Aerial-hawking bats can glean prey items from surfaces similar to wind turbine towers: implications for reducing bat fatalities at wind facilities

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AERIAL-HAWKING BATS CAN GLEAN PREY ITEMS FROM SURFACES SIMILAR TO WIND TURBINE TOWERS: IMPLICATIONS FOR REDUCING BAT FATALITIES AT WIND FACILITIES

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Introduction

Greenhouse gas emissions are a large contributor of climate change, which has been predicted to threaten biodiversity and result in the loss of hundreds of species from a wide variety of taxa (Hughes 2000; Butchart et al. 2010; Younger et al. 2016).The US government recognizes the need to expand and diversify its renewable energy resources to offset the impacts of greenhouse gas emissions created from the use of coal and oil on the climate and environment (US DOE 2015 retrieved from http://energy.gov/eere/wind/maps/wind-vision; US EPA 2014). As such, wind energy is a promising, renewable energy resource for the US, with Texas leading in both wind energy potential and production (US DOE 2015; Texas Wide Open for Business 2014). Wind power generation is considered most productive where annual average wind speeds are above 7 m/s and in the US, such wind resources generally occur across the Great Plains (US EIA 2011). For example, Lu et al. (2009), indicated that states within the Great Plains could provide up to 10,000 TWh of wind energy, compared to some states outside this region producing <1 TWh. Wind energy, however, has some potentially negative environmental impacts on wildlife (Kunz et al. 2007; Schuster et al. 2015).

Wind turbines have been linked to high numbers of bat fatalities worldwide (Voigt et al. 2012; Hayes 2013; Lehnert et al. 2014), with estimates of over 600,000 bats killed in the US alone for the year of 2012 (Hayes 2013). Within the US, the majority of bats killed at wind turbines are echolocating, insectivorous, migratory species that roost in trees (the top 3 species collected in carcass searches at wind turbines are the hoary (*Lasiurus cinereus*), eastern red (*Lasiurus borealis*), and silver-haired (*Lasionycteris noctivagans*) bat; reviewed in Arnett and Baerwald 2013; Schuster et al. 2015). Many of these fatalities correlate with nights with lower wind speeds, as bats will often restrict their movement during periods of strong wind velocities, and between the mid-summer to early autumn months, a time in which migratory bats will relocate to their winter habitats (Horn 2008; Arnett et al. 2011). A possible strategy to reduce fatalities has been to increase the cut-in speed (the speed at which a wind turbine begins to produce electricity); however, this mitigation measure results in a decrease in the amount of electricity produced by the wind turbines. Furthermore, the ultimate causes, why the bats are coming close enough to be hit by the wind turbine blades, remain largely unknown (Kunz et al. 2007; Arnett et al. 2008).

Several hypotheses have been proposed to explain why bats may come into contact with wind turbines (Cryan and Barclay 2009). These hypotheses are grouped into three categories: random collisions, coincidental collisions, and collisions due to attraction. It should be noted, however, that these hypotheses are not mutually exclusive and may be species-specific. Random collisions represent fatalities that occur by chance and reflect the population density within a given area. Coincidental collisions represent fatalities that occur because the wind turbines are located in an area where bat activity may be high during certain times of the year (Arnett et al. 2008). For example, many birds and bats use wind corridors as migration routes and wind facilities are often located within these corridors to maximize wind energy generation (Kunz et al. 2007; Baerwald and Barclay 2009).

Finally, bats may be attracted to wind turbines because they perceive or misperceive them to provide a resource (Rydell et al. 2016), or because bats may simply be investigating the turbines out of curiosity (Cryan and Barclay 2009). In support of the attraction hypothesis, Jameson and Willis (2014) found migratory tree bats to be attracted to tall structures such as wind turbines. Additional studies have shown that bats will also approach wind turbines, at times close enough to touch the turbine surfaces (e.g., Horn et al. 2008, McAlexander 2013). This type of activity suggests that bats are attracted to wind turbines, perhaps because the turbines provide or appear to provide resources. There are five main resources that bats require: 1) water, 2) foraging sites, 3) roost sites, 4) mating opportunities, and 5) access to these resources (i.e., commuting and migratory routes). For a wind turbine to be perceived or misperceived as, for example, a foraging site, it would have to: 1) support or provide a potentially diverse assemblage of prey species, 2) have an abundance of prey that occur in similar or greater numbers than in the surrounding area, and 3) have prey that are as easy to capture as from the surrounding area. While a wind turbine does not appear to have any obvious resources that would necessarily attract the types of invertebrate prey insectivorous bats are likely to eat, a recent study has shown that the white or light coloration of the turbines attracts insects (Long et al. 2011). Cochran (2013) found that the invertebrate assemblage on turbines was made up of species that were representative of the prey found in the diets of local bats, and that invertebrate abundance near turbine towers did not differ from the surrounding area. Additionally, invertebrate remains in fecal samples from bats found on turbine towers and transformers matched the invertebrate species found on the turbine towers (Bennett, Hale, and Foo unpublished data). Finally, acoustic surveys conducted at wind turbines by McAlexander (2013) recorded both foraging and feeding buzz calls in close proximity to the tower surfaces, indicating that bats are actively foraging around turbine towers.

The results of all these studies support the foraging attraction hypothesis. Thus, a way to stop bats from foraging around wind turbines would be to eliminate the insects. However, the use of insecticides is not economically or logistically realistic. Similarly, if the current color of operational wind turbines is attracting invertebrates, then altering that color might be a potential solution. Yet again, the current color of turbines has been specifically selected to prevent the turbine mechanics from overheating, therefore changing the color may not be an option.

When foraging, Vespertilioniforme bats use returning echoes from ultrasonic vocalizations (i.e., echolocation) to find and capture prey. While there are a variety of foraging strategies that echolocating bats can employ to effectively catch prey, bats commonly killed at wind turbines in the US specialize in aerial hawking (Ammerman et al. 2012; Arnett and Baerwald 2013). As a foraging strategy, aerial hawking involves identifying and capturing volant prey in flight (Jones and Rydell 2003; Harvey et al. 2011). Nevertheless, a number of studies have shown that bats can switch foraging strategies to take advantage of more readily accessible prey (Ratcliffe and Dawson 2003; Todd and Waters 2007; Hackett et al. 2014). For example, the little brown bat (*Myotis lucifugus*) and the northern long-eared bat (*Myotis septentrionalis*) were both found to be able to switch from aerial hawking to gleaning pinned moths from a bark-covered trellis (Ratcliffe and Dawson 2003). In contrast to aerial hawking, gleaning involves bats approaching and grabbing or scooping (using feet, tail membrane, or mouth) sedentary prey from surfaces. Gleaning has been shown to be more efficient from smooth surfaces such as large leaves and water compared to textured surfaces (Siemers et al. 2005; Geipel et al. 2013; Clare and Holderied 2015). The smooth surface facilitates echolocation as most of the returning echo that a bat receives is reflected back from the prey, whereas all other call energy is reflected away from the bat by the smooth surface (known as specular reflection; Fig. 1). In other words, prey items on smooth surfaces become acoustically conspicuous to gleaning bats, a phenomenon known as the acoustic mirror effect (Jones and Rydell 2003; Geipel et al. 2013).

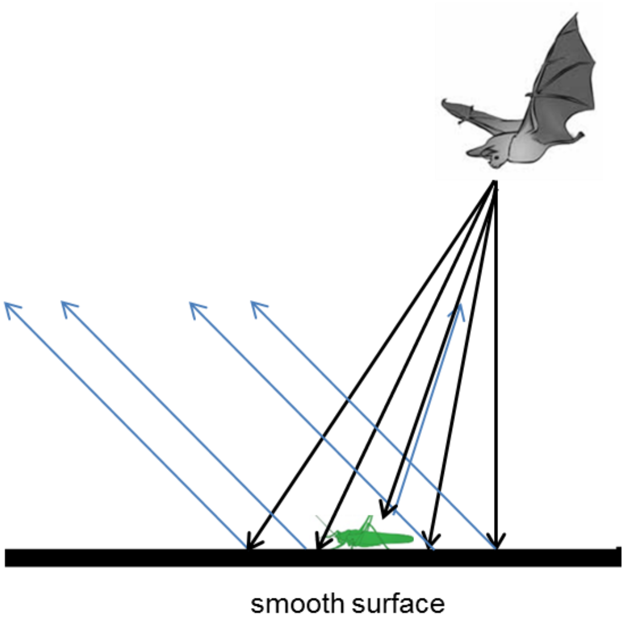

Figure 1: Diagram demonstrating the reflection pattern generated when a bat echolocates at a prey item on a smooth surface.

McAlexander (2013) also demonstrated that wind turbine towers are acoustically similar to smooth surfaces such as water. Based on this result, we hypothesized that the smooth surface of a wind turbine tower could act as an acoustic mirror, and any invertebrates aggregating on the light-colored surface may represent a readily accessible foraging resource for bats. In order to take advantage of prey resting on the turbine towers, however, bats would have to switch from an aerial hawking strategy to a gleaning foraging strategy. If bats that are commonly killed at wind turbines can switch foraging strategies to take advantage of conspicuous and abundant prey on turbine towers, then this foraging activity (i.e., bats entering the rotor swept zone, defined as the area occupied by the blades of the wind turbine when they are in motion, to glean prey from the tower surfaces) may be contributing to bat-wind turbine mortality. We further predict that if the turbine tower surfaces were altered so that they were no longer smooth, then prey items would not be as conspicuous to echolocating bats because of the background clutter generated by returning echoes from the textured surface itself (Clare and Holderied 2015; Fig. 2). Thus, we hypothesize that texturizing wind turbine towers would eliminate the acoustic mirror effect, thereby reducing a bat's ability to efficiently locate prey items on the towers, which in turn would make wind turbines a less suitable foraging resource.

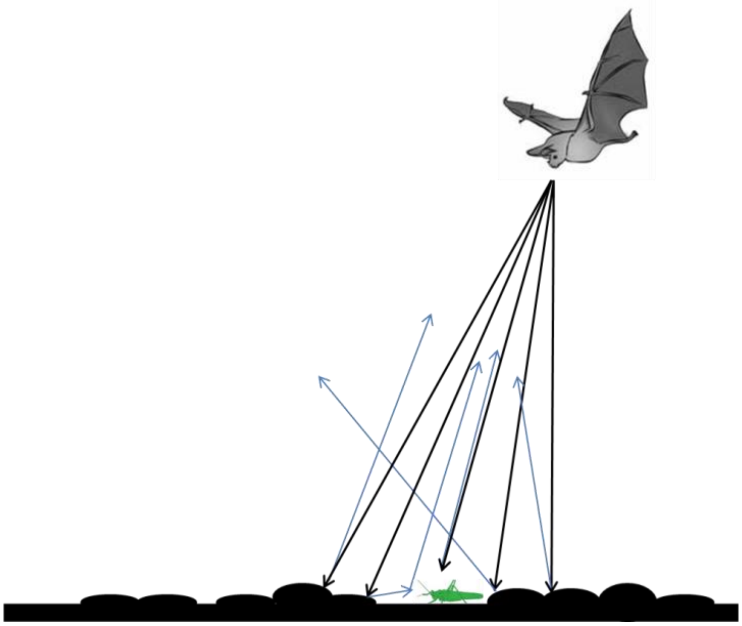

Figure 2: Diagram demonstrating the reflection pattern generated when a bat echolocates at a prey item on a textured surface.

We therefore designed a two-part experiment using wild-caught bats (including species commonly killed at wind turbines) in a flight facility to 1) determine if aerial-hawking bats could switch to a gleaning foraging strategy, and 2) estimate foraging success at a range of smooth and textured surfaces. Ultimately, the results from these experiments will provide important insights into bat foraging behavior. In addition, this research may be used to inform the development of a texture coating that could be used as a novel mitigation strategy to reduce bat foraging activity at turbine towers, especially within the rotor swept zone, and thus reduce bat fatalities at wind facilities worldwide.

Methods

Mist netting surveys

We conducted mist netting surveys to capture bats at 7 local parks; 6 were owned and operated by the City of Fort Worth, including Trinity Park (N 32° 43’ 4”, W 97° 21’ 36”), Forest Park (32° 43’ 10”, W 97° 21’ 09”), Foster Park (N 32° 41’ 0”, W 97° 22’ 26”), Overton Park (N 32° 42’ 6” W 97° 22’ 59”), Z Boaz South Park (N 32° 41’ 38”, W 97° 27’ 6”), and Oakmont Linear Park (N 32° 39’ 45”, W 97° 25’ 36”); and 1, Rocky Creek Park (N 32° 36’ 22”, W 97° 27’ 8”), owned and operated by the US Army Corps of Engineers. These parks, ranging from about 5 to 405 hectares, were primarily used for public recreation comprising walking trails, maintained lawns, and water features (e.g., rivers, lakes, and ponds). Preliminary acoustic monitoring surveys at these parks revealed that all 6 bat species found in north-central Texas were present including evening (*Nycticeius humeralis)*, tri-colored (*Perimyotis subflavus*), and Mexican free-tailed (*Tadarida brasiliensis*) bats, as well as the three migratory species commonly found in wind farm fatalities, hoary, eastern red, and silver-haired bats.

At specific locations, where we identified frequent bat activity in the preliminary acoustic monitoring surveys, we put up mist nets, a commonly used technique to catch bats (Fig. 3). We used a combination of mist net setups across our survey locations to maximize bat capture, including standard assembles with 2.5 m high poles and a single monofilament net from Avinet Inc. (Dryden, NY) and triple high assembles with 7.3 m high poles and 3 nets. In addition, depending on the topography of a location, mist net length ranged from 6 to 18 m. Once set up, we opened mist nets 10 minutes before dusk and kept them open for up to 3 hours after dusk. Note that this time coincides with the primary emergence of local bats from their day roosts and is a major foraging period for them (Duverge et al. 2000; Reichard et al. 2009). Using headlamps, we checked each net for captured bats every 10 minutes. In addition, between checks we moved >10 m away from the mist nets and limited the use of headlamps to minimize disturbance to the bats. Upon capture, we carefully removed bats from the nets by hand using bite-proof gloves (e.g. leather golf gloves or leather mechanic/gardening gloves). If we could not remove a bat from the net within a 5 minute period, the bat was then quickly cut out of the net ensuring that its total time in a net did not exceed 15 minutes. Once a bat was successfully removed from a net, we immediately assigned it a unique identification code, recorded species, sex, breeding status, location of capture, time, and date. Bats identified as pregnant, lactating, carrying young, or federally endangered (note that no federally endangered bats are known to currently reside in north-central Texas) were taken away from the mist nets and released as quickly as possible. We placed all other bats in cloth bags (one bat per bag) prior to being transported to the bat flight facility (see below). Nets were then closed and taken down at the end of the mist netting survey period or when up to 8 bats had been caught.

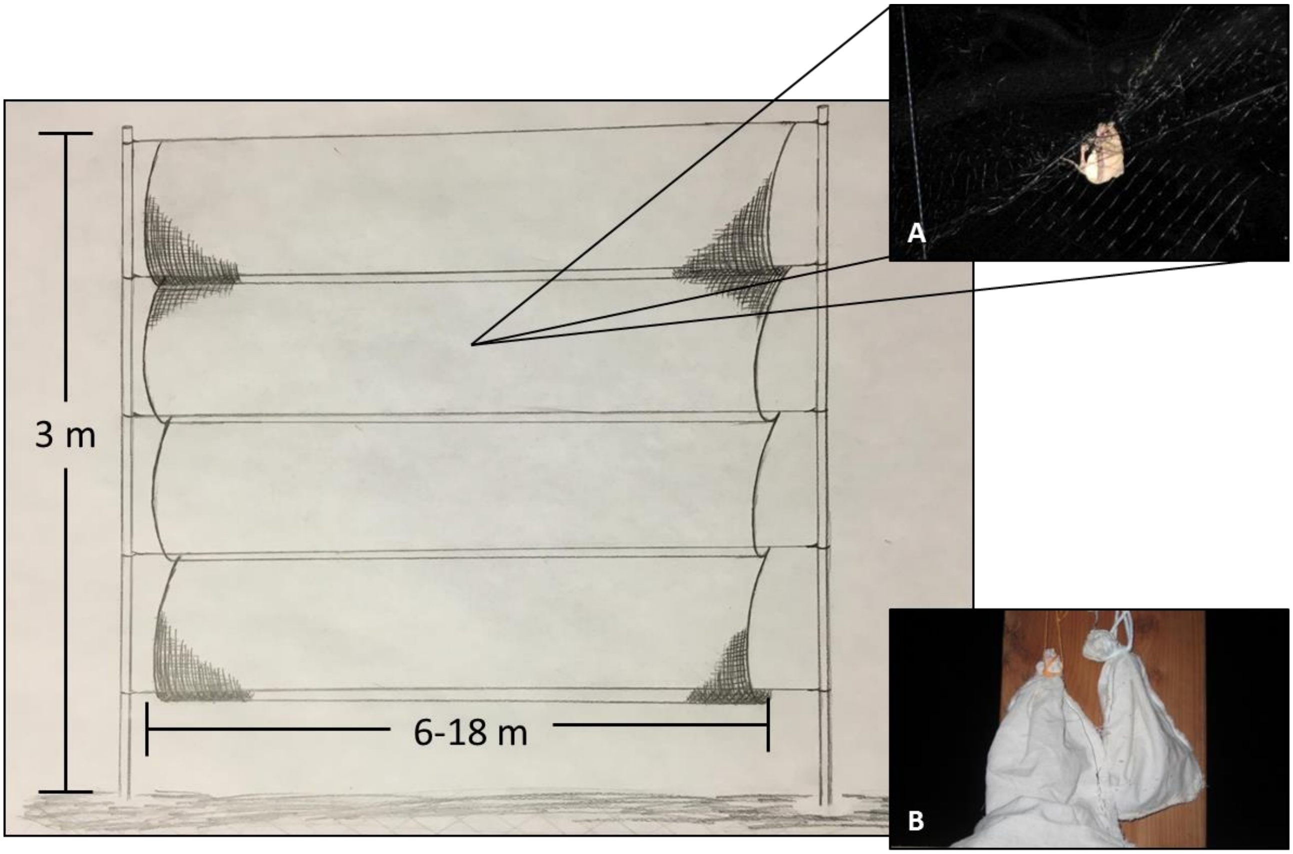

Figure 3: Illustration of a standard mist net assembly with images of A) a bat caught in a mist net and B) bats in cloth bags waiting to be transferred to the flight facility.

We conducted mist netting surveys from the end of April to the end of September 2015, but only undertook surveys when bats were needed. Individual bats were kept in the flight facility for up to 4 weeks after which time they were released back to their site of capture. In addition, to prevent resident bats from learning to avoid the mist nets, surveys were only conducted at each park once a week.

Note that for these mist netting surveys, we had an Institutional Animal Care and Use Protocol (IACUC permit #14-01) in place. This approved protocol was required by federal regulations to use vertebrate animals in research, teaching, and testing under the Health Research Extension Act (HREA) and key amendments to the Animal Welfare

Act (AWA). Furthermore, as part of the IACUC, all surveyors involved with mist netting had received the rabies pre-exposure vaccination series. Finally, we received permits from the City of Fort Worth and the US Army Corps of Engineers allowing us to be in the parks after daylight hours.

Bat flight facility

The flight facility in which we kept the wild-caught bats and completed the foraging behavioral trials (see below) was located at Texas Christian University. The building consisted of a ClearSpan, white polyethylene canvas tent, with a triple-galvanized steel-frame (8.5 m x 14.6 m x 3.3 m TekSupply, Dryersville, IA) and a dirt floor (Fig. 4).

Figure 4: Images of the bat flight facility; exterior (left) and interior (right) with roosting areas and water tray.

As we wanted the bats in the flight facility to behave as naturally as possible, conditions within the facility were kept as similar to the bats’ natural environment as possible. Subsequently, the tent did not have any artificial lights with the exception of the headlamps and UV lights we used during the trials. Similarly, to keep temperature and humidity within the facility comparable to the conditions outside the tent, we installed a series of mesh-covered windows to increase air flow within the tent. In addition, 4 high-velocity floor fans were placed on the outside of the tent in front of windows to increase air movement within the tent. Note these fans were only turned on when temperatures exceeded 36.5°C during the daytime. Finally, to prevent temperatures in the tent exceeding those outside, we covered the roof of the tent in double reflective insulation (Reflectix, Markleville, IN).

We conducted foraging behavioral trials in an 8.5 m x 7.3 m x 3.3 m room within the flight facility. The size of this room was established from preliminary surveys in 2014 to be an effective size for eastern red, evening, and Mexican free-tailed bats to fly and maneuver. In the center of the room, we placed a custom-made, shallow, galvanized steel water tray (2 m x 1 m x 1.5 cm) from which the bats could drink. The tray was coated with EMI5005 RTV Food Grade Adhesive Silicone Sealant (EMI Supply Inc., Monroe NC) to prevent rusting and zinc leaching into the water. We also provided species-specific roosting opportunities along the sides of the room. Soft puppy carriers and carpeted cat houses were placed approximately 2.5 m above the ground for crevice-roosting bats (evening, tri-colored, and Mexican free-tailed bats), and branches held together in tree stands were provided for tree-roosting species (eastern red, hoary, and silver-haired bats; Fig. 4; Lollar 2010).

Bat care

Upon each bat's arrival at the flight facility, we confirmed sex and species, and recorded weight and forearm length, and for identification purposes uniquely marked each individual. For this, we applied different colored or combinations of different colored UV sensitive, non-toxic powder from Eco Pigments (Day-Glo Color Corp., Cleveland, OH) to the dorsal side of the bats, excluding the wings. The colors that were used included signal green, Saturn yellow, horizon blue, blaze orange, aurora pink, and purple (Fig. 5).

Figure 5: Images of Mexican free-tailed bats with UV sensitive powder under white light (left) and UV light (right).

Once released into the flight facility, we checked both the bats and the flight facility daily at 8 am, 12 noon, 4 pm and just prior to the bats' emergence in the evening. For each check, we first searched for the bats to determine where they were roosting, confirm their presence, and identify and attend to any bats showing signs of distress (e.g., lying on the ground). We then inspected the ceiling, walls, and floor of the tent to find and fix any holes and tears that the bats may be able to escape through. In addition, on days when the temperature exceeded 36.5°C, we turned on the fans. During the 4 pm check, all bats were re-powdered to ensure they were adequately marked prior to the foraging behavior trials.

Individual bats were not included in foraging behavior trials until they had acclimated to the flight facility which included flying, voluntarily drinking from the water tray, and foraging activity. Preliminary surveys in 2014 revealed that this process took approximately 1-3 days. Bats that were unable to acclimate were released back to their site of capture accordingly.

Finally, aerial invertebrate prey were available inside the tent, albeit in limited quantities. We therefore supplemented the bats' diet with additional invertebrates caught using UV light traps placed outside the flight facility. After the foraging behavioral trials, the invertebrates on and around the traps were released into the flight facility. In addition to these prey items, each bat was offered mealworms (*Tenebrio molitor*) by hand after the trials were completed. Each mealworm was coated with a vitamin supplement (at a ratio of 1/16 tsp. Pure Coenzyme Q10 (COQ10) powder from BulkSupplements.com to 2 tsp. Miracle Care Vionate Vitamin Mineral Powder; Lollar 2010). Note that the care of bats follows approved IACUC protocols.

Foraging behavioral trials

Can bats switch foraging strategies?

To explore whether insectivorous bats could switch foraging strategies, we conducted a series of foraging behavioral trials to determine whether aerial hawking bats could glean prey items from a smooth vertical surface. We first conducted a pilot experiment to identify a suitable prey item that we could use in our trials. For this, we tested two different prey items; house crickets (*Achetus domesticus*) which are commonly found in the diets of bats (Valdez and Cryan 2013; Bennett, Hale, and Foo unpublished), and mealworms, which are commonly used to supplement the diet of bats in rehabilitation facilities (Lollar 2010). We tied strings (sewing thread) around the thorax of each cricket and mealworm. Note to do this with crickets, we first immobilized them by refrigerating each cricket for >15 minutes. We then hung the crickets and mealworms within the flight facility and observed whether bats took or attempted to take either prey item. In this experiment, we found the bats did not attempt to forage for the crickets, but would take the mealworms. We therefore proceeded with our foraging behavioral trials using mealworms.

We then began foraging behavior trials by confirming that aerial hawking bats in the flight facility could actively forage for prey items in the air. For this, we suspended three live mealworms on strings attached to a clothesline pulley system from the ceiling of the flight facility. The mealworms were positioned ~1 m apart in the center of the room, 1.5 m to 2 m above the water tray (hereafter known as position 1; Fig. 6). The bats were given 3 consecutive nights to demonstrate they were capable of foraging for prey from position 1 before the bats were eliminated from the trials.

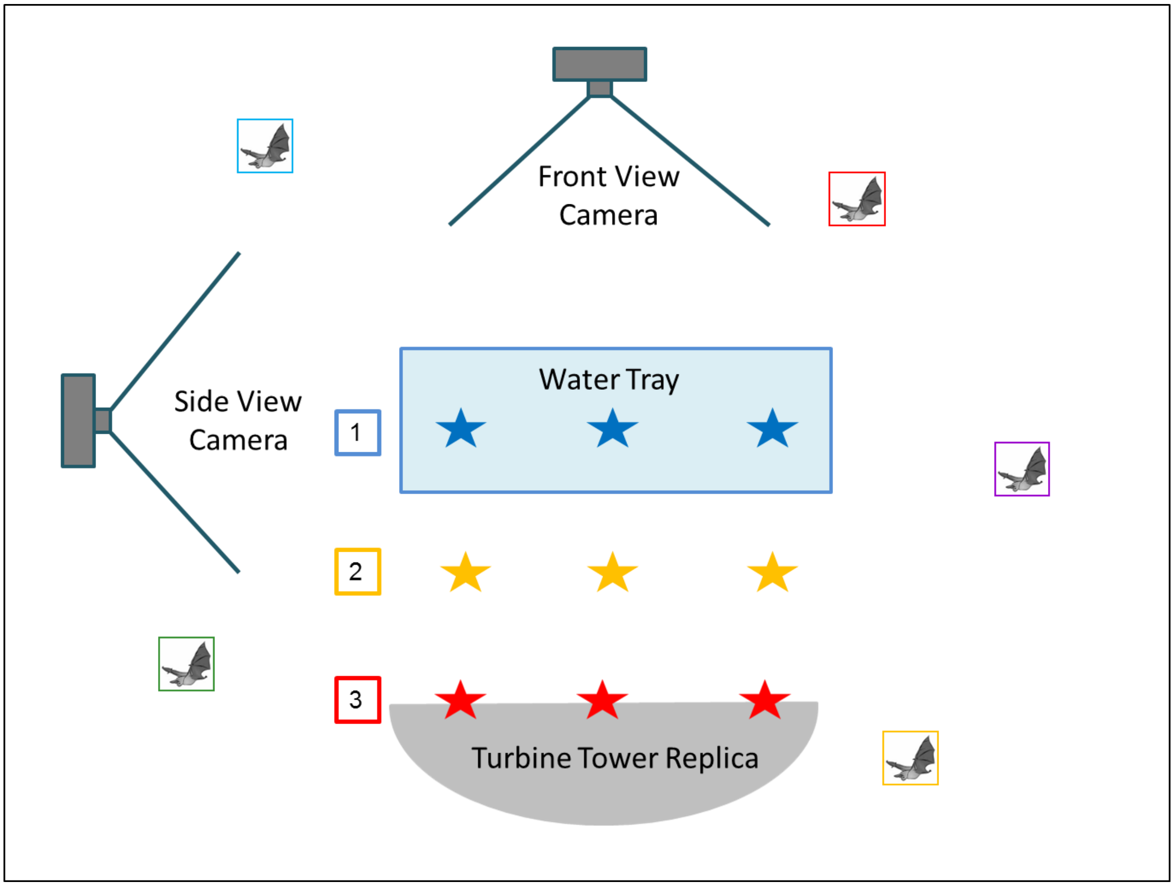

Figure 6: Layout of the bat flight facility during foraging behavioral trials. The stars indicate mealworm position; blue stars for position 1, orange stars for position 2, and red stars for position 3.

If a bat successfully removed mealworms from the strings at position 1, the mealworms were moved closer to the replica portion of a wind turbine tower (hereafter known as position 2; Fig. 6) to determine if the bats were capable of foraging in a more cluttered environment (i.e.,1 m away from the replica surface). The replica portion of a wind turbine tower was made of galvanized steel with one flat and one curved outward facing surface (dimensions provided in Fig. 7). The maximum width of the curved surface was equivalent to the radius midway up the tower (~40 m) of an 80 m high wind turbine tower. The replica was also placed on top of a 1.5 m high table (Fig. 8).

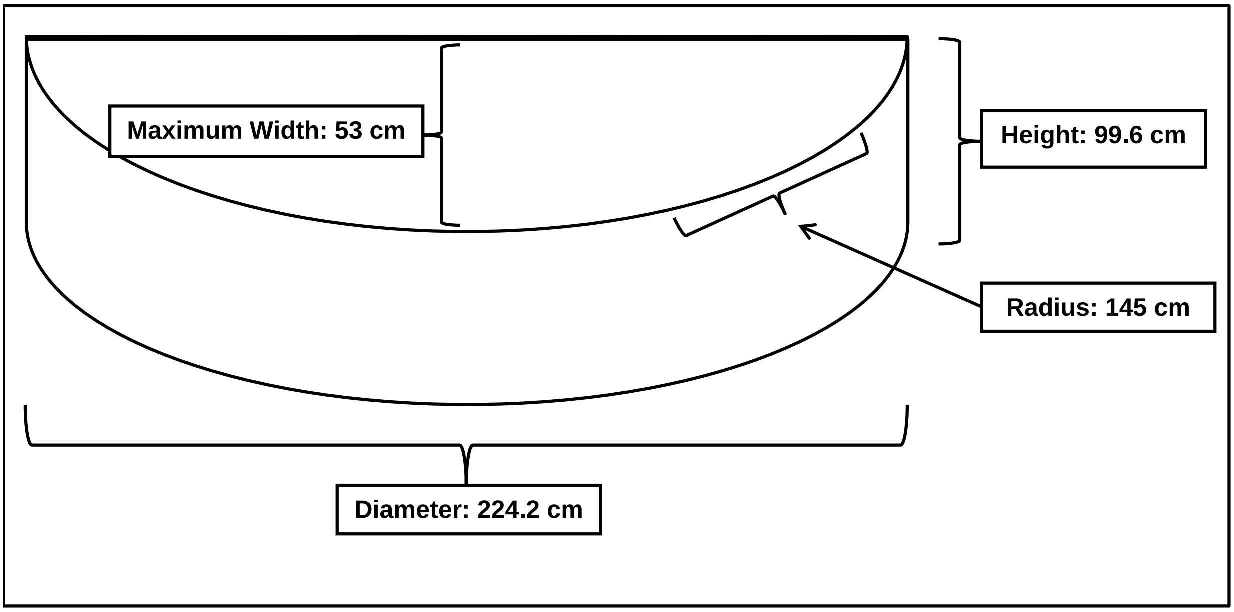

Figure 7: Dimensions of the replica portion of a wind turbine tower used in bat foraging behavioral trials in the flight facility.

Figure 8: Image of the replica portion of a wind turbine tower used in bat foraging behavioral trials in the flight facility.

Again, the bats were given 3 consecutive nights to demonstrate they were capable of foraging for prey from position 2 before the bats were removed from the trials. If individual bats were able to take mealworms from position 2, the mealworms were then suspended against the flat smooth metal surface of a turbine tower replica (hereafter known as position 3, Fig.6).

Based on the properties of this surface (it is flat, smooth, and reflective), we presumed it would represent a surface on which prey items would be acoustically conspicuous to bats. Thus, position 3 tested whether the bats could glean prey items from a smooth vertical surface. We gave bats the opportunity to glean from the wind turbine replica over 3 nights, and between each night, if the bats were unsuccessful, we moved mealworms back to position 2 to ensure the bats were still capable of foraging naturally.

If the bats successfully gleaned from the flat metal surface, the bats were next presented with mealworms against the curved metal surface of the replica portion of a wind turbine tower (hereafter referred to as position 4). For this, the turbine tower replica was turned around so that the curved edge faced the water tray (Fig.9). The curved metal surface represented a smooth surface on which the prey items would still be acoustically conspicuous, albeit curved, to assess whether bats could glean from a smooth vertical curved surface. The curvature of the surface was equivalent to a GE 1.5 MW wind turbine tower at ~40 m from the ground.

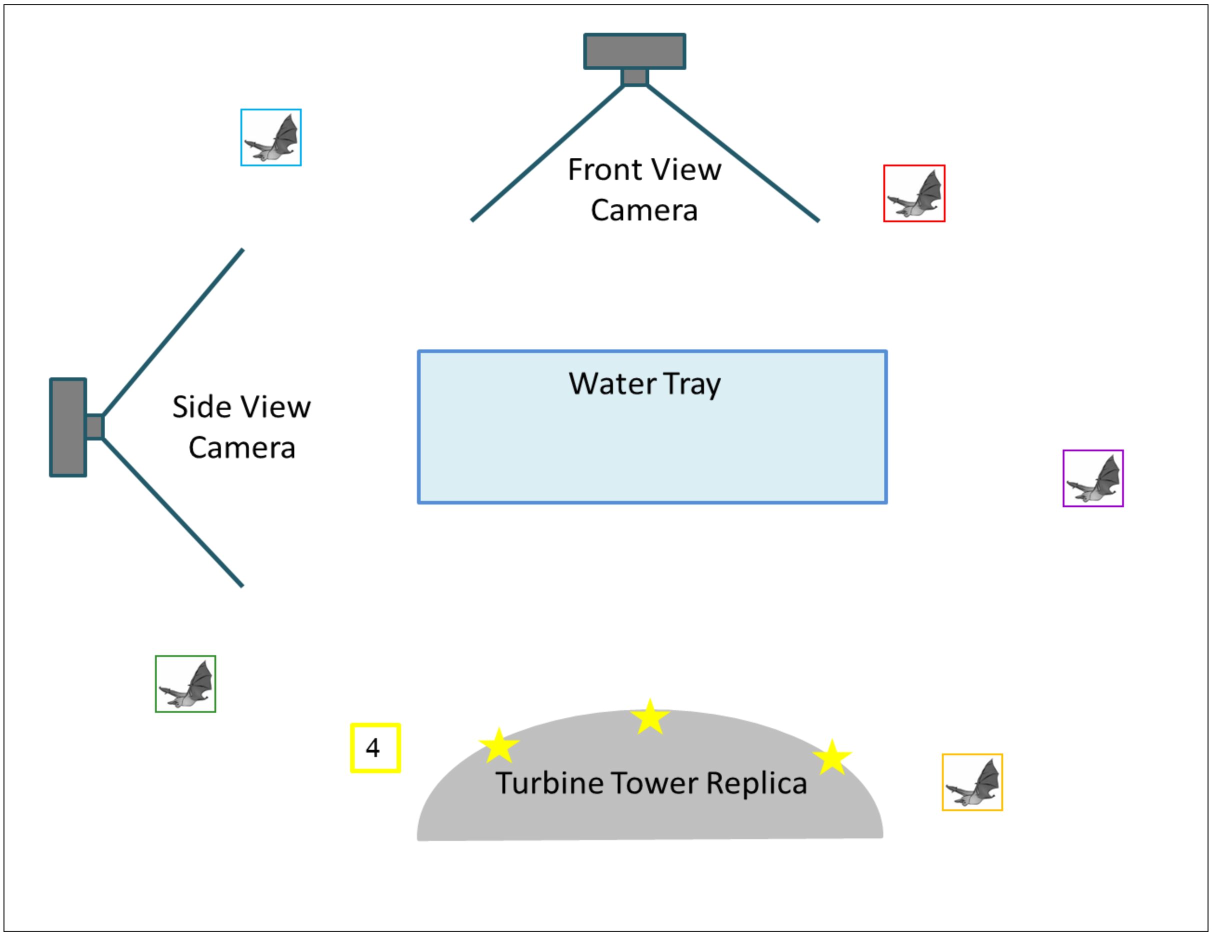

Figure 9: Layout of the bat flight facility during foraging behavioral trials. The yellow stars indicate mealworm position 4.

After the bats were able to glean from the curved metal surface, a smooth painted surface was placed over the surface of the wind turbine replica facing the water tray. This surface was created from a 26 gauge galvanized steel plate measuring 2.5 m x 1 m, which was first painted with two coats of Intergard 345, then a topcoat of Interthane 990 (the same paint treatment currently applied to operational GE wind turbine towers). The bats were then presented with mealworms against the smooth painted surface on the turbine tower replica to determine whether the bats could glean prey items from a surface more similar to a wind turbine tower.

Does foraging efficiency change when a surface is texturized?

As part of the second set of trials, the bats that were able to glean from the smooth painted surface were presented with mealworms against 5 different textured surfaces to investigate whether the type and grade of a texture influenced gleaning rates. The different textured surfaces were selected based on a playback experiment that explored the acoustic characteristics of synthetic bats echolocation calls returning from smooth and textured surfaces (Yuen 2015). Based on the results of this study, we created fine sand, intermediate sand, coarse sand, woodchip, and an applique texture treatment to provide a range of different textures for foraging bats (Fig. 10).

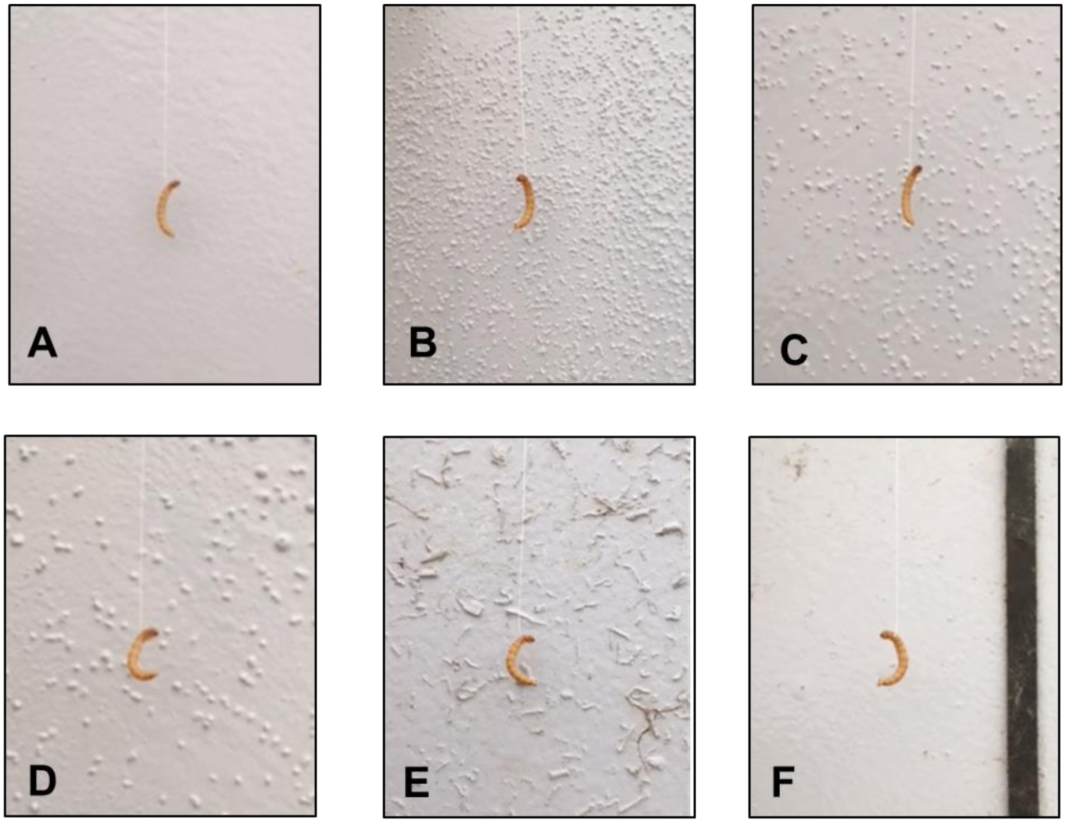

Figure 10: Images of mealworms hanging on string against the six treatment surfaces used to test foraging efficiency: A) smooth painted, B) fine sand, C) intermediate sand, D) coarse sand, E) woodchip, and F) applique.

Similar to the smooth painted surface treatment, we created the texture treatments from 26 gauge galvanized steel plates measuring 2.5 m x 1 m. For the 3 sand texture treatments, we first painted each plate with one coat of Intergard 345. We then added sand particles into the second coat of Intergard 345, at 2 cups of sand to a ½ gallon of paint. For the fine, intermediate, and coarse textures, we used sand particles sized 600-850 microns, 850-1180 microns, and 1400-2000 microns, respectively. Finally, we applied the topcoat of Interthane 990 to each plate. To create the woodchip texture treatment, we substituted sand with mulch in the second coat of Intergard 345 (2 cups per ½ gallon of paint). For the last treatment surface, applique, we created another smooth painted plate and applied 12.7 mm x 19 mm x 1 m Tight Fit foam tape (General Counsel Ace Hardware Corp., Oak Brook, IL) to the vertical axis of the plate at 0.5 m intervals. Based on the study conducted by Yuen (2015), we included this latter treatment surface to explore whether the raised edges created by the tape would disrupt the continuity of the surface and decrease the foraging efficiency of the bats.

We conducted a series of experimental trials in which bats were presented coarse sand, applique, and woodchip texture treatments (i.e., textures with larger particles) in a random order. We presented each treatment texture over three consecutive nights. If all the bats were unable to glean the mealworms from one of these texture treatments, we would move the mealworms back to position 2 before proceeding to the next texture treatment the following night. This process ensured the bats were still capable of foraging for mealworms. Once the bats had been presented with all 3 texture treatments, we either released the bats or initiated a second series of trials. These second trials were conducted only when bats were unable to glean from the coarse sand texture treatment. In these trials, bats were presented with the fine and intermediate sand textured surfaces in a random order to determine whether sand particles size (i.e., grade) influenced the bats' ability to glean.

Experimental trial set-up and implementation

At the start of each survey night, prior to the emergence of the bats, we set up the equipment used to record bat activity in the experimental trials and placed the first set of mealworms into position. We used 2 Canon XA20 infrared camcorders (Canon USA Inc., Melville, NY) positioned 1.25 m from the ground at 90° from one another and 4 ATN IR450-B3 infrared lights (ATN Corp., San Francisco, CA) placed along the wall behind the side view camera to illuminate the room further (see Figs. 8 and 9). We then focused the cameras on the suspended mealworms. Additionally, we recorded time of sunset, temperature, moon phase, cloud cover, and precipitation in case bat activity was altered by one of these variables.

The experimental trials were initiated immediately after the first bat emerged from its day roost. Two surveyors simultaneously turned on the cameras and verbally stated the date, time, trial number, position of mealworms, and treatment texture (if applicable) for the cameras. As colors could not be distinguished in the video recordings, the surveyors used UV flashlights to identify and verbally state the color of the bats active during each experimental trial. In preliminary surveys, we determined 10 minutes was sufficient time for foraging bats to successfully glean all 3 mealworms. Thus, an individual trial was completed when 10 minutes had elapsed or when no mealworms remained. The surveyors would then verbally state the trial number and the ending time before turning off the cameras simultaneously. Once a trial was complete, another set of 3 mealworms would be suspended and the next trial would begin. Trials continued until 3 hours after sunset or when the bats stopped flying for >10 minutes. The videos from the camcorders were saved as MP4 files on SD cards which were transferred nightly to an external hard drive to be stored and analyzed.

Data Analysis

We processed all video recordings in Studiocode (version 5, Studiocode Business Group, Sydney, AU), a video analysis software program, to estimate 3 response variables: number of gleaning attempts, number of successful gleans, and closest approach to mealworms. A gleaning attempt was defined as a bat making contact with the mealworm or the treatment surface, but did not result in the removal of the mealworm, whereas a successful glean was defined as the removal of a mealworm from the treatment surface. To more efficiently identify gleaning attempts and successful gleans, we divided the front camera view into 3 zones (Fig. 11). The first zone comprised an area the size of the replica model of the wind turbine tower (i.e., about 1 m by 2 m). The second zone represented a 0.5 m by 0.5 m area, centered around each mealworm. Finally, the third zone represented a 0.16 m by 0.16 m area in the center of the second zone. Using these zones as a guide, we then counted the number of gleaning attempts and the number of successful gleans made at each treatment surface by each individual bat included in the study.

For the closest approach, we determined the closest distance at which the bats approached the mealworms and the frequency of this behavior. For this, we divided the field of view of the side camera into 3 distance zones (0-1 m, 1-2m, and 2-4.5m) extending out from the replica model of the wind turbine tower surface. Using these zones, we recorded the closest approach bats made (hereafter referred to as a pass) to each treatment surface (excluding gleaning attempts and successful gleans). For this variable, we only included the bats that were actively flying within the first minute of the trials to ensure that each bat had the same amount of time with each treatment surface. Finally, we divided the number of passes made in each zone by the total of number of passes made at each treatment surface and then compared the mean passing rate of the bats in each of the 3 zones.

To collect these data, we used Studiocode to save the 2 videos (front and side views) together to form a single timeline (known as stacked videos), thus allowing us to analyze videos from a single trial simultaneously (Fig. 11). In addition, to aid with the analysis of the stacked videos, we created a code window containing a variety of linked buttons (including label and action buttons) that could be used to characterize 1) bat identity (based on color), 2) the six surface treatments, 3) the specific zones in which the bats flew, and 4) bat behavior (i.e., gleaning attempts, gleaning, and passing). Label buttons (identified with a circle symbol; Fig. 12) were created to specifically identify individual bats actively flying and the surface treatment used in each trial. Action buttons (identified with a diamond symbol; Fig. 12) were created to detail bat behavior, including the type and duration of bat behavior observed, as well as the locations in which these behaviors were exhibited. We then overlaid the code window onto the stacked videos and changed the window setting to make the code window transparent (Figs. 12). Thus, as we manually watched the stacked videos, we used the code window buttons to record the data we observed. For example, each gleaning event was labeled with the bats’ associated unique identification code to determine the species and sex of each bat, which are explanatory variables that could influence a bat’s ability to glean. Once a stacked video was coded, we exported the data to Microsoft Excel 2010 (Microsoft, Redmond, WA) for further analysis.

Figure 11: Screenshot of the front and side camera views stacked together to form a single timeline in Studiocode. The front view is highlighted with yellow for zone 1, orange for zone 2, and red for zone 3. The side view is highlighted with red for the 0-1 m zone, orange for the 1-2 m zone, and yellow for 2-4.5 m zone

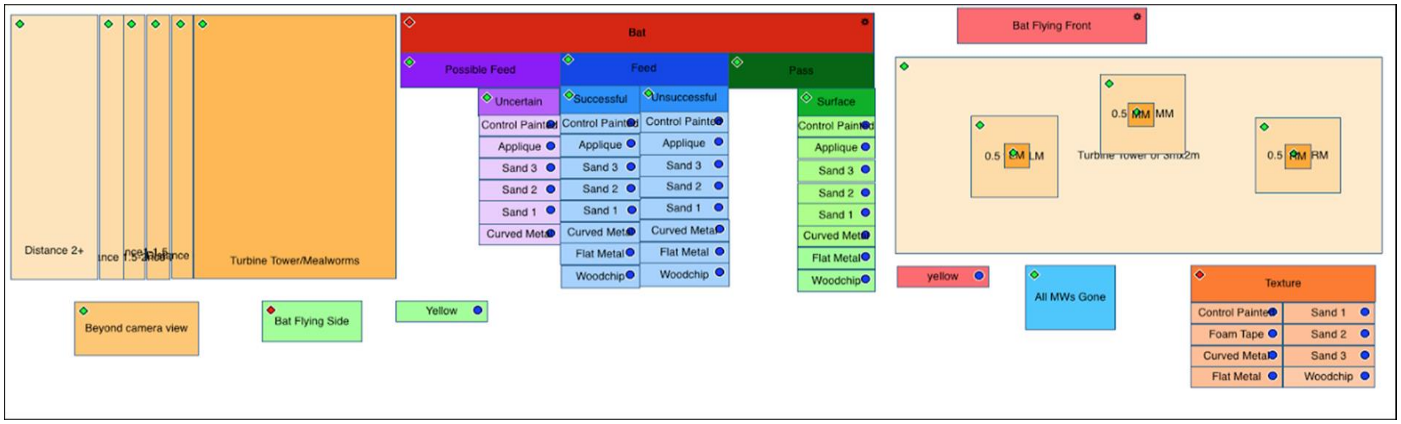

Figure 12: Image of the Studiocode code window used to insert behavioral and observational data into a timeline. Label buttons, which identify bats and surface treatments, are identified with a circle symbol. Action buttons, which detail bat behavior, are identified with a diamond symbol.

Results

From April 30 through September 29, 2015, we captured 3 species of bats for a total of 79 individuals: 8 eastern red, 58 evening, and 13 Mexican free-tailed bats. Of those 79 bats, 65 were captured following the pilot experiment (from July 1 through September 29, 2015) and 43 individuals successfully acclimated: 5 eastern red (1 female; 4 male) and 38 evening bats (19 female; 19 male). Note that the Mexican free-tailed bats did not exhibit foraging behavior within the flight facility; therefore we deemed them unable to acclimate to the flight facility, and they were therefore not included in the trials.

A total number of 559 foraging behavioral trials (approximately 93 hours) were conducted, with a maximum of 11 trials per night. Figures 13 and 14 detail the number of eastern red and evening bats, respectively, that were able to pass through each stage of the foraging behavioral trials. Trials excluded from analysis included trials at positions 1 and 2 (n = 315; Fig. 8), as these positions were executed to demonstrate the bats could aerial hawk for prey items within the flight facility, and trials in which there were errors in the set up (e.g., cameras were out of focus or infrared lights not turned on; n = 139). Thus a total of 105 foraging behavioral trials (approximately 17.5 hours) were examined; 28 at position 3 (Fig. 8) and 77 at position 4 (Fig. 9) with flat metal, curved metal, smooth painted, coarse sand, applique, and woodchip treatment surfaces.

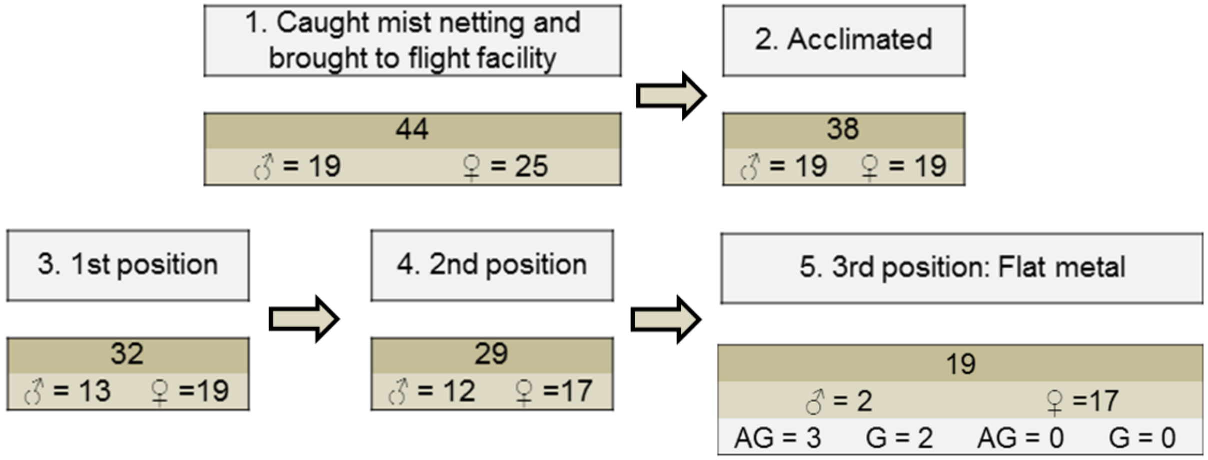

Figure 13: Flow chart of evening bats through each stage of the trials, separated into sex and the number of bats that attempted to glean (AG) and gleaned (G).

