A New Disturbance in the Sky:
The Effect of Drones on Bat Activity in Singapore

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DECLARATION

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

Lim Kai Ning
8 April 2019

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ABSTRACT

The introduction of a novel stimuli, Unmanned Aerial Vehicles (UAVs), also known as “drones”, to the aerosphere presents volant animals with yet another challenge. Despite the growing popularity of drones, effects on flying animals are not well studied. Bats especially, depend heavily on the aerosphere. In particular, aerial hawking species that echolocate to navigate and forage in open to semi-open airspaces. Their habitat overlaps with areas where drones are frequently used and drones might physically obstruct or interfere with echolocation of these bats. As such, this study aims to determine the effect of drones on bats in Singapore. By carrying out acoustic recording using Anabat Express Passive Bat Detectors, I compared bat activity and foraging activity between nights (n = 55) with and without drones. I predicted the decline of bat activity and foraging activity in the presence of drones. Quantitative results showed no statistical difference, but visual examination of spectrograms reveal the decline of bat calls in the presence of drones. Bat calls even resumed after the drone left, indicating a disturbance. The reduction in echolocation calls may represent an energetic cost to the animal because hunting is not possible.

Keywords: drones, Chiroptera, disturbance, noise, acoustic monitoring

1. INTRODUCTION

1.1 Drones – a new disturbance

Unmanned Aerial Vehicles (UAVs), more commonly called “drones”, have been in use for over a century (i.e., starting with the first pilotless plane in 1917), but they only became common in the past decade or so, after the first commercial applications were permitted (Dormehl, 2018). Today’s drones have many uses, including aerial surveillance, disaster relief, scientific monitoring and recreation, and their popularity is growing (Mulero-Pazmany *et al.*, 2017; Choi-Fitzpatrick *et al.*, 2016). Commercial applications (e.g., parcel delivery), in particular, will definitely increase the number of drones flying in the sky at any time (Castellano, 2019).

However, drones still represent rather novel stimuli in the aerosphere, and their impacts on wildlife remain largely unknown. On one hand, they have clear positive impacts, e.g., allowing researchers to monitor wildlife in an efficient and relatively non-intrusive way (compared to capture or helicopter surveys) (Arona *et al.*, 2018). On the other, they are potential sources of auditory and visual disturbance. The noise they emit is enough to irritate people (Christian and Cabell, 2017) and it stands to reason that it may disturb non-human animals too. In addition, drones arguably present visual disturbances (by their mere presence, lights and silhouettes) and it is possible that animals perceive them as predators. Finally, they could collide with flying animals.

Most investigations of the impacts of drones on wildlife have focused on birds (McEvoy *et al.*, 2016; Borrelle and Fletcher, 2017; Vas *et al.*, 2015) and aquatic mammals (Arona *et al.*, 2018; Christiansen *et al.*, 2016; Pomeroy *et al.*, 2015). However, results thus far have been inconsistent. For example, grey seals’ (*Halichoerus grypus*) reactions to drones were variable, e.g., while juveniles and moulting individuals fled, breeding females were resistant to leaving their area (Pomeroy *et al.*, 2015). In bears (*Ursus americanus*), approaching drones caused heart rates to increase (Ditmer *et al.*, 2015). Although many online videos document strong avian reactions, some studies have found the opposite. Some species of birds displayed no observable behavioural reactions when drones were flown carefully at a large enough distance (McEvoