An effective survey method for studying volant species activity and behavior at tall structures

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Anthropogenic modification of air space presents a growing threat to wildlife, particularly volant species. Thus, it is essential to understand wildlife-interactions with tall structures to implement effective mitigation strategies. Yet, we are currently lacking standard protocols for visual surveys of wildlife behavior at such heights. Our study sought to determine an effective, repeatable method using readily available night vision (NV) and thermal technology to survey wildlife at tall structures. Using bats as the taxonomic group of interest, we 1) created a key to identify bats and their behavior, 2) compared the effectiveness of 2 different technologies, and 3) assessed optimal equipment placement to visually capture bat activity and behavior in proximity to wind turbine towers. For the latter, we tested thermal cameras at 4 distances from the base of the tower. The results of our study revealed that thermal cameras captured ~20% more flying objects than NV. However, due to the heat signature of the turbine towers themselves, we were unable to observe the behaviors and interactions that occurred in close proximity to the towers. In contrast, while it was difficult to identify bats approaching the towers using NV, we were able to clearly observe interactions with the towers themselves. With regards to equipment placement, we visually captured more bats with the thermal cameras placed 2 m from the tower base compared to father distances. From our findings, we recommend that when using either thermal or NV technology at tall structures, they be placed 2 m from the base to effectively observe interactions along the length of these structures. In addition, we further recommend that consideration be given to the use of these two technology types together to effectively conduct such surveys. If these survey techniques are incorporated into standard protocols, future surveys at a variety of tall structures are likely to become comparable and repeatable, thereby more effectively informing any mitigation strategies that may be required.

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Abstract

Anthropogenic modification of air space presents a growing threat to wildlife, particularly volant species. Thus, it is essential to understand wildlife-interactions with tall structures to implement effective mitigation strategies. Yet, we are currently lacking standard protocols for visual surveys of wildlife behavior at such heights. Our study sought to determine an effective, repeatable method using readily available night vision (NV) and thermal technology to survey wildlife at tall structures. Using bats as the taxonomic group of interest, we 1) created a key to identify bats and their behavior, 2) compared the effectiveness of 2 different technologies, and 3) assessed optimal equipment placement to visually capture bat activity and behavior in proximity to wind turbine towers. For the latter, we tested thermal cameras at 4 distances from the base of the tower. The results of our study revealed that thermal cameras captured ~20% more flying objects than NV. However, due to the heat signature of the turbine towers themselves, we were unable to observe the behaviors and interactions that occurred in close proximity to the towers. In contrast, while it was difficult to identify bats approaching the towers using NV, we were able to clearly observe interactions with the towers themselves. With regards to equipment placement, we visually captured more bats with the thermal cameras placed 2 m from the tower base compared to father distances. From our findings, we recommend that when using either thermal or NV technology at tall structures, they be placed 2 m from the base to effectively observe interactions along the length of these structures. In addition, we further recommend that consideration be given to the use of these two technology types together to effectively conduct such surveys. If these survey techniques are incorporated into standard protocols, future surveys at a variety of tall structures are likely to become comparable and repeatable, thereby more effectively informing any mitigation strategies that may be required.

Introduction

Air space is important habitat for many volant species, providing foraging sites, mating opportunities, vantage points for predators, and access to resources (Alerstam 1979; Avila-Flores & Fenton 2005; Diehl 2013). Thus, any anthropogenic use of the air space can potentially have an impact. For example, airplanes are estimated to strike over 25,000 birds annually in the United States (Erickson 2005; Pfeiffer, Blackwell & DeVault 2018). Yet, we have modified the air space in many other ways as well. For decades, we have been installing tall anthropogenic structures including electrical, radio, meteorological, satellite, and cell phone towers, along with power lines and skyscrapers. Studies have confirmed that such tall structures can disorient migratory birds (Avery, Springer & Cassel 1976; Gehring, Kerlinger & Manville 2009), reduce breeding success (Dahl et al. 2012), and are a source of bird and bat fatalities due to collisions (Crawford & Wilson Baker 1981; Timm 1989; Longcore et al. 2012; Loss, Will & Marra 2015). Moreover, the construction and installation of wind turbines in the last few decades has led to increased bird and bat fatalities (Arnett & Baerwald 2013; Erickson et al. 2014). Projections of annual mortality vary, but studies have estimated between 140,000 - 573,000 bird and 600,000 - 888,000 bat fatalities/yr in the United States (Hayes 2013; Loss, Will & Marra 2013; Smallwood 2013; Arnett et al. 2016). Demographic studies predict that these mortality rates will have population-level implications for certain species (de Lucas et al. 2012; Balotari-Chiebao et al. 2016; Frick et al. 2017).

Yet, the threats caused by the modification of the air space are increasing with ongoing wind energy installations and other technological advances associated with urbanization, such as an increase in cell phone towers (Lu, McElroy & Kiviluoma 2009; Vasenev et al. 2018). There is, therefore, a need to 1) better understand the impacts of air space modification on wildlife, and 2) potentially implement mitigation strategies that can effectively alleviate such impacts.

While some strategies have already been developed and are now standard practice, such as avian-safe protections on electrical wires (Avian Power Line Interaction Committee 2006), there are still areas of research that need to be explored in order to develop further mitigation at tall structures. For example, research is currently investigating minimizing effects of tall structures (i.e., migratory disorientation, collisions, etc.) on birds and bats through acoustic and visual deterrents (Arnett et al. 2013; Swaddle & Ingrassia 2017; Goller et al. 2018) or operational minimization (Arnett et al. 2011; Martin et al. 2017). While these approaches can be effective, there is still much room for improvement as we do not fully understand why and how different species are interacting with tall structures (Wang, Wang & Smith 2015; Bennett & Hale 2018; Bernardino et al. 2018). Typically, behavioral surveys are undertaken to explore these questions, but such surveys conducted at height have, until recently, been challenging. With the advancement of technology, it has become easier to conduct surveys using affordable, high quality equipment like night vision and thermal cameras. For example, in the last 10 years, a number of behavioral studies have been conducted on volant species at tall structures (e.g., Long, Flint & Lepper 2011; Mirzaei et al. 2012; Jameson & Willis 2014; Watson, Keren & Davies 2018). However, the use of such technology in this field of study is still relatively new and there are no standardized protocols or even recommended guidelines available, making quantitative comparisons between different studies difficult.

To address this need, we conducted a study to determine best practice techniques for assessing behavior of any volant species (e.g., bats, birds, or invertebrates) at tall structures. Using bats as our taxonomic group of interest, we 1) created a customized classification key to identify flying objects and behaviors; 2) compared the effectiveness of currently available technologies for surveying flying objects; and 3) assessed optimal equipment placement in proximity to a tall structure. Based on the findings of our study, we hope to make recommendations on survey methods that can be widely implemented when investigating wildlife interactions with tall structures.

Methods

Study site

We conducted our study at a utility-scale wind energy facility that has been operational since 2008 in north-central Texas, USA (N 33°43'53.538", W 97°24'18.186"). This facility consists of 75 1.5-MW General Electric wind turbines comprising an 80 m tower, a 2 m nacelle, and 3 40 m blades (maximum height = 122 m). The 48 km^2 wind resource area encompasses a matrix of cattle pastures, hayfields, cultivated fields, and scrub woodland. Surveys conducted from 2009 to 2013 identified 7 bat species at this site, including 6 species found in post-construction fatality monitoring surveys (*Lasiurus borealis*, *Lasiurus cinereus*, *Lasionycteris noctivagans*, *Perimyotis subflavus*, *Nycticeius humeralis*, and *Tadarida brasiliensis*) and one additional species that was recorded in acoustic surveys (*Parastrellus herperus*; Bennett & Hale 2014; Lindsey 2017; Bennett & Hale 2018). Furthermore, bats have been observed in close proximity to the wind turbine towers at this facility (McAlexander 2013). We, therefore, deemed the facility to be an appropriate location to survey bat behavior and activity at wind turbine towers.

Behavioral observation surveys

In 2016 during the fall bat migratory period from July to mid-August (Krauel 2013; Bennett & Hale 2018), we conducted a series of behavioral surveys to explore bat interactions with wind turbine towers. For these surveys, six turbines were selected that had high levels of bat fatalities recorded in the aforementioned fatality monitoring surveys (Bennett & Hale 2014; Bennett & Hale 2018).

At 1-2 turbine sites per night, we conducted surveys to record bat activity in proximity to the turbine tower. For this, we investigated the effectiveness of 2 currently available technologies previously used to study volant species: night vision (NV; Warren et al. 2006; Fuller, Hammond & Tomasi 2012) and thermal (Blowers et al. 2015; Matzner, Cullinan & Duberstein 2015; Hayman et al. 2017). We then determined whether 1) the number of flying objects observed differed; 2) flying objects could be identified (e.g., bird, bat, moth, etc.); and 3) specific behaviors were readily discernable between these two technologies.

A NV setup consisted of an ATN NVM14 night vision scope attached to Sony HDR-PJ790 video camcorder and placed on a Manfrotto MT055XPRO3 tripod, and 2 ATN Super Long Range Infrared Illuminator IR450 lights mounted atop VELBON EF tripods. For the thermal setup, we used an Axis Q1932-E 19MM thermal camera mounted on Manfrotto MT055XPRO3 tripod, connected via an Ethernet cable and a Netgear ProSAFE 8-Port Fast Ethernet PoE Switch to an HP Compaq 8510w laptop with Axis Companion software (version 3.20.010, Axis Communications AB, Lund, Sweden), and powered by a 12 Volt 35 Amp automotive battery through a Cen-Tech Power Inverter.

Previous behavioral surveys using NV at our site (2012 and 2013) had demonstrated that the identification and behavior of flying objects could best be distinguished when 2 NV setups were placed on opposite sides of the structure (for wind turbine towers, this would be the windward and leeward sides), 2 m from its base (Fig. 1; McAlexander 2013). We angled the field-of-view upward to incorporate the full length of the structure (e.g., from ~10 m above the gravel pad of a wind turbine tower to the lower surface of the nacelle hub ~80 m up). We also placed the 2 infrared lights ~1 m from either side of the NV setup, angling them upward to effectively illuminate the tower surface.

For the thermal setups, there were currently no definitive recommendations regarding placement of equipment. Previous research that has used thermal cameras to study bats at wind turbines varied camera placement between 25 and 80 m from the base of the structure (Horn, Arnett & Kunz 2008; Cryan et al. 2014). Thus, we sought to establish a thermal camera location that could effectively be used to survey the interactions of volant species with tall structures. For this, we incrementally tested a variety of distances to determine the camera location that yielded the highest number of observed flying objects per hour, and not only optimized our ability to identify these objects (e.g., bird, bat, moth, etc.), but also allowed for specific behaviors to be distinguished.

We conducted a series of surveys with thermal cameras placed 2 m, 25 m, 50 m, and 95 m from the base of the leeward side of wind turbine towers (Fig. 1). We selected the leeward side as research has shown higher bat activity relative to the windward side of wind turbine towers (Cryan et al. 2014). For each distance tested, we adjusted the angle of the camera to maximize tower coverage from ~10 m above the ground to the base of the nacelle (~80 m up) within the field-of-view. Note that the placement at 95 m from the base was tested because it encompassed the entire turbine from the base to the top of the rotor swept zone (RSZ) in the field-of-view.

During all surveys, we also used an ultrasonic acoustic detector to record species-specific bat activity around the towers as an additional tool to identify flying objects (see below). The acoustic recording equipment setup comprised an AR-125-EXT Ultrasonic Receiver and an iFR IV Integrated Field Recorder System from Binary Acoustic Technology, LLC with the microphone mounted atop a standard tripod. We pre-set the detectors to trigger at frequencies between 20 and 110 kHz at a gain threshold of 12.0 dB, trigger volume of 12.0 dB, and a duration of 4.0 seconds. Sound files were recorded as 4-second standard .wav files. Note that the detection range was limited to a maximum of 45 m (frequency-dependent). These detectors were placed at the base of each turbine alongside the NV set-up on the leeward side of the turbine (Fig. 1). Ultrasonic detectors were turned on prior to starting the behavioral surveys and turned off when surveys were completed each night.

A survey night began 20 minutes after sunset and continued for up to 200 minutes to encompass the primary bat activity period (Hayes 1997; Baerwald & Barclay 2011; McAlexander 2013). Within this time, we conducted a series of 12 10-min trials and ensured that all cameras were turned on and off in sync. Note that night vision scopes were not used for the first trial as they would not function during low light levels. Prior to each trial, we recorded the temperature (°C), wind speed (km/hr), and gust speed (km/hr) and did not conduct trials if temperatures were <5°C, wind speeds were >24 km/hr, gusts >32 km/hr, or precipitation occurred.

We processed all trial recordings using Studiocode video analysis software (version 5, Studiocode Business Group, Sydney, AU). In this software, corresponding thermal and NV recordings were synchronized to allow them to be viewed together. We then marked and timestamped any flying objects (≥ 8 cm) that were observed in each trial. We defined a 'bat' as any object that had a silhouette resembling a bat (i.e., visible head, body, and wings) and characteristics specific to a bat (such as visible finger bones in the patagium; Fig. 2A). In addition, if an acoustic bat call recorded within 3 sec of the observed object, it further confirmed identification, potentially to species. We defined a 'non-bat' as any object with characteristics of, for example, an insect (such as two pairs of wings) or bird (such as a bird-like tail; Fig. 2B). Lastly, we defined a 'possible bat' as any object that had no defining characteristics visible (Fig. 2C). As the goal of our study was to maximize flying object identification, an effective survey method would minimize the number of objects classified as 'possible bats'.

To understand how bats were interacting with tall structures, one aspect of our survey method was to recognize specific behaviors. Thus, we defined 9 distinct bat behaviors including: *passing* – when a bat flew across the field-of-view in a relatively straight flight path (≤1 turn); *reversing* – when a bat entered the field-of-view and turned back the way it came without passing the tower; *looping* – when a bat turned around at or after passing in front or behind the tower and returned back the way it came; *foraging* – when a bat flew in a zig-zag pattern with ≥2 changes in direction (i.e., turns); *chasing* – when a bat was closely followed by another bat; *skimming* – when a bat flew low over the tower, with its body parallel to the surface potentially making contact; *sweeping* – when a bat flew low over the tower and made contact with an outstretched wing tip; *colliding* – when a bat flew directly into the tower; and *gleaning* – when a bat hovered briefly over the surface of the tower before making contact with the surface (i.e., to potentially grab a prey item) before flying away. We then classified the behaviors exhibited, where possible, by every 'bat' observed and indistinguishable behaviors (i.e., less than 1 sec appearance in a corner of the field-of-view, or a lack of image clarity) were classified as *unknown*. As our study focused on the identification of bat behaviors in proximity to tower surfaces, we combined behaviors into 3 categories for the following analyses: *contact* (all behaviors in which a bat appeared to touch the turbine tower surface, including skimming, sweeping, colliding, and gleaning), *unknown*, and *all other behaviors* (including passing, reversing, looping, foraging, and chasing). As our survey goal was to facilitate behavioral identification, an effective method would minimize the number of *unknown* behaviors.

To determine whether flying object detectability, identification, and behavioral classification differed between NV and thermals, or between thermals at differing distances, we compared the following response variables: the mean number of flying objects observed, the proportions of unidentifiable objects (i.e., 'possible bats'), and the proportions of *unknown* behaviors. For each distance tested, we used a paired *t* test (or a Wilcoxon's signed rank test with nonparametric data) to compare the number of flying objects observed, and Fisher's exact tests to compare the proportions of 'possible bats' and *unknown* behaviors (if applicable) between thermal and NV recordings. Finally, we compared object and behavioral identification between thermal cameras at all distances tested to determine which was the most (or least) effective. For this, we first used a Kruskal Wallis test and if a difference was found between all camera distances, we then conducted a Games Howell test. Next, we conducted Fisher's exact tests to determine if there were differences in the proportions of 'possible bats' and *unknown* behaviors (if applicable) between thermal camera distances. For all statistical analyses, we used Minitab software (version 18, Pennsylvania, USA) with $\alpha = 0.05$.

Results

From 1 July to 10 August 2016, we conducted surveys on 21 nights and recorded a total of 432 trials and 417 flying objects. We also recorded 194 bat acoustic calls, from which we identified: *Lasiurus borealis* (*n* = 103); *Lasiurus cinereus* (*n* = 1); *Lasionycteris noctivagans* (*n* = 7); *P. subflavus* (*n* = 39); and *N. humeralis* (*n* = 44).

When thermal cameras were placed alongside the NV setup 2 m from the base of the turbine tower, we recorded 146 trials over 6 survey nights. We observed 236 flying objects in thermal recordings and 157 in NV. From these flying objects, we identified 68 'bats' and 118 'non-bats' using thermal recordings compared to 22 'bats' and 71 'non-bats' using NV. Of those flying objects classified as 'bats,' we identified 66 behaviors (including 2 *contacts*) using thermal recordings and 20 behaviors using NV.

When we tested thermal cameras 25 m from the turbine base, we also opted to keep a second thermal camera 2 m from the base for an additional comparison as we knew that bats were readily identifiable at this distance. Over 2 survey nights, we recorded 24 trials. We observed 5 flying objects in thermal recordings at 25 m, 12 in NV at 2 m, and 13 in thermal recordings at 2 m. Of these flying objects, we identified 3 'bats' and 1 'non-bat' in thermal recordings from 25 m, 5 'bats' and 3 'non-bats' from NV at 2 m, and 7 'bats' and 4 'non-bats' from thermals at 2 m. Of the objects classified as 'bats', we identified 3 behaviors from thermals at 25 m, 5 from NV at 2 m, and 7 from thermals at 2 m. No *contact* behaviors were observed in any camera's recordings.

We then tested thermal cameras at 50 m and 2 m from the turbine tower base. Over 2 survey nights, we recorded 19 trials and observed 14 flying objects in thermal recordings from 50 m, 39 in NV from 2 m, and 42 in thermal recordings from 2 m. From these flying objects, we identified 5 'bats' in thermal recordings from 50 m, 15 'bats' and 8 'non-bats' in NV recordings from 2 m, along with 25 'bats' and 8 'non-bats' in thermals at 2 m. From those objects classified as 'bats,' we identified 5 behaviors in thermal cameras at 50 m, 15 behaviors in NV at 2 m, and 25 behaviors in thermal cameras at 2 m. No *contact* behaviors were observed in these surveys.

Finally, for surveys with thermal cameras placed 95 m from the tower base, we recorded 147 trials over 7 survey nights. During these surveys, we recorded 3 flying objects in thermal recordings and 27 in NV (placed 2 m from the tower base). From these flying objects, we identified 2 'bats' in thermal recordings compared to 19 'bats' and 2 'non-bats' in NV. Of those flying objects identified as 'bats', we identified 2 behaviors using thermal recordings and 19 behaviors (including 1 *contact*) using NV. With thermal cameras at this distance from the tower, flying objects were indistinguishable from the horizon because they were saturated by the infrared radiation signature. In contrast, these flying objects remained visible in NV recordings and we were able to identify distinct bat behaviors, including close contact with the turbine tower.

To then determine whether the number of flying objects observed differed between NV and thermal cameras, we compared the mean number of flying objects (including bats, non-bats, and possible bats) observed per hour between camera types for each distance tested (Fig. 3). With both thermal and NV technologies placed 2 m from the base of the tower, we detected significantly more flying objects in thermal recordings compared to NV (t = 7.05, df = 11, P < 0.0001). In contrast, we observed a significantly higher number of flying objects in NV when compared to thermals at 25 m (t = -3.66, df = 3 P = 0.035) and found no significant difference between camera types with thermals at 50 m (t = -2.78, df = 3, P = 0.069). Lastly, for surveys with thermal cameras at 95 m and NV at 2 m, we found no significant difference in the flying objects observed per hour (W = 0.00. df = 21, P = 1.00).

Using a series of Fisher's exact tests to determine whether object identification differed between NV (at 2 m) and thermal cameras, we compared the proportions of 'possible bats' (Fig. 4) between camera types and found a significantly lower proportion of 'possible bats' in thermal recordings from 2 m ($\hat{p}_{2\ m\ thermal}$ = 0.212, $\hat{p}_{NV}$ = 0.408, P < 0.0001). In contrast, we found no significant differences with thermals placed at 25 m, 50 m, and 95 m ($\hat{p}_{25\ m\ thermal}$ = 0.200, $\hat{p}_{NV}$ = 0.333, P =1.00; $\hat{p}_{50\ m\ thermal}$ = 0.643, $\hat{p}_{NV}$ = 0.410, P = 0.212; $\hat{p}_{95\ m\ thermal}$ = 0.333, $\hat{p}_{NV}$ = 0.261, P

= 1.00, respectively). Similarly, when we compared the proportion of *unknown* behaviors observed between camera types (where applicable; Fig. 5), we found no significant difference between NV at 2 m and thermals at 2 m or 95 m ($\hat{p}_{2\text{ m thermal}} = 0.029$, $\hat{p}_{NV} = 0.091$, $P = 0.250$; $\hat{p}_{95\text{ m thermal}} = 0.00$, $\hat{p}_{NV} = 0.067$, $P = 1.00$).

Finally, to determine whether the mean number of flying objects, and proportions of 'possible bats' or *unknown* behaviors observed in thermal cameras differed at varying distances, we tested these variables between all thermal distances. For the number of flying objects observed per hour, we found a significant difference among the camera distances ($H = 29.33$, $df = 3$, $P < 0.0001$); thermals at 2 m captured a significantly higher number of flying objects than thermals at 25 m, 50 m, and 95 m, but these 3 farther distances did not differ from each other (Fig. 3; Table 1). Due to the small number of flying objects observed in thermal cameras placed at 25 m ($n = 5$), 50 m ($n = 14$), and 95 m ($n = 3$), for the 'possible bats' analysis we combined these categories and compared the resulting proportion of 'possible bats' observed with thermals at 2 m using a Fisher's exact test. From this, we detected a significantly smaller proportion of 'possible bats' at 2m compared to farther distances ($\hat{p}_{2\text{ m}} = 0.226$, $\hat{p}_{>2\text{ m}} = 0.5$, $P = 0.008$). As *unknown* behaviors were only observed in thermals at one distance tested (2 m), we could not compare these data.

Discussion

From our study, we can recommend survey protocols to study volant species activity at tall structures. We found that the detectability, identification, and behavioral classification of flying objects varied between NV and thermal recordings, indicating that the data collected by these two technologies is different. For example, objects and behavioral detail in front of tower surfaces were easily observed in NV; however, objects approaching the tower were virtually indistinguishable from the night sky. This limitation made it more challenging to detect flying objects approaching the towers, and also made it difficult to identify specific behaviors unless they were directly in front of the tower. Similarly, approaching objects could not be clearly seen in thermal cameras at 25, 50, and 95 m, due to an infrared radiation signature generated by the horizon. In contrast, thermals at 2 m allowed for visibility of approaching objects, but the surface of the tower also generated an infrared radiation signature that tended to obscure visibility when objects passed directly in front of the tower (Fig. 6). Subsequently, while NV (at 2 m) effectively allowed flying objects and associated behaviors in front of the towers to be identified, and thermals at 2 m picked up ~ 20% more flying objects approaching and interacting with the sides of the towers, we recognized the contrasting benefits of both camera types. While many studies have used NV or thermal technology separately to detect flying objects and analyze volant wildlife behaviors (Horner, Fleming & Sahey 1998; Jerem et al. 2015; Hayman et al. 2017), our findings indicated that using the two technologies in combination with one another yields more reliable results.

We acknowledge that the shortcomings of thermal cameras in our study may have been exacerbated by high ambient temperatures at our site; thus, future studies could explore whether surveys conducted in colder climates experience similar radiation-related issues. Regardless, in areas with similar climates to our study site, we certainly recommend the combined technology setup. If economically feasible, we further recommend that 2 setups are implemented on either side of a structure to capture all volant species interactions. However, at tall structures such as wind turbines, studies have shown that the majority of activity occurs on the leeward side of the turbine (Cryan et al. 2014; Hein & Schirmacher 2016); therefore, in these instances, one setup may be effective. In addition, for all surveys we recommend the creation of an object identification key to allow comparable and repeatable flying object identification. Note that our key was customized for our taxonomic group of interest and study site, we therefore recommend that keys are customized and verified to specific surveys.

Conclusion

As the construction of anthropogenic structures continues to modify air spaces, behavioral surveys will only become more important (Cousins et al. 2012; Arnett & Baerwald 2013; Vasenev et al. 2018). Furthermore, existing structures could be modified and improved (i.e., increased height of towers, length of wind turbine blades, etc.), thus understanding how these changes could impact wildlife should be considered (Thomsen 2009). For these future studies, our recommendations for a standardized survey protocol would allow for behavioral comparisons between structure types to thereby inform mitigation strategies to alleviate anthropogenic effects.

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Figure 1(on next page)

Diagram of the thermal and night vision setups used at our site.

Thermal cameras were tested (**A**) 2 m, (**B**) 25 m, (**C**) 50 m, and (**D**) 95 m from the tower base. At each thermal distance tested, NV was 2 m from the base of the tower, with IR lights on either side on the NV cameras. The microphone icon represents the ultrasonic recording equipment.

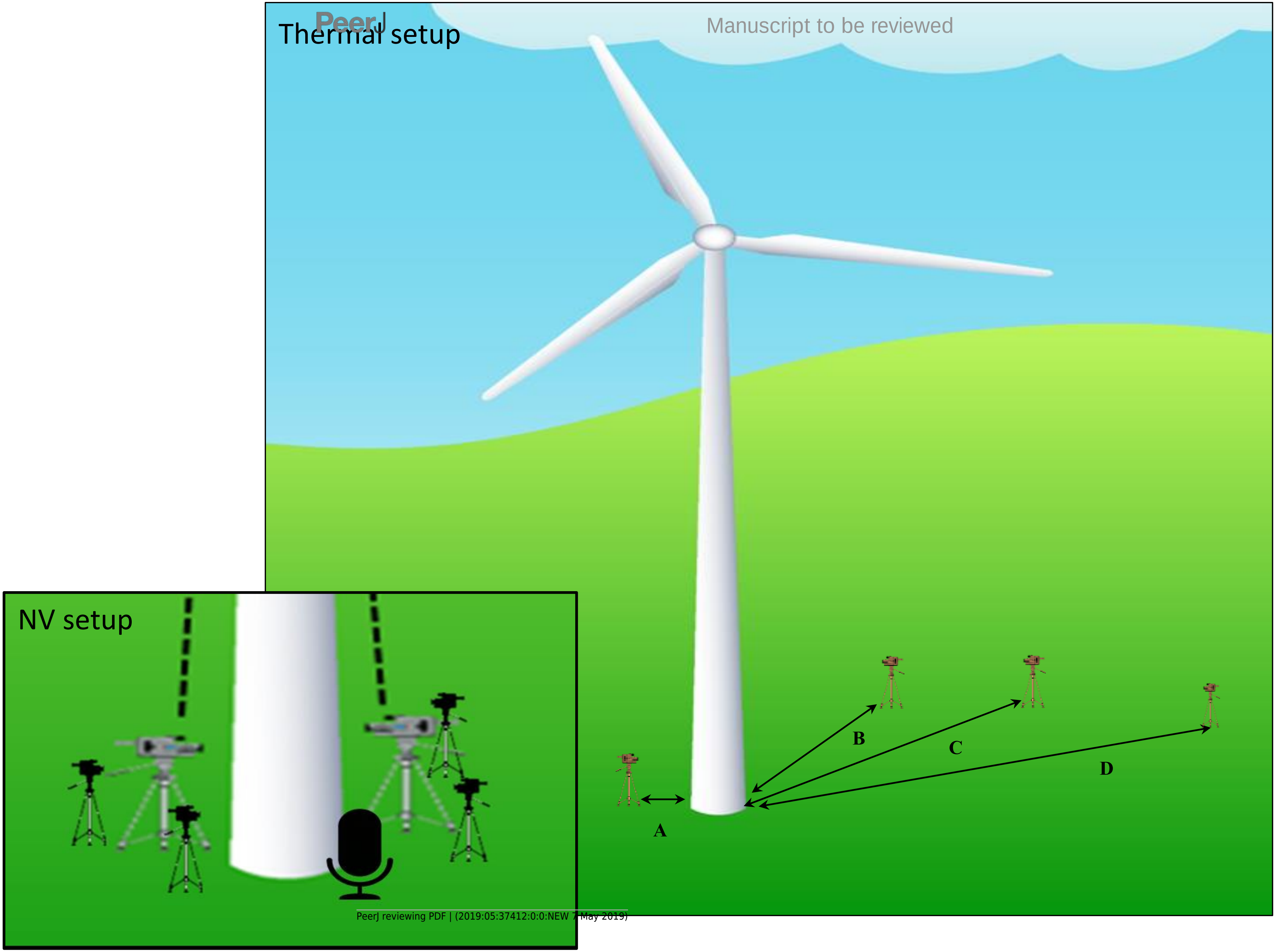

Thermal setup
NV setup
A
B
C
D

Figure 2 (on next page)

Images from thermal (left) and night vision (right) fields-of-view demonstrating the 3 options for categorizing flying objects.

(A) demonstrates ‘confirmed bats’, (**B)** shows ‘non-bats’, and (**C)** shows ‘possible bats’.

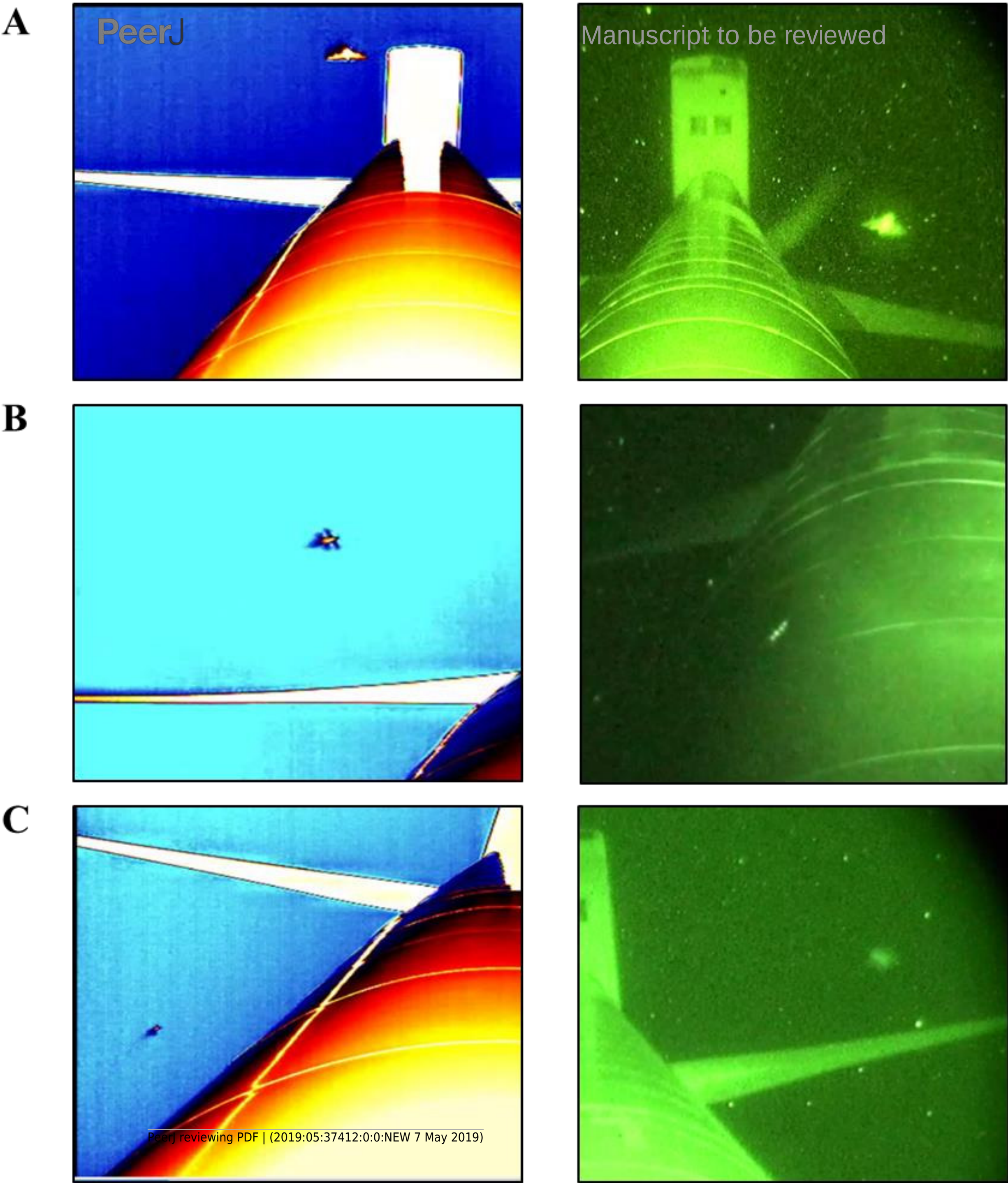
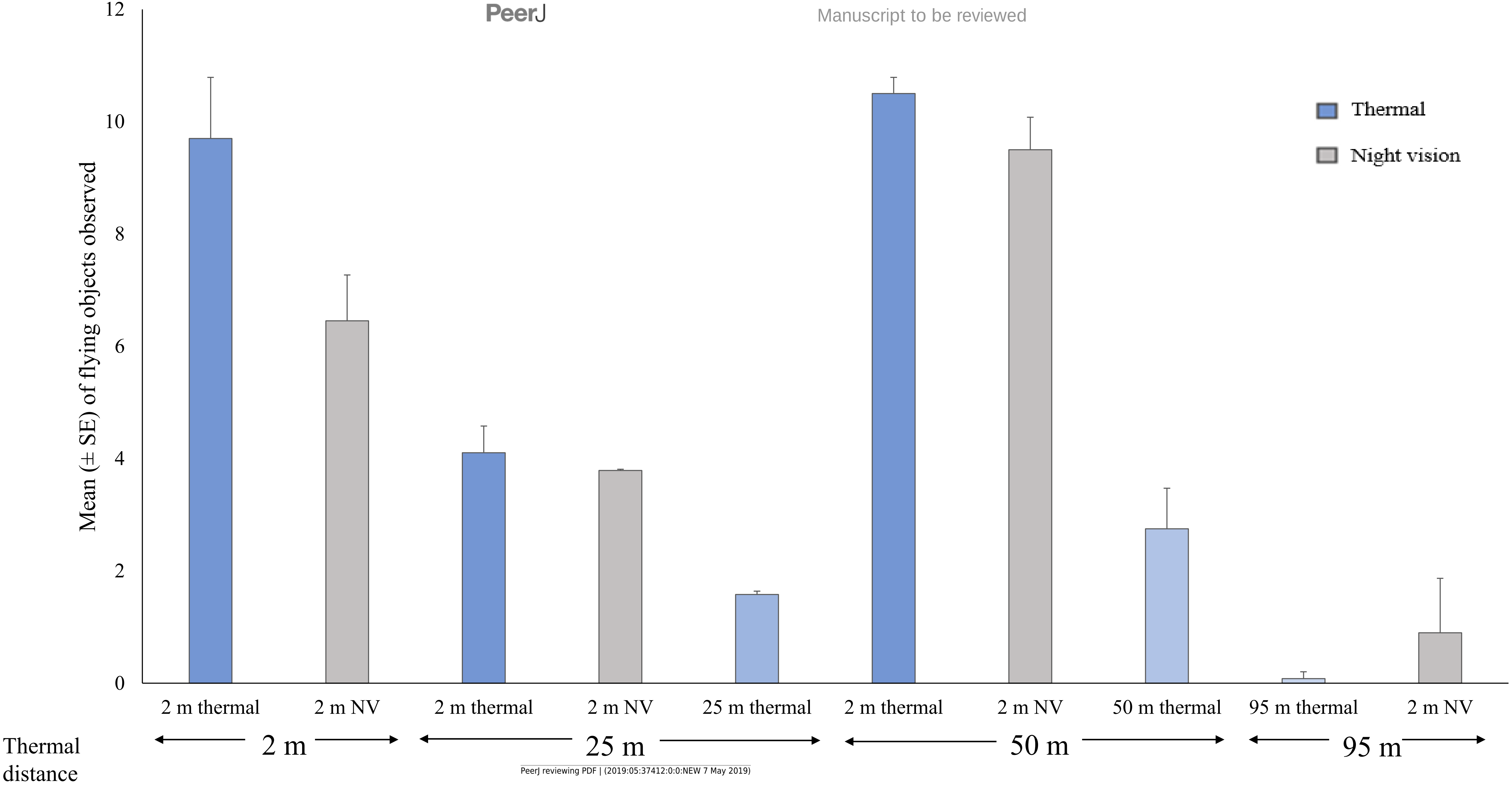

A
B
C

Figure 3 (on next page)

(on next page)

Mean (+ SE) number of flying objects (including bats, non-bats, and possible bats) identified per hour in thermal and night vision recordings at each distance trial tested.

Gray indicates night vision at 2 m, and blue delineates thermals, while lighter shades of blue indicate thermal camera placement at farther distances.



Mean (± SE) of flying objects observed
0
2
4
6
8
10
12
Thermal
Night vision
2 m thermal
2 m NV
2 m thermal
2 m NV
25 m thermal
2 m thermal
2 m NV
50 m thermal
95 m thermal
2 m NV
Thermal distance
2 m
25 m
50 m
95 m

Figure 4(on next page)

Proportion of unidentifiable objects (i.e., ‘possible bats’) observed in thermal and night vision recordings at each distance trial tested.

The *n* above each camera type indicates the total number of flying objects observed.

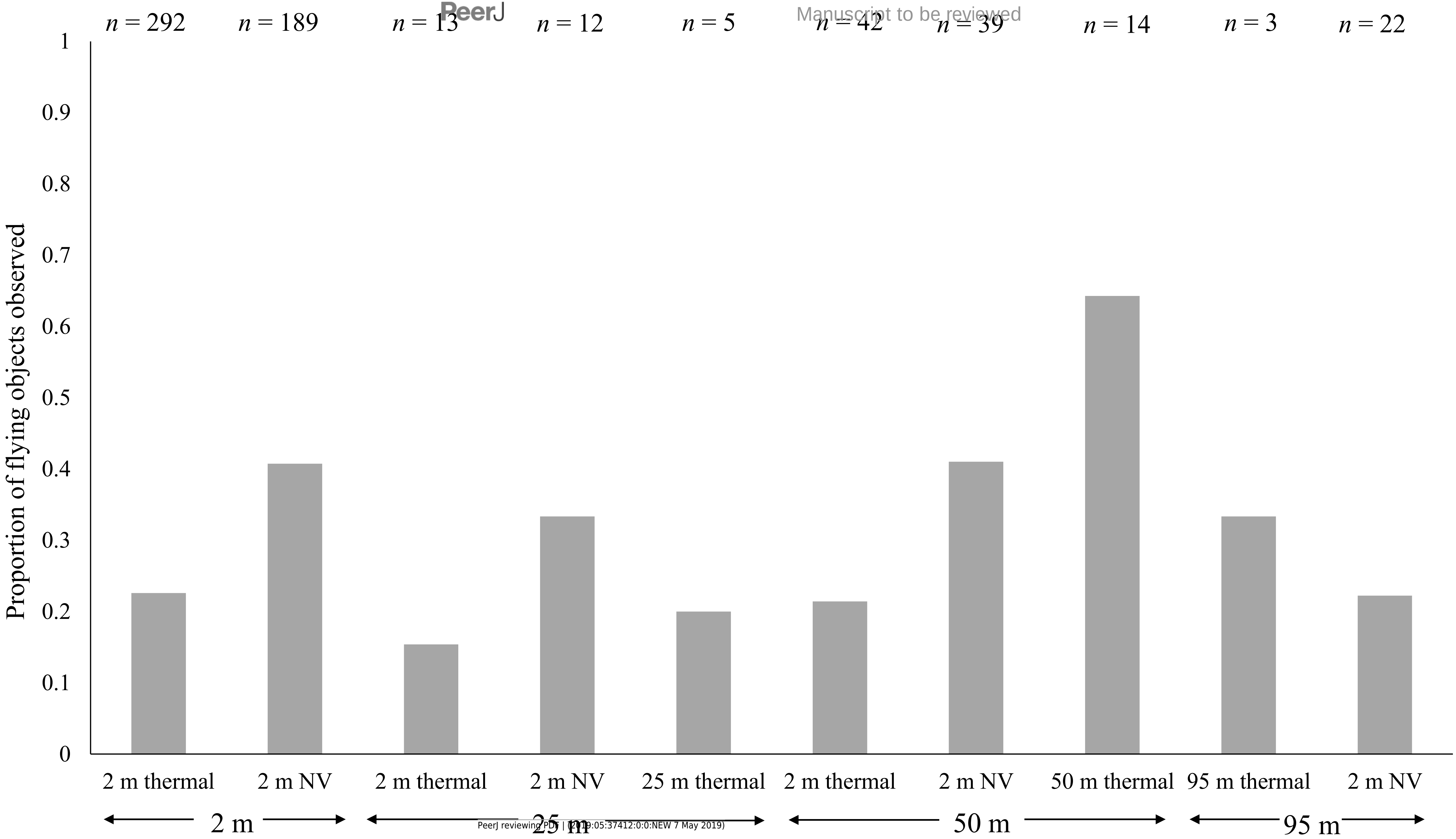

n = 292
n = 189
n = 13
n = 12
n = 5
n = 42
n = 39
n = 14
n = 3
n = 22
Proportion of flying objects observed
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2 m thermal
2 m NV
2 m thermal
2 m NV
25 m thermal
2 m thermal
2 m NV
50 m thermal
95 m thermal
2 m NV
2 m
25 m
50 m
95 m

Figure 5 (on next page)

Proportion of bat behaviors observed in thermal and night vision recordings at each distance tested.

The *n* above each camera type indicates the total number of ‘bats’ observed.

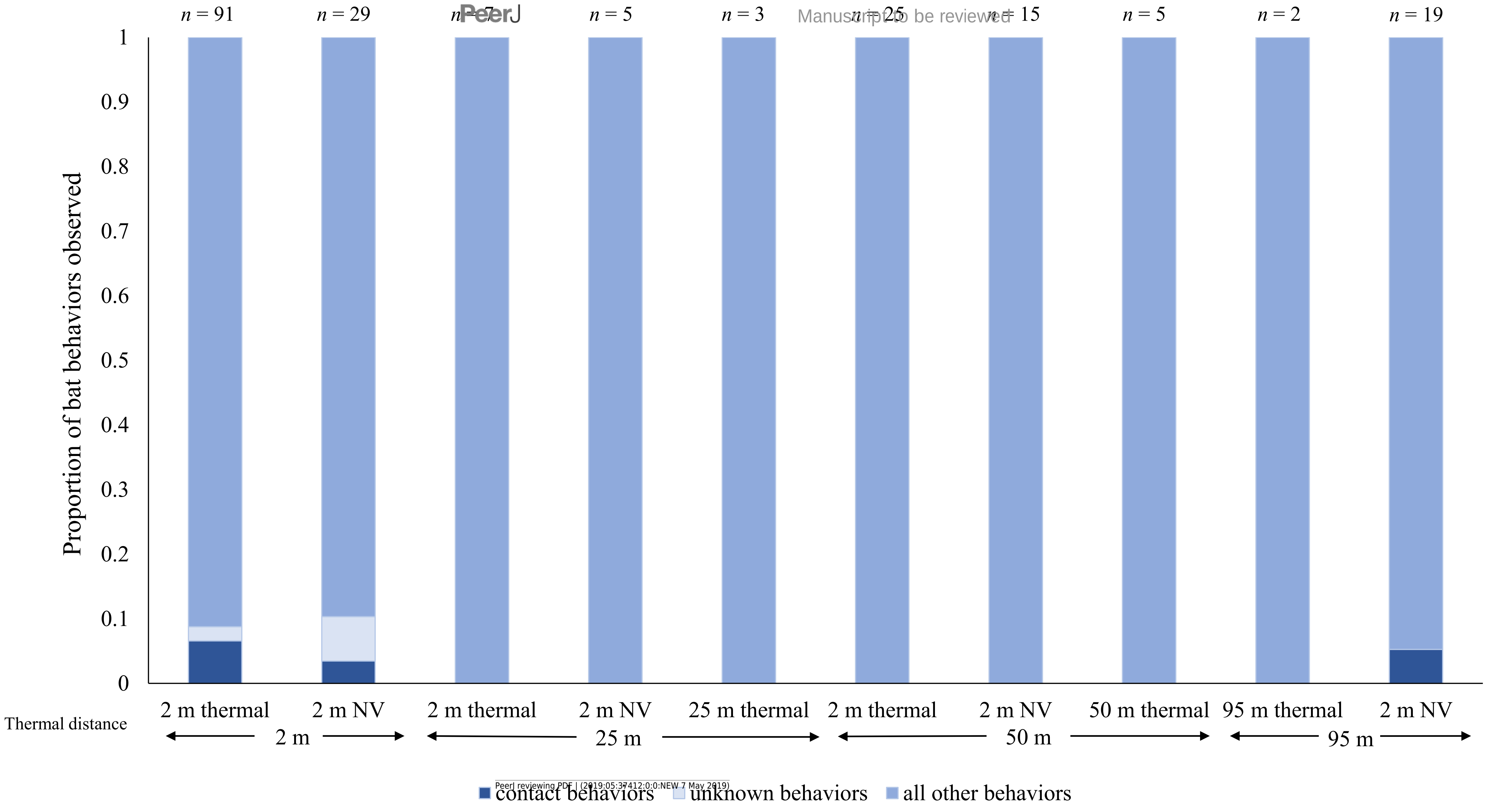

n = 91
n = 29
n = 7
n = 5
n = 3
n = 25
n = 15
n = 5
n = 2
n = 19
Proportion of bat behaviors observed
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Thermal distance
2 m thermal
2 m NV
2 m thermal
2 m NV
25 m thermal
2 m thermal
2 m NV
50 m thermal
95 m thermal
2 m NV
2 m
25 m
50 m
95 m
contact behaviors
unknown behaviors
all other behaviors

Figure 6 (on next page)

Thermal and night vision images of a bat (circled in red) approaching and passing closely in front of a wind turbine tower.

(**A**) shows that the bat is readily visible approaching in the thermal image. (**B-C**) demonstrates that the bat becomes obscured by the infrared heat signature from the turbine tower. (**D**) shows bat is difficult to see when approaching the tower in the night vision image. (**E**-**F**) demonstrates that the bat readily visible in front of the tower.

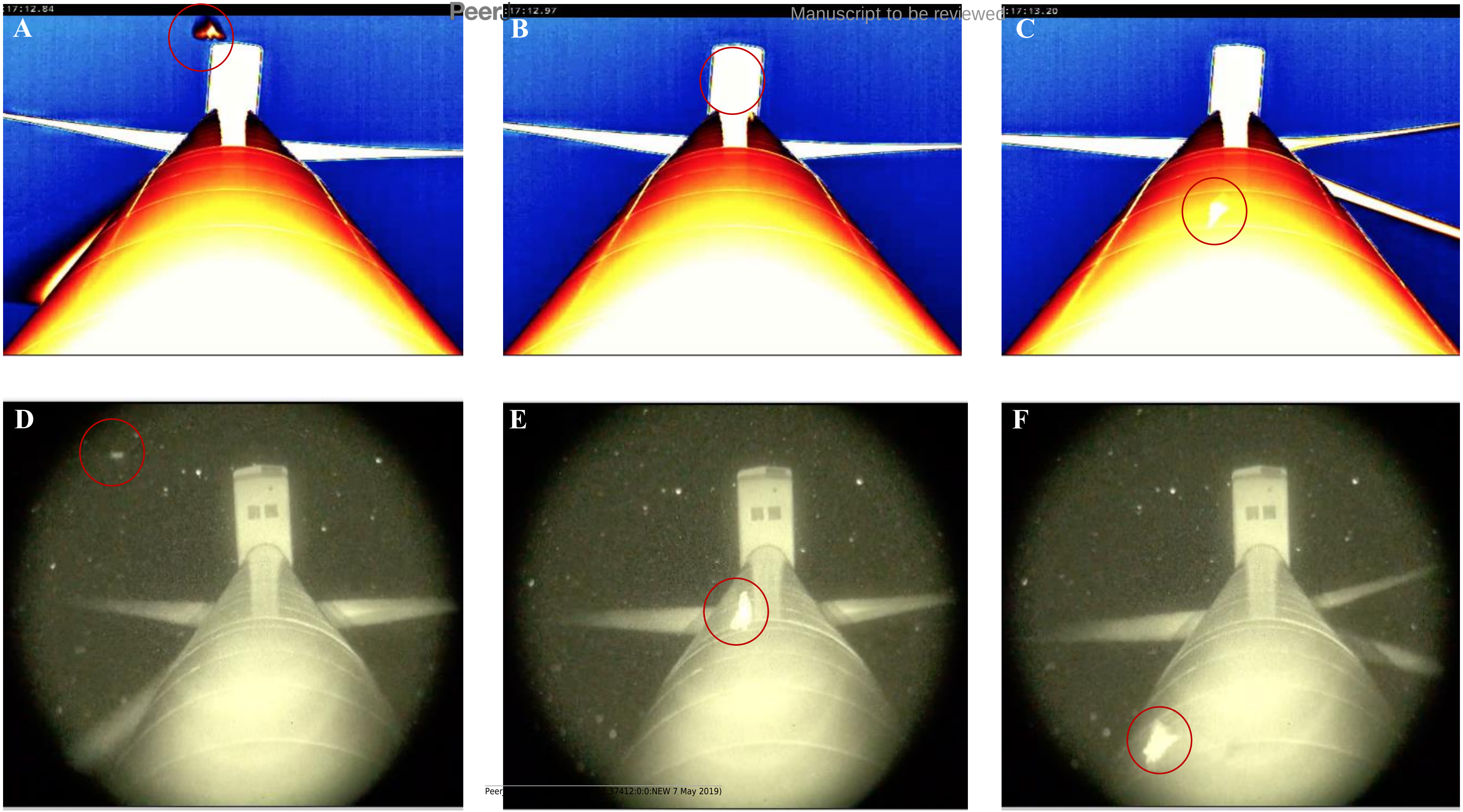

:17:12.84
A
:17:12.97
B
:17:13.20
C
D
E
F

Table 1 (on next page)

The results of a Games-Howell test comparing the mean number of flying objects observed per hour between thermal cameras at 2 m, 25 m, 50 m, and 95 m distances from 1 July to 10 August 2016.

Thermals compared	Difference of means	SE of Difference	95 % CI	*T*-Value	Adjusted *P*-Value
25 m – 2 m	-18.75	1.42	(-22.93, -14.57)	13.20	< 0.0001
50 m – 2 m	-16.00	1.85	(-21.62, -10.38)	-8.66	< 0.0001
95 m – 2 m	-19.58	1.36	(-23.68, -15.49)	-4.36	< 0.0001
50 m – 25 m	2.75	1.31	(-2.88, 8.38)	2.09	0.305
95 m – 25 m	-0.833	0.418	(-2.729, 1.062)	-1.99	0.345
95 m – 50 m	-3.58	1.25	(-9.59, 2.43)	-2.86	0.177