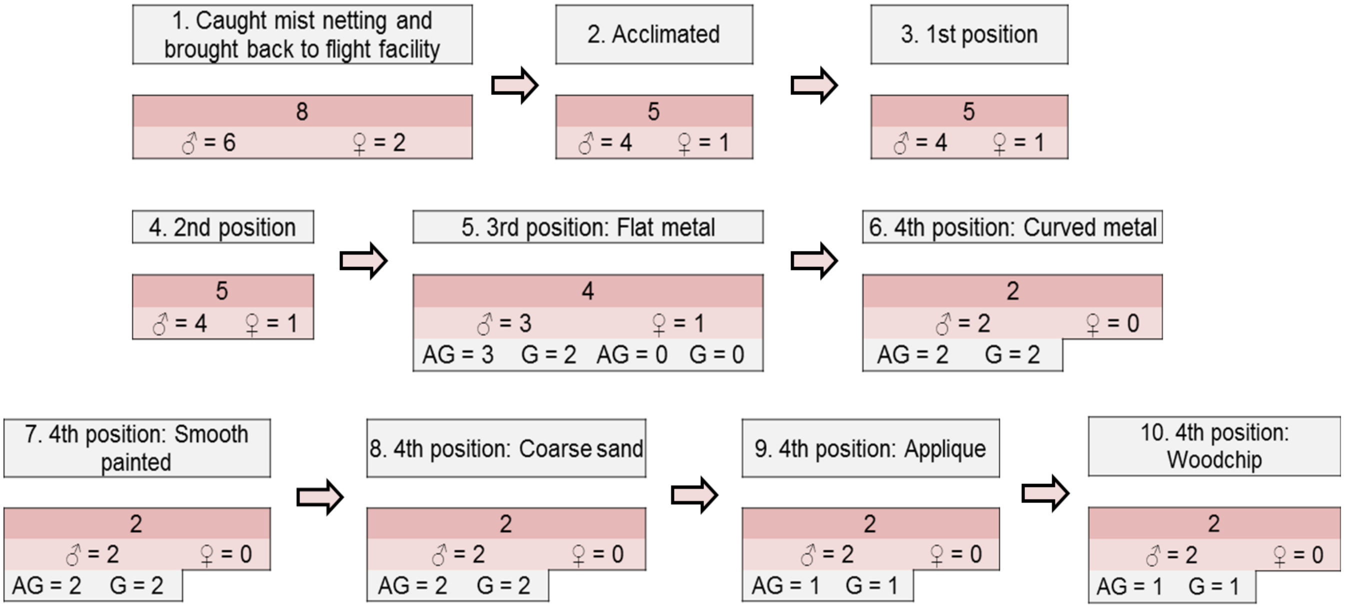

Figure 14: Flow chart of eastern red bats through each stage of the trials, separated into sex and the number of bats that attempted to glean (AG) and gleaned (G).

Can bats switch foraging strategies?

In our foraging behavioral trials, of the 19 evening bats that advanced to position 3, none were able to glean mealworms from the flat metal treatment surface. In contrast, we found that 3 (all male) of the 4 eastern red bats that advanced to position 3 attempted to glean mealworms from the flat metal treatment surface. Furthermore, 2 of these male eastern red bats (representing 40% of the eastern red bats included in the trials) successfully gleaned mealworms from this surface, and subsequently advanced to position 4. In this final position, we found that the 2 male eastern red bats were also able to glean from both the curved metal and the smooth painted treatment surfaces (Fig. 15). Tables 1 and 2 below detail the number and percentage of prey items gleaned from each treatment surface by each individual eastern red bat. Note that for one of the male eastern reds, we observed a more than 50% decrease in gleaning success at the smooth painted treatment surface compared to both the flat metal and curved metal treatment surfaces.

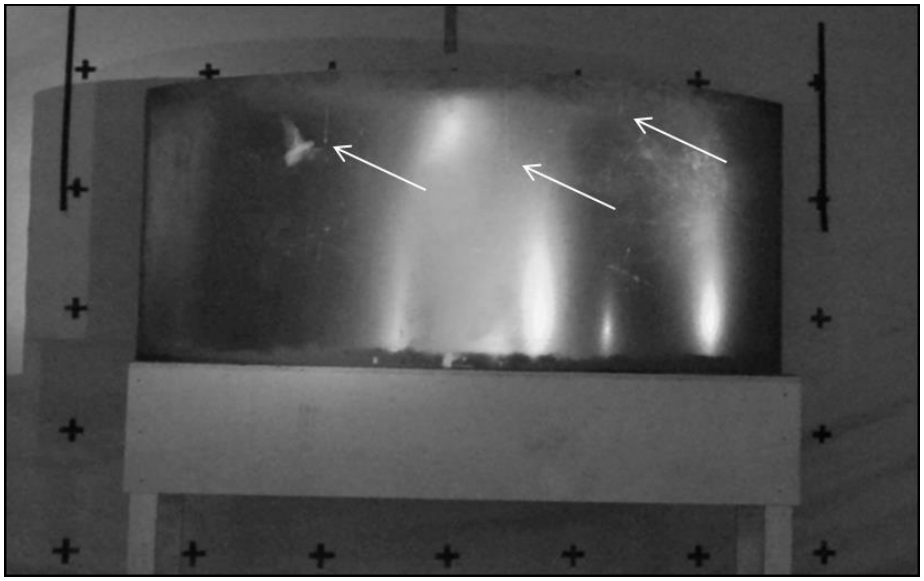

Figure 15: Infrared camera image of a male eastern red bat gleaning from the curved metal treatment surface. White arrow indicates where mealworms are located.

Table 1: Total number and percentage of mealworms gleaned by individual 3Labo06Jul2015. Note we were unable to analyze the foraging behavioral trials for this individual at the woodchip treatment surface, as shown by *.

	Treatment surfaces					
Mealworms	Flat metal	Curved metal	Smooth painted	Sand 3	Applique	Woodchip
Gleaned	11	14	5	5	5	*
Not gleaned	11	6	27	18	21	*
Total available	22	20	32	23	26	*
Percentage gleaned	**50.0%**	**70.0%**	**15.6%**	**21.7%**	**19.2%**	*

Table 2: Total number and percentage of mealworms gleaned by individual 1Labo22Jul2015. Note that although we recorded this individual gleaning from the flat metal treatment surface in the flight facility, we were unable to analyze the foraging behavioral trial videos for this individual, as shown by *.

	Treatment surfaces					
Mealworms	Flat metal	Curved metal	Smooth painted	Sand 3	Applique	Woodchip
Gleaned	*	11	10	3	0	6
Not gleaned	*	7	14	3	30	20
Total available	*	18	24	6	30	26
Percentage gleaned	*	**61.1%**	**41.7%**	**50.0%**	**0.0%**	**23.1%**

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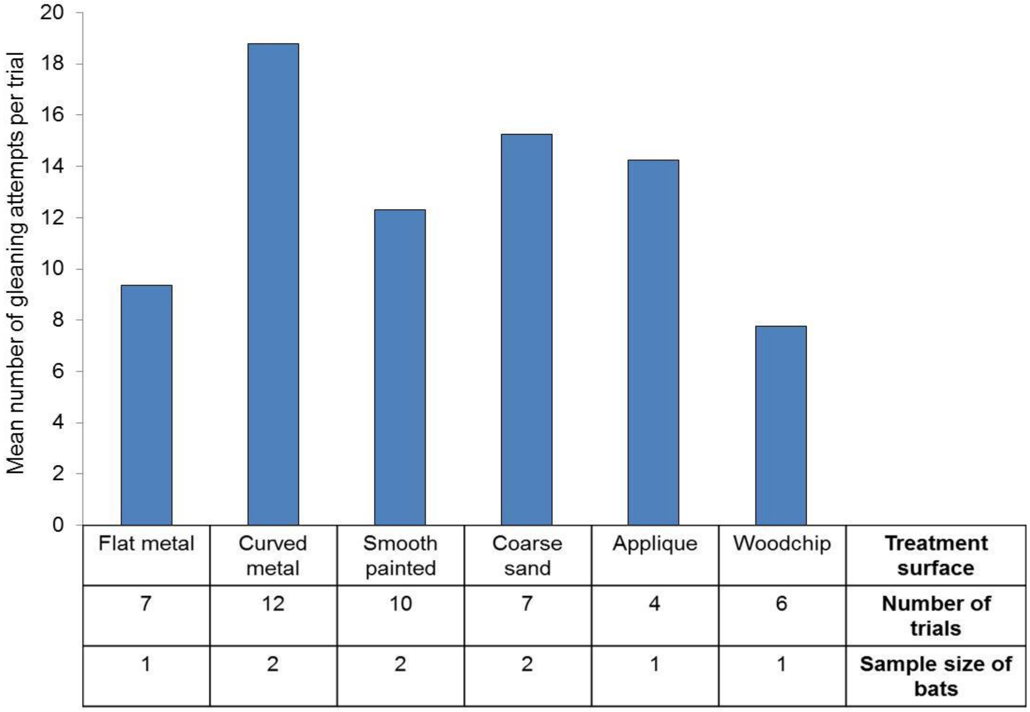
Does foraging efficiency change when a surface is texturized?

Two male eastern red bats that were able to glean from the smooth painted treatment surface at position 4, then advanced to foraging behavioral trials in which they were presented with mealworms against 3 textured treatment surfaces (Tables 1 and 2).

Gleaning attempts

Of the two males included in these foraging behavioral trials, we found that the highest rate of gleaning attempts occurred at the curved metal treatment surface, followed by coarse sand (Fig. 16). Nevertheless, overall there did not appear to be clear differences in the numbers of gleaning attempts between the smooth treatment surfaces and the coarse textured treatment surfaces tested.

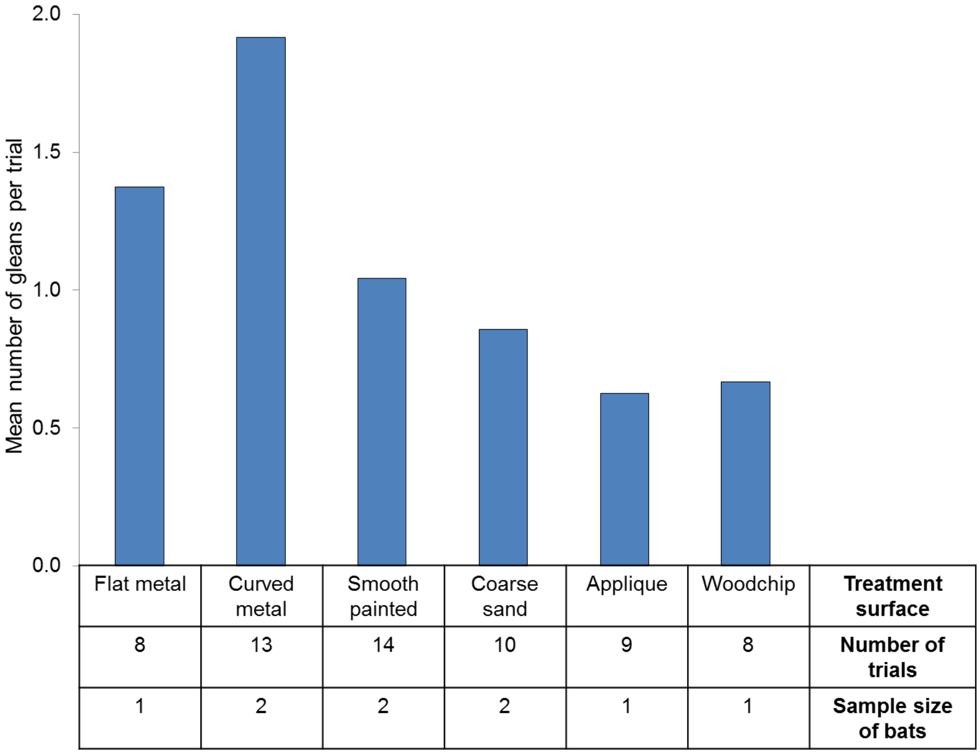


Flat metal	Curved metal	Smooth painted	Coarse sand	Applique	Woodchip	**Treatment surface**
7	12	10	7	4	6	**Number of trials**
1	2	2	2	1	1	**Sample size of bats**

Figure 16: Mean rate of gleaning attempts per trial by eastern red bats at each treatment surface. The number of trials and sample size of bats from each treatment surface is detailed along the x-axis.

Successful gleans

In our trials, we found that both eastern red males were able to glean mealworms from the coarse sand treatment surface. One male was able to glean from the applique treatment surface, whereas the other male did not. We also recorded one eastern red successfully gleaning from the woodchip treatment surface, but were unable to confirm whether the other male could also glean from this surface, as videos for this individual were out of focus. For gleaning rates, we observed a minor reduction at the textured treatment surfaces compared to the smooth painted treatment surface, but overall we observed very little difference in gleaning rates between the different textured treatment surfaces (Fig. 17).

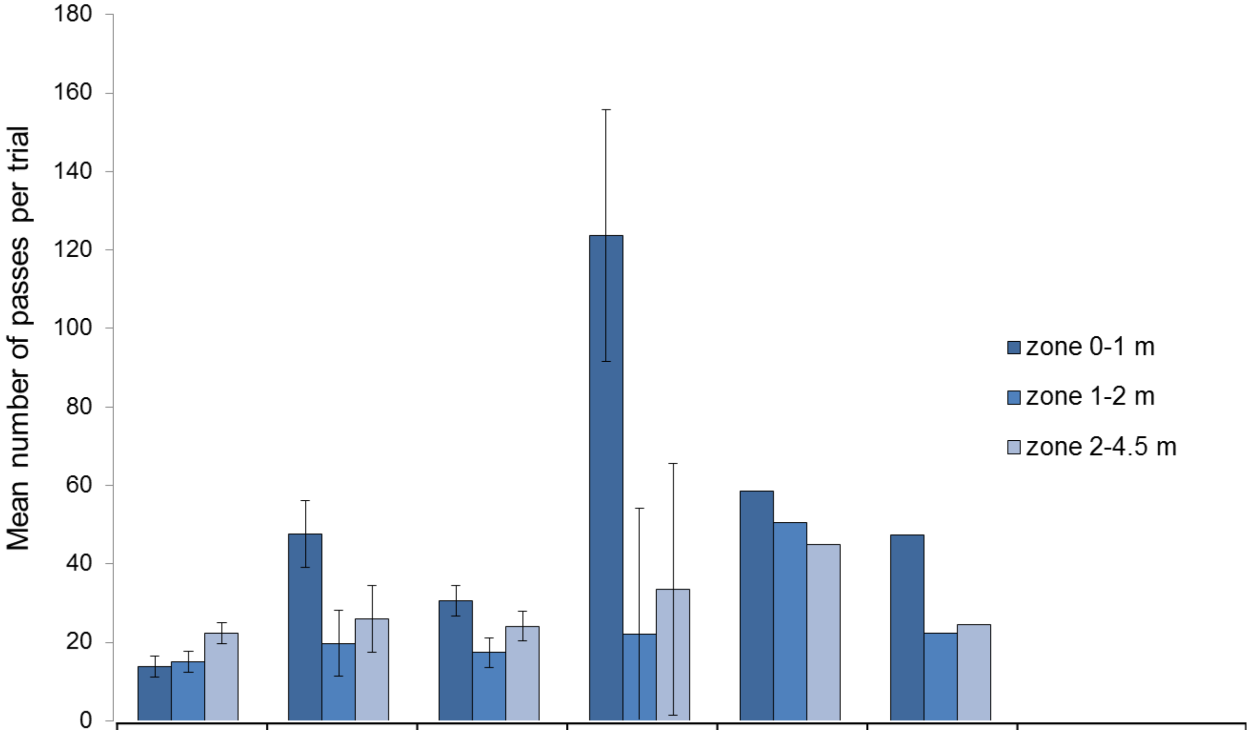


Flat metal	Curved metal	Smooth painted	Coarse sand	Applique	Woodchip	**Treatment surface**
8	13	14	10	9	8	**Number of trials**
1	2	2	2	1	1	**Sample size of bats**

Figure 17: Mean gleaning rate per trial by eastern red bats at each treatment surface. The number of trials and sample size of bats from each treatment surface is detailed along the x-axis.

Closest approach

To evaluate closest approach, we compared the mean number of passes within the 3 distance zones for 4 eastern red bats. We found the bats made more passes in close proximity (i.e., 0-1 m) to the coarse sand treatment surface compared to the other treatment surfaces (Fig. 18). Apart from this result, overall we found that the passing rate was similar between all other treatment surfaces at all 3 distance zones.



Flat metal	Curved metal	Smooth painted	Coarse sand	Applique	Woodchip	**Treatment surface**
12	16	16	14	9	11	**Number of trials**
3	3	3	3	1	2	**Sample size of bats**

Figure 18: Mean ± SE number of passes per trial by eastern red bats occurring in the 3 distance zones extending from each of the 6 treatment surfaces. The number of trials and sample size of bats from each treatment surface is detailed along the x-axis.

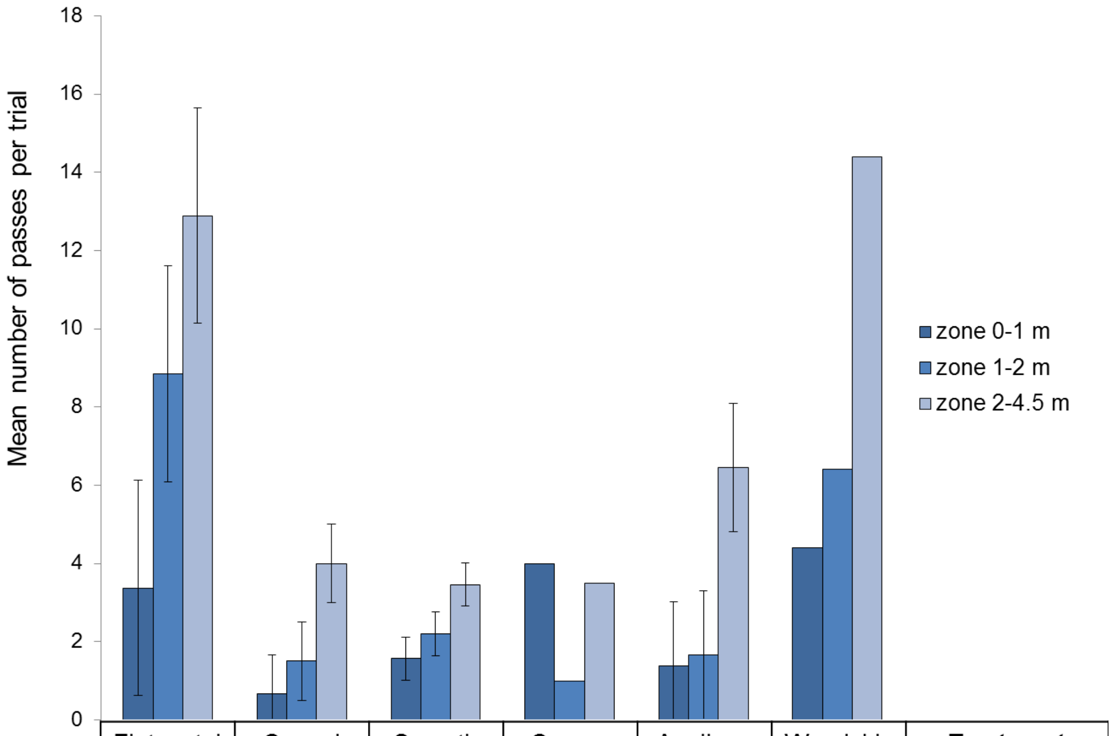
Discussion

For our foraging behavioral trials, we captured 3 bat species (evening, eastern red, and Mexican free-tailed bats) and found 1 species (eastern red bat) capable of switching from an aerial hawking to a gleaning foraging strategy. We observed gleaning attempts and successful gleans at both smooth and textured treatment surfaces. Furthermore, we recorded a higher number of gleaning attempts at the curved metal treatment surface, and over 50% more gleans at both flat metal and curved metal surfaces compared to the smooth painted and textured treatment surfaces. Finally, we found that bats approached coarse sand more readily at <1 m compared to any of the other treatment surfaces and distance zones.

Our study provides evidence that eastern red bats, which are commonly found among wind farm fatalities, are capable of switching foraging strategies and can glean prey items from surfaces similar to wind turbine towers. The ability to glean prey items supports the hypothesis that bats may perceive wind turbine towers as a foraging resource and thus be attracted to them, thereby increasing the bats' chance of being hit by rotating wind turbine blades.

The results of our study strongly suggest that there are species-specific differences in the ability of bats to switch foraging strategies. For example, we observed that 50% of eastern red bats (2 of 4 bats tested) were able to readily glean from the flat metal treatment surface at position 3, however in contrast, we found that 0% of evening bats (n = 19) were able to glean mealworms from the same surface. Furthermore, we observed species-specific differences in closest approach, as eastern reds readily flew in close proximity to the treatment surfaces (Fig. 18), whereas only a small proportion of the evening bats came within <1m of the turbine tower replica (Fig. 19). Nevertheless, on two separate occasions we did observe one evening bat attempt to glean a mealworm from the smooth painted treatment surface and a separate evening bat successfully gleaned a mealworm from the applique treatment surface. Despite these anecdotal observations, our study revealed that evening bats are less likely to switch foraging strategies and glean or attempt to glean prey items. Such species-specific differences are also recorded in fatality monitoring searches at wind resource facilities across the US, with some species being more susceptible to collisions than others. For example, eastern red bats comprise 22% of reported fatalities, whereas evening bats consist of 0.2% (Arnett and Baerwald 2013). Thus, if certain species, such as the eastern red bat, are more readily able to switch foraging strategies and glean prey items from wind turbines, which in turn results in them being more susceptible to collisions, then it may be important to identify the characteristics that enable bats to glean.

Species-specific differences in foraging strategy switching and more specifically gleaning might be due to a number of physiological, behavioral, and ecological differences. Studies have shown that gleaning bats have specifically adapted wing morphologies, including short stubby wings (i.e., low wing loading and low wing aspect ratio; Fenton and Bogdanowicz 2002; Dechmann et al. 2006). These features enable gleaning bats to fly slowly, hover, and maneuver effectively in cluttered environments to remove stationary prey items from surfaces (Altringham 2011). Similarly, Schmeider et al. (2014) found that a larger tail length to body size ratio increased maneuverability, which could facilitate gleaning.



Flat metal	Curved metal	Smooth painted	Coarse sand	Applique	Woodchip	**Treatment surface**
25	5	15	3	8	5	**Number of trials**
12	3	5	2	3	1	**Sample size of bats**

Figure 19: Mean ± SE number of passes per trial by evening bats occurring in the 3 distance zones extending from each of the 6 treatment surfaces. The number of trials and sample size of bats from each treatment surface is detailed along the x-axis.

Comparing the wing and tail morphology of evening and eastern red bats, evening bats have a lower wing aspect ratio and eastern red bats have lower wing loading (wing aspect ratio = 2.10 and 2.29; wing loading = 0.15 and 0.13, respectively) (Menzel et al. 2005). In addition, eastern red bats have a tail length to body length ratio that is larger than evening bats (0.738 and 0.582 respectively; Ammerman et al. 2012). These morphological differences suggest the eastern red bats may be more maneuverable than evening bats, which would support our findings.

Evening and eastern red bats also have different characteristics to their echolocation calls. Eastern red bats typically call within a frequency range that is higher than evening bats (37-81 kHz and 34-78 kHz, respectively) (Szewczak et al. 2011). Higher frequency calls are known to relay more detailed information and bats that forage in more closed cluttered environments and/or glean have higher frequency echolocation calls (Denzinger and Schnitzler 2013). Again, these differences in echolocation characteristics suggest that eastern red bats are more adapted to gleaning than evening bats.

Finally, the diet of the bats may reveal whether they are likely to glean or not. Typically, gleaning bats prey on invertebrates such Lepidoptera (moths), Diptera (true flies), and Orthoptera (crickets; Andreas et al. 2012). In comparison, eastern red bats primary forage for Lepidopterans, whereas evening bats primarily forage on Hymenopterans (flies and ants) and Hemipterans (true bugs; Feldhamer 1995; Carter et al. 2004; Feldhamer et al. 2009). These differences in diet preferences further support our findings that eastern red bats are more adapted to gleaning than evening bats.

An important result of our study is that we found that eastern red bats were capable of gleaning from a curved, smooth painted surface similar to that of a wind turbine tower. The rate of successful gleans at this surface was more than 50% lower than at the flat and curved metal treatment surfaces. These results support our hypothesis that the properties of these latter surfaces (i.e., smooth and reflective) would make prey items more acoustically conspicuous to bats. Thus, a reduction in the ability of bats to glean from the painted treatment surface suggests that the paint changes the properties of the surface, so that the prey items are less conspicuous to gleaning bats.

Furthermore, these results suggest that texturizing a surface would further alter the properties of a surface and potentially reduce the acoustic mirror effect, further reducing the bats’ ability to glean.

For the second part of our experiment, we did observe eastern red bats gleaning from the 3 textured treatment surfaces that were tested (coarse sand, applique, and woodchip). In addition, gleaning rates at these surfaces did not appear to be different from the painted treatment surface. These results appeared to contradict our hypothesis that texturizing a surface would further reduce the ability of bats to glean, however our sample sizes may have been too low to effectively reveal such differences. Alternatively, the texture treatment surfaces selected may not have altered the properties of the surface enough to further reduce gleaning efficiency in eastern red bats. Note that we did not test the intermediate and fine sand textures, as we had initially assumed that if the bats could glean off the coarse sand texture, they would be able to glean off these treatment surfaces. In a separate, but concurrent, study using the same treatment surfaces, it was discovered that the textures with large gap sizes (the distance between two particles) led to bats approaching the surfaces more frequently than textures with smaller gap sizes, such as intermediate and fine sand textures (Bienz 2016). The results of this concurrent study suggest that we should have tested surfaces with more densely distributed particles and we may then have seen a reduction in gleaning rate. We also noted a very interesting pattern in closest approach, as the eastern red bats tested made more passes in close proximity to the coarse sand treatment surface (the 0-1 m zone) than any of the other treatment surfaces. Currently, we do not have an explanation for this pattern and it will require further investigation.

Finally, we found that the woodchip treatment surface at times would serve as a perch for foraging bats (Fig. 20). These findings suggest that the woodchip treatment surface may provide roosting or resting opportunities, which would in turn increase bat activity near such a surface. We therefore recommend that textures should not contain elements that may be found in nature, such as bark-like materials, nor should particles be large enough for the bats to utilize as a perch.

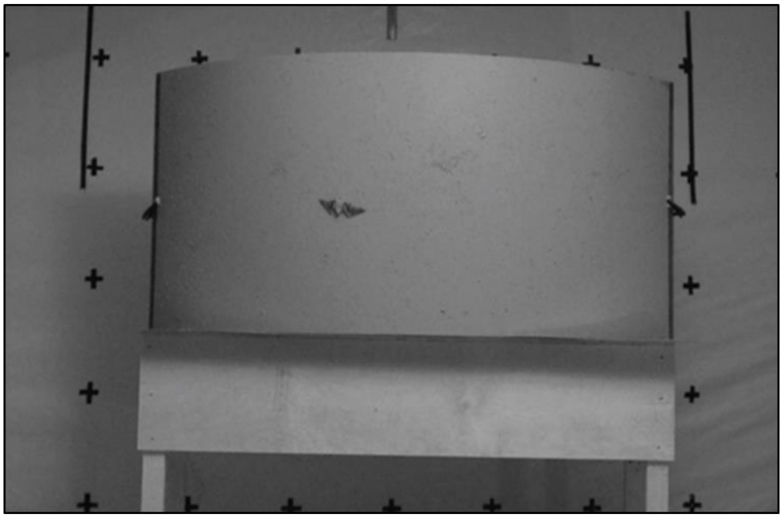


Figure 20: Infrared camera image of a male eastern red bat perching on the woodchip treatment surface.

Overall, our study was limited by very small sample sizes. This limitation was due to two factors; 1) we had very few bats that made it through to position 4 (i.e., bats that were able to glean from a smooth painted surface), and 2) we caught very low numbers of eastern red bats. As this species is solitary, unlike evening bats which roost and forage together, we typically only caught one eastern red bat during a mist netting survey. Thus, capture effort would have to be substantially greater (i.e., multiple parks surveys simultaneously and more often) to increase sample sizes. We also recommend that future experiments test one bat at a time to eliminate possible interference and interactions with other bats during the trials. This alteration in procedure would make video analysis more efficient and remove any confusion in the identification of individuals. Furthermore, we recommend that other prey items are tested, such as moths, to more effectively determine whether the bats would glean prey items similar to those found on wind turbines. Similarly, we recommend conducting future trials with the hoary and silver-haired bats (i.e., 2 of the 3 bats that make up the majority of windfarm mortality) to determine if they, like the eastern red bat, are able to switch foraging strategies and glean prey items from surfaces similar to wind turbine towers.

Finally, we believe that our research highlights the need for further studies into the acoustic mirror effect. For example, a complimentary playback experiment could be conducted that explores the characteristics of echoes returning from different invertebrates placed on a variety of smooth and textured surfaces. Such a study may help us better understand echolocation, how bats perceive prey items on turbine towers, and provide additional information on more effective texture treatments that could be applied to wind turbines.

Conclusion

If bats are approaching wind turbine towers because they provide a readily accessible food resource and bats are able to glean the prey off the tower surfaces, then a texture application that reduces the availability of the invertebrates on the wind turbine towers should ultimately help reduce bat fatality rates at wind resource facilities. Such a coating could then potentially be applied to operational wind turbine towers and towers in the manufacturing stage as a mitigation strategy to reduce bat fatalities at wind resource facilities globally.

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ABSTRACT

Aerial-hawking bats can glean prey items from surfaces similar to wind turbine towers: implications for reducing bat fatalities at wind facilities

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Large numbers of insectivorous tree bats are killed at windfarms worldwide, but the causes of mortality are largely unexplored. One possible explanation is that bats may perceive wind turbines as a foraging resource. The acoustic mirror effect of smooth surfaces, such as wind turbine towers, can lead to insects resting on the surface to be conspicuous to foraging bats. In 2015, we conducted a flight facility experiment (by suspending prey items against a range of surface types) to 1) determine if aerial-hawking bats could switch foraging strategies to glean prey items from surfaces similar to turbine towers, and 2) estimate foraging success at smooth and textured surfaces. Despite having a low sample size, we found that eastern red bats could glean prey from smooth surfaces similar to wind turbine towers, suggesting bats may be using the surface of turbine towers as a foraging resource. Compared to smooth surfaces, gleaning rates also appeared lower at textured surfaces.