasing distance over which the acoustic signal is travelling, while geometric attenuation is expressed per doubling of distance. Therefore, geometric attenuation causes a strong initial SPL drop with increasing distance to the bat, while atmospheric attenuation causes a linear decline in SPL with increasing distance between a calling bat and the AUD, particularly for high-frequency calling bats.

We simulated sound propagation for two vespertilionid bats that are representative of the taxa most likely to be killed at WTs (Rydell et al. 2010): an open-space foraging bat calling at low frequency and high sound pressure level (20 kHz and 110 dB peSPL re 20 μ Pa at 1 m),

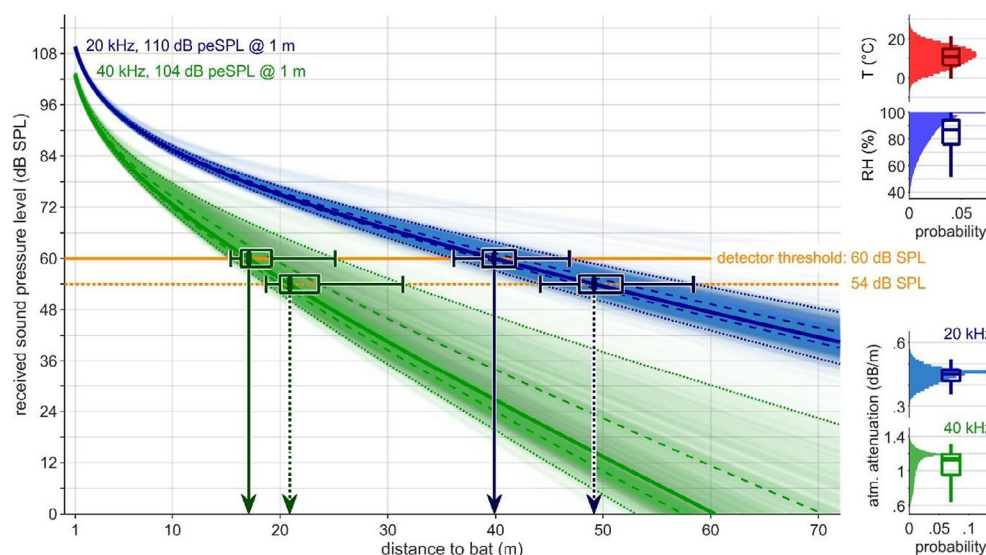


Fig. 2. The sound pressure level (SPL) of echolocation calls is attenuated as they propagate through air. The lines show the estimated received SPL at the automated ultrasonic detectors (AUDs) with increasing distance to the bat, for two typical bats calling at 20 kHz and 110 dB peSPL (upper lines in blue) and 40 kHz and 104 dB peSPL (lower lines in green; source SPLs are referenced to 20 μ Pa at 1 m in front of the bat). The received SPLs were calculated from source SPL by subtracting geometric attenuation (−6 dB per doubling of distance) and frequency- and weather-dependent atmospheric attenuation (see insets on the right). The received SPLs are shown for the full range of atmospheric attenuation (coloured areas), with lines highlighting the received levels for the median (solid), quartiles (dashed), and 95% range (dotted) of the atmospheric attenuation. The solid horizontal orange line indicates the triggering threshold of an AUD at 60 dB SPL (Brinkmann et al. 2011). Even when the detector sensitivity is doubled (+6 dB; i.e. threshold lowered to 54 dB SPL, dotted horizontal orange line), the detection distance is much less than doubled, due to geometric and atmospheric attenuation (vertical arrows, with box plots showing the median, quartiles, and 95% range). Insets on the top right show the distribution of ambient temperature (T) and relative humidity (RH) for all nights from April to October in 2015–2019 in Germany (hourly data of 495 weather stations <1200 m above sea level), and insets on the bottom right show the corresponding atmospheric attenuation for calls of 20 kHz and 40 kHz used to calculate the SPL received at the AUD.

approximating a noctule *Nyctalus noctula*; and an edge-space foraging bat calling at higher frequency and at slightly lower SPL (40 kHz and 104 dB peSPL at 1 m), such as a Nathusius' pipistrelle *Pipistrellus nathusii* or a Kuhl's pipistrelle *Pipistrellus kuhlii* (Holderied & von Helversen 2003, Goerlitz 2018, Currie et al. 2020). At ambient conditions typical for the temperate zone, e.g. a night in Germany (temperature 10.8 °C; range 6.4–14.8 °C, relative humidity 87%; range 76–94%; median with quartiles of all nights from April to October 2015–2019), echolocation calls of a noctule will be attenuated by 0.45 dB (median; quartiles: 0.42–0.47 dB) and those of a pipistrelle will be attenuated by 1.13 dB (0.95–1.20 dB) for each metre travelled (Fig. 2). Assuming that the AUD has a detection threshold of 60 dB SPL re 20 µPa (Brinkmann et al. 2011), the median detection range equals approximately 40 m for noctules, but only 17 m for pipistrelles (Fig. 2; Weber et al. 2018, Runkel 2020). Note, however, the large weather-induced variation of the detection distance around these median values: the quartiles, i.e. 50% of all detection distances, are within 39–42 m for noctules and 16–19 m for pipistrelles, while the remaining 50% of all detection distances are shorter or longer by several metres. By doubling the sensitivity of the AUD (lowering the trigger threshold by 6 dB), the detection range only increases mildly for both examples, i.e. by an additional 9 and 4 m, respectively, while variation also increases further. As a consequence, the detection range of AUDs is severely limited, ranging mostly between 10 and 50 m, depending on the species-specific echolocation call traits (frequencies and SPL), daily and seasonal changes in ambient conditions (temperature and humidity), and detector settings. It is possible that bats partially or fully compensate for changes in sound attenuation, yet the intensity of echolocation seems to be intrinsically constrained by the physiology and morphology of bats (Currie et al. 2020). As a consequence, the presence of bats within the rotor-swept area is likely to be underestimated by AUDs, particularly for those species calling at high frequencies and relatively low SPL.

It is important to note that the physical laws of sound propagation and attenuation also apply to any ultrasonic deterrent system. Such systems have recently been proposed as a way to reduce the activity of bats at WT. Current evidence about the efficacy of such deterrent systems provides mixed results, with some studies showing high interannual variation and also an effect on some, but not all, species (Arnett et al. 2013, Romano et al. 2019, Gilmour et al. 2020, Weaver et al. 2020). Depending on the specific frequencies used as a deterrent, atmospheric and geometric attenuation may limit the effectiveness of ultrasonic deterrents to a distance <40 m for lower frequencies and even shorter distances for high-frequency calling bats (Gilmour

2020). This raises the question whether acoustic deterrents are efficient for the size range of WT that are currently operating.

Detection range of automated ultrasonic detectors in relation to rotor-swept area

The zone with the highest bat mortality risk at WT (the risk zone) consists at least of the discoid area formed by the operating blades (the rotor-swept area). The risk zone is likely to extend three-dimensionally into the space beyond the rotor-swept area due to the shape and volume of blades and the relevance of vortices for causing fatal barotrauma in bats, yet the exact dimensions of the risk zone are largely unknown. In the light of this uncertainty, we use the two-dimensional circular area, i.e. the rotor-swept area, formed by the rotating blades as a proxy for the size of the risk zone. The aim of nacelle monitoring of bat activity by using AUDs is to quantify the likelihood that bats are hit by blades or get within the reach of barotraumatizing vortices in the risk zone, but two major factors impair the application of AUDs to achieve this. First, AUDs are usually installed at the bottom of nacelles, with the microphone pointing downwards. Therefore, the AUD cannot detect echolocation calls from above the nacelle, even though AUDs are usually equipped with omnidirectional microphones. It is therefore reasonable to assume that AUDs cover only half of the discoid risk zone, specifically the lower part. Occasionally, AUDs are installed behind the tower so that most of the risk zone is beyond AUD reach due to the acoustic shadow of the WT.

Second, owing to geometric and atmospheric attenuation, AUDs may cover only a fraction of the total rotor-swept area, because rotor blades are usually longer than the detection distance of echolocation calls. This fraction becomes smaller for longer blades and higher call frequency of bats (Fig. 3). Particularly, species calling at intermediate or high frequencies, such as those of the genus *Pipistrellus* (about 40 kHz at 104 dB peSPL re 20 µPa; Fig. 3), are largely undetectable in the risk zone, even for medium-sized WT. The same applies to somewhat lesser extent to species with lower echolocation call frequencies, such as members of the genera *Nyctalus*, *Vespertilio*, *Tadarida*, and *Eptesicus* in Europe (about 20 kHz at 110 dB peSPL re 20 µPa; Fig. 3) or *Lasiurus* and *Tadarida* in North America (Barclay et al. 1999, Gillam & McCracken 2007, Corcoran & Weller 2018).

When considering these two impairing factors, i.e. blockage of the upper 50% of the rotor-swept area by the physical structure of the nacelle, and effects of geometric and atmospheric attenuation, then a blade length of 60 m leads to only approximately 23% coverage of the rotor-swept area for bats calling at 20 kHz, and approximately

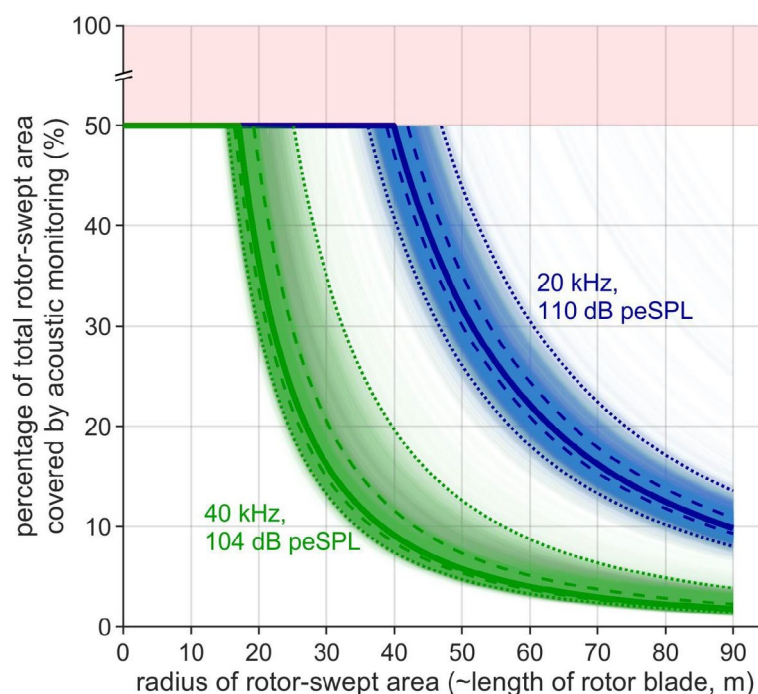


Fig. 3. Percentage of the rotor-swept area of wind turbines covered by automated ultrasonic detectors (AUDs) with increasing blade length, for bats calling at 20 kHz and 40 kHz; ambient conditions and meaning of solid, dotted, and dashed lines as in Fig. 2. For this estimate, we assumed the risk zone to equal the circular rotor-swept area with the blade length as radius. AUDs usually do not cover the upper half of this zone (>50% on y-axis), because AUDs are installed at the nacelle bottom (between tower and blades) with the microphone pointing downwards. We further used the maximum distance at which bats can be detected by AUDs (trigger threshold: 60 dB SPL), which only applies for bat calls that are directed towards the AUD.

4% coverage for bats calling at 40 kHz (Fig. 3). Thus, the risk zone of a modern large WT is not well covered by AUDs installed at the bottom of nacelles. This picture does not change if a single AUD is installed on top of the nacelle pointing upwards, since the lower half of the risk zone is then missed.

Our estimates are conservative, because they rely on relatively high SPLs close to the maximum values recorded for wild bats (Holderied & von Helversen 2003, Goerlitz 2018). In conclusion, the probability of detecting echolocating bats at WTs remains overall low, since AUDs installed at the nacelle cover only a small fraction of the rotor-swept area: about 4% (and lower) of the risk zone for bats calling at high frequencies, such as pipistrelles, at an assumed rotor length of 60 m. This problem will be exacerbated in the future with increasing blade lengths of newly installed WTs.

Directionality of bat echolocation calls constrains the probability of detecting them with automated ultrasonic detectors

Bats use directional echolocation calls to orient themselves based on the weak echoes reflected from objects such as

trees and prey in their environment. Flight-room experiments show that bat species of different sizes produce sonar beams of similar shape (Jakobsen et al. 2013), which may be more directional in the field than in a flight room (Surlykke et al. 2009). The resulting 'acoustic field of view' represents the three-dimensional space ahead of a calling bat that is sufficiently ensonified to generate detectable echoes. To modify this acoustic field of view according to the context and habitat, bats may vary the amplitude, frequency, and directionality of calls (Jakobsen et al. 2013, 2015). During the search phase, bats emit echolocation calls at high SPL and high directionality. When bats zoom in on an insect, the echolocation beam can be broadened and the call frequency lowered by almost one octave at the end of the attack (Jakobsen & Surlykke 2010). SPL is adjusted accordingly, with the highest values emitted during the search phase and the lowest values emitted during the terminal phase of an insect capture event. We adjusted the concept of a bat's acoustic field of view to obtain the maximum distance at which bat echolocation calls will be detected by the AUD in the three-dimensional space surrounding a bat. We define this as the field of detection. Similar to a bat's acoustic field of view, a bat's field of detection is not a sphere, but rather a cone; i.e., it is elongated in the forward

direction and contracted laterally (Jakobsen et al. 2013, Ratcliffe & Jakobsen 2018). Owing to the non-spherical shape of the field of detection, the **detection probability at the nacelle depends on the approach angle of the bat in relation to the microphone (Fig. 4)**. This relationship gets stronger with increasing directionality of echolocation calls. **Bats remain undetected when approaching WT's from the leeward (downwind) side**, because the acoustic shadow cast by the tower prevents the echolocation calls from reaching the AUD. In summary, the probability of detecting bats is severely impaired if the bats do not approach the AUD directly in a straight line from the upwind side, for AUDs installed in the nacelle between tower and blades (Fig. 4). A recent study suggested that some bats may forego echolocation, which would reduce detection probability further (Gorresen et al. 2017, Corcoran & Weller 2018), even if the omission of echolocation is limited to short periods. Further evidence is needed about how often bats forego echolocation when flying at high altitudes.

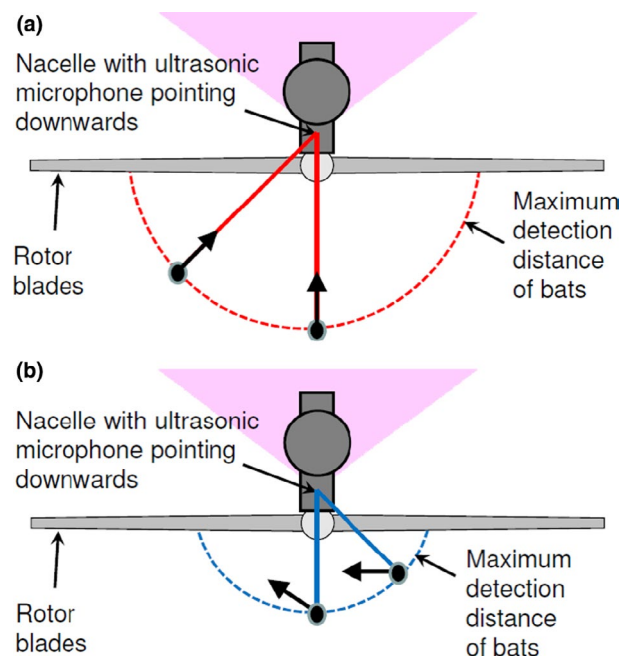


Fig. 4. Schematic depiction of how bat flight direction in relation to automated ultrasonic detectors (AUDs) affects detection distance. The image is of a wind turbine as seen when looking upwards from the ground, showing tower and nacelle (dark grey) and rotor blades (light grey). The backward triangle marks the area on the leeward (downwind) side where bats will remain undetected due to the tower's acoustic shadow. (a) Two bats flying directly towards the AUD at the nacelle in a straight line (points and black arrows). The dashed line depicts the maximum detection distance for the echolocation calls of those bats. (b) Two bats flying at an angle of about 45° relative to the direction of the AUD. Owing to the forward directionality of the emitted calls, the maximum detection distances for these bats are shorter than for those bats flying directly towards the AUD (a).

Variable flight behaviour of bats affects the probability of detecting them with automated ultrasonic detectors

Nacelle monitoring of bats makes the implicit assumption that the distribution of flight altitudes is uniform within the risk zone, yet this assumption simplifies the true flight behaviour of bats. Information on bat flight altitude is scarce, yet available data show that flight altitude varies between species. **Edge-space foraging bats fly closer to the ground than open-space foraging bats** (Roemer et al. 2017, Wellig et al. 2018). Species-specific flight behaviour also varies seasonally. For example, noctules fly up to several hundred metres above ground, yet on average within the risk zone of WT, during the non-migration period (Roeleke et al. 2016, O'Mara et al. 2019a), but they fly at much higher altitudes during the spring migration period (O'Mara et al. 2019b). **Species- and context-specific flight altitudes lead to variation in bat acoustic activity at nacelle height** (Fig. 5). Consequently, the probability of detecting bats with AUDs installed at nacelles will not correlate with the collision risk at the WT if the species and context are not taken into account (Fig. 5).

The estimated risk zones formed by bat flight altitude and WT heights are **based on the additional assumption that flight trajectories remain unaffected in the presence of an operating WT**. Recent studies suggest that this assumption is invalid, because **bats may actively approach WT's for several reasons**: 1) bats may mistake the turbine for a tree in which they could roost (Cryan et al. 2014); 2) they may feed on insects that aggregate at WT's (Rydell et al. 2016); 3) they may get disoriented close to WT's because of ultrasonic noises or artificial light (Voigt et al. 2017); or 4) they may use WT's as landmarks for orientation and for social interactions (Kunz et al. 2007). **When approaching WT's, bats do not necessarily fly in a straight line, but rather perform loops, dives, hovering flights, and chases**. Cryan et al. (2014) reported that bats most often approached WT's from the leeward (downwind) side, and the frequency of such approaches increased with increasing wind speed (Cryan et al. 2014). Since AUDs are usually placed upwind from the tower (i.e. at the front of the nacelle, which is oriented towards the wind), leeward approaching bats may not get detected, unless bats emerge out of the space where the tower casts an acoustic shadow on the AUD (Fig. 4). Bats approaching the nacelle by flying upwards along the tower may enter the collision risk zone before being detected by the AUD. This is particularly relevant for bats gleaning insects from the tower surface by using low-amplitude echolocation calls, because the detection distance for these bats is likely to be shorter than the rotor length (Budenz et al. 2017). The bats' flight speed and calling rate also crucially influence the

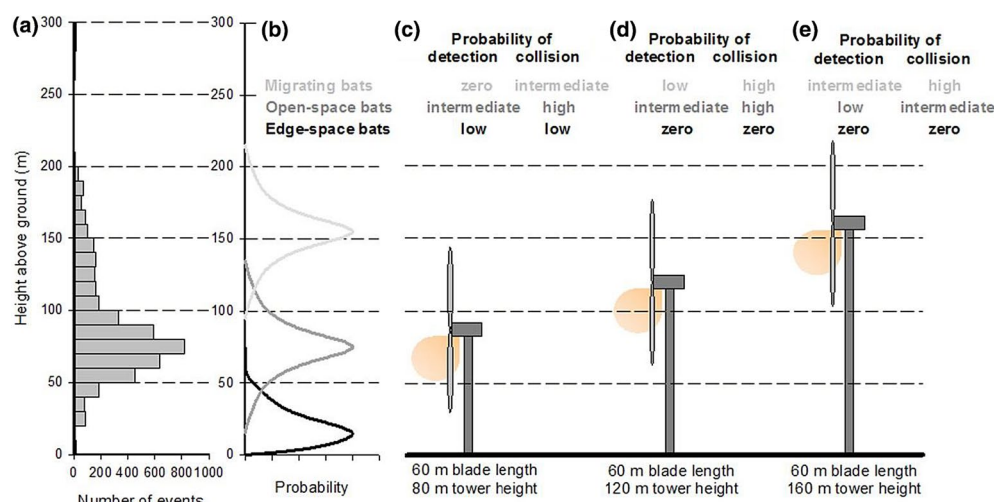


Fig. 5. Schematic description of probable flight altitude of bats in relation to the detection probability and collision risk at wind turbines (WTs) with variable tower height (80–160 m). (a) Flight altitudes of non-migrating noctules *Nyctalus noctula* (Roeleke et al. 2016) when foraging above farmland. (b) Schematic density plots of flight altitudes for edge-space foraging bats (black), open-space foraging bats (dark grey), and migrating bats (light grey). (c–e) Detection probability and collision risk at three different WT heights for the three flight scenarios depicted in (b) and for the focal area of acoustic bat detection (depicted in light pink) at each WT. Note the mismatch between detection probability and collision probability under certain conditions.

likelihood of detection: the faster a bat flies and the less often it calls, the fewer echolocation calls will be available to trigger recordings, and thus, the fewer echolocation calls will be available for species identification (Runkel 2020). On the contrary, bats hovering or searching at nacelle height in an upwind direction will result in many recorded echolocation calls, which will be misinterpreted as a high number of bat individuals; thus, their estimated fatality risks may be overestimated. As a consequence, the conventional assumption that the total number of echolocation calls per night at WTs is a good predictor of the number of bats interacting with WTs may be violated (Solick et al. 2020, Bach et al. 2020a).

ECHOLOCATION CALLS ARE DETECTED BY THE AUTOMATED ULTRASONIC DETECTOR (STEP 2)

Runtime duration and failure of automated ultrasonic detector

A large variety of techniques are available as ultrasonic detectors, but the most dominant technique is full-spectrum recording (Fraser et al. 2020). Optimally, an AUD would record any bat flying into the risk zone of the operating blades, neglecting all non-bat ultrasonic noise. Yet, the type of AUD may have a strong influence on its ability to differentiate between echolocation calls and background noise. Testing five typical ultrasonic detectors in a field situation revealed that detectors recorded between 40 and

93% of all broadcast calls (Adams et al. 2012), showing that some detectors may miss a substantial proportion of bats passing by. When combined with sufficient memory, real-time AUDs can be left unattended for extended periods of time at nacelle height. This is important, because consultant ecologists are rarely granted frequent access to the nacelle of a WT. The capacity of the memory card defines largely how many calls can be stored before data have to be downloaded and memory cleared. Recently, AUDs became available which offer the option to download data remotely (see <http://www.bioacousticstechnology.de/?lang=en>, <https://ecoobs.com/products/hardware/gsm-batcorder/>, and https://www.batlogger.com/en/products/batlogger_we/) if a wired or wireless network is available at the site. Besides storage capacity, power supply and consumption may also determine the actual runtime of an AUD. Computer-based AUDs usually require a mains power supply, while conventional AUDs may run from batteries for multiple weeks or even months. Runtime parameters of AUDs have a strong impact on the detection probability of bats. AUDs with high sensitivity increase the probability of detecting bat passes, yet they may also lead to more false-positive recordings and result in a higher number of recordings for later screening. AUDs with a low sensitivity generate fewer data, but faint bat calls may be missed, thereby reducing the probability of recording the true number of bat passes. AUDs are also known to fail for various reasons; failure rates have been documented to amount to 6 to 38% of the total monitoring time (Weber et al. 2018).

Limited microphone sensitivity

The sensitivity of ultrasonic microphones depends largely on their size: **small microphones are usually less sensitive than large microphones** (Ratcliffe & Jakobsen 2018). Based on practical considerations, small electret condenser Knowles microphones are most often used for nacelle monitoring, because they are less prone to damage or ageing. Although regular calibration may document and partly control for ageing effects, full compensation for ageing is impossible. Even though the AUD technique is suitable for recording bat echolocation in a reproducible way, microphones influence the recorded sound, which may even prevent species identification under certain situations (Ratcliffe & Jakobsen 2018). The sensitivity of ultrasonic microphones has not largely increased over past decades; i.e., **the detection thresholds of ultrasonic microphones seem to be intrinsically limited by the physics of acoustics and electromechanics**. Parabolic microphones with a larger detection range seem impractical, since these are tuned to a specific frequency and since lateral coverage is low. Thus, more parabolic microphones would have to be installed to take advantage of their increased detection distance. In conclusion, the construction of larger WTs is unlikely to be accompanied by increasingly sensitive microphones with larger detection distances.

Triggering of recordings

The likelihood of recording a passing bat depends strongly on the trigger function of the AUD (Table 1). The main criteria for triggering a recording are that **the received SPL or energy level at the AUD must exceed a critical threshold in relation to noise**, with downstream criteria used to distinguish bat echolocation calls from non-bat noises. **A crucial parameter defining the triggering of recordings is the SNR, i.e. the ratio between the recorded amplitudes of the signal of interest (bat call) and noise (all non-bat sounds)**. The SNR depends both on external factors (such as the distance of the bat to the AUD and

the environmental noise) and on factors specific to the AUD (such as the microphone, preamplifier and amplifier circuitry, and filter banks). A high SNR facilitates the downstream detection and extraction of calls, extraction of call parameters, and automated species identification. As low internal noise of an AUD increases SNR, AUDs should be equipped with appropriate hardware, such as low-noise circuits and appropriate amplification, to maximise detection distances while minimising noise conditions. **The specific criteria applied for activating the recording of AUDs vary across types and are most often the intellectual property of the manufacturer**. As a consequence, criteria and algorithms are usually not well documented, let alone evaluated for precision and accuracy.

SNR and triggering of recordings can be affected by ultrasonic and electromagnetic interferences, which may mask bat calls and trigger unintended recordings when strong ultrasonic and electromagnetic noise produced by the WT interacts with the AUD (Table 1). **Some AUDs automatically adjust their threshold to the ambient noise**, while others offer trigger functions that lead not only to fewer recordings of environmental noise, but also to lower trigger sensitivity for echolocation calls of low frequencies. As a consequence, either low-frequency calling bat species are missed more often than high-frequency calling bats, or the threshold, and thus detection distance, varies over time.

In addition to technical aspects intrinsic to the specific AUD, extrinsic acoustic factors influence the recorded call quality close to the nacelle (Table 1). **Large structures, such as the nacelle, tower, and blades, may reflect the call, resulting in (multiple) echoes being recorded** in addition to the actual calls. Furthermore, depending on the relative position of bats in relation to echo-reflecting structures, echoes and calls may reach the microphone at similar times. **Overlapping calls and echoes may then lead to interference of the acoustic waves**, i.e. cancelling and amplifying specific frequencies, leading ultimately to lower quality recordings of echolocation calls and impaired species identification. Lastly, the application of ultrasonic

Table 1. Matrix illustrating the possible relationships between correct or incorrect triggering of recording of bat echolocation calls by automated ultrasonic detectors (AUDs) and the underlying causes. False negatives and false positives must be avoided in order to generate biological meaningful data from AUDs at wind turbines. SNR = signal-to-noise ratio

		Recording triggered?	
		No (no recording)	Yes (recording)
Bat present?	Yes (bat present)	False positive: bat present, but no recording, e.g. caused by: low SNR, AUD failure, full memory	Bat present and bat calls recorded
	No (no bat present)	No bat present and no bat calls recorded	False negative: no bat present, but non-bat noise recorded, e.g. ultrasonic noise or electromagnetic noise

deterrents at WTs may impair the triggering of echolocation recordings by AUDs. The use of ultrasonic deterrents and the monitoring of acoustic activity of bats by means of AUDs may not be practical at the same time.

AUTOMATED IDENTIFICATION OF BAT SPECIES BASED ON ECHOLOCATION CALL PARAMETERS (STEP 3)

The widespread use of AUDs has facilitated the rate at which large numbers of data can be recorded. Depending on the level of bat activity at a study site, several thousand to several hundreds of thousand files may be stored, awaiting later analyses. Inspecting all these files manually, i.e. visually checking for echolocation calls and comparing their acoustic parameters to those of a call library, is a prohibitively time-consuming effort. This painstaking task led to the development of software tools that promise to identify bat species automatically, within a confidence margin, based on spectral and temporal features of echolocation calls. The limitations of the available programmes have already been addressed (Russo & Voigt 2016, Rydell et al. 2017, Russo et al. 2018); therefore, we will focus on only a few details here.

The potential and limitations of call libraries in the face of echolocation call variability

Echolocation has evolved, for the benefit of the calling bat, to aid its orientation at night. Thus, echolocation calls are adapted to the specific habitats in which bats fly, leading to the convergent evolution of call structures and ultimately to low interspecific variation within species of the same guild (Schnitzler & Kalko 2001, Russo et al. 2018), which complicates species identification. For example, the echolocation calls of open-space foraging bats are characterised by low ultrasonic frequencies, long call durations, high SPL, and low repetition rate. A second critical point is the large intraspecific (in fact intra-individual) variation in echolocation call parameters. Within seconds, the same individual may change call structure dramatically in response to habitats with varying levels of clutter (Obrist 1995, Jakobsen & Surlykke 2010, Russo et al. 2018) or when switching from orientation to prey attack (Kalko & Schnitzler 1989, Schnitzler & Kalko 2001). Although knowing the level of intraspecific variation in a reference library helps to identify a bat species based on its echolocation calls, extreme call parameters may not be covered by a reference library. Lastly, there is a significant geographical variation in echolocation calls within species (Russo et al. 2018), which limits the usability of available reference libraries.

Owing to the small interspecific and large intraspecific variation, it is often challenging and sometimes even impossible to assign the recorded echolocation calls to a species with any degree of certainty (Russo & Voigt 2016). Accordingly, species are lumped to acoustic groups with similar call shapes. For example in Europe, bats of the genera *Nyctalus*, *Vespertilio*, and *Eptesicus* are often grouped as 'nyctaloid' or 'NEV'. Pooling species has strong implications for conservation practice, since knowing which species are mostly affected by WTs is of crucial importance for protecting affected populations. Bat populations that lose more individuals due to anthropogenic factors, such as WTs, than they are able to recruit as juveniles will ultimately decline and go extinct in the future (Frick et al. 2017). Further, national legal frameworks usually focus on species rather than species groups, making data on species group levels useless in the worst case. Missing species-specific impacts at WTs may mask the real effects on single species and complicate the implementation of mitigation schemes.

FUTURE RESEARCH DIRECTIONS

Research is required in several areas if we are to overcome the limitations of acoustic monitoring at WTs, to evaluate the fatality risk for bats, and to warrant that proxies for bat activity at WTs match more closely the true mortality risk of bats at WTs.

Additional AUDs could improve the probability of detecting bats at WTs. We consider it particularly critical to overcome the problem of acoustic shadows imposed by the physical structures of the nacelle and the tower. This problem could be solved by installing complementary AUDs on top of and at the leeward side of the nacelle (Cryan et al. 2014). We acknowledge that these might be more exposed to weather and thus may deteriorate faster, making ultrasonic recordings impossible at certain times, for example after heavy rainfall. To account for bats approaching the risk zone by circling upward along the tower and to increase the surveillance of the risk zone, it may be advisable to install AUDs on the tower, a few metres below the lowest point of the operating rotor blades (Bach et al. 2020b). Such AUDs would also detect bats flying at lower altitudes, such as edge-space foraging bats, and bats gleaned insects from the tower surface. Acoustic recordings at these lower heights may reveal larger numbers of bats, because wind speed decreases from nacelle to ground level, thus providing more favourable conditions for most bats (Wellig et al. 2018). However, we acknowledge that stationary AUDs fixed to the tower at a specific height may not adjust to the 360° horizontal rotation of the nacelle when wind direction changes.

Complementary methods for monitoring bats in the risk zone could be considered, to overcome the limitations of acoustic monitoring. Radar, thermal imaging, or camera systems could provide additional data to predict the risk for bats at operating WTs (Gorresen et al. 2017, 2019). Such complementary systems could even help in identifying flight trajectories in real time and in forecasting the movements of bats near operating WTs. So far, radar, thermal imaging, and camera systems have not been used to identify bat taxa – an undeniable advantage of acoustic methods. However, they might allow researchers to obtain information on wing-beat frequency and specific flight trajectories, which might help to identify the target species.

There is an urgent need to improve our knowledge of bat movement behaviour in general, and specifically of bat movements near WTs. Large-scale movements could be quantified with Global Positioning Systems or automated very-high-frequency tracking systems, to reveal the distances at which bats respond to WTs. This may also help to inform stakeholders about which factors make WTs attractive for bats.

Connected and synchronised microphones with a remote access option would allow better and faster data access, and thus enable consultant ecologists to monitor movements of bats around WT structures in real time.

Although recent studies have extended our libraries of species-specific echolocation calls, we still need a more comprehensive knowledge of the echolocation call features of bat species worldwide. Providing free access to reference calls would help in establishing a global call library of bat echolocation calls. This would also meet the need for call libraries to encompass as much call variation as possible, in order to account for all variation in call characteristics. Neural networks and machine vision have strongly advanced image analysis in recent years. In comparison, machine learning and automated call analyses are lagging behind. Further improvement of neural networks (MacAodah et al. 2018) and non-spectrogram-based algorithms could help improve the accuracy of species identification (Heim et al. 2020).

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Data Availability Statement

Data from our study are freely available at datadryad at <https://doi.org/10.5061/dryad.ffbg79ctp>

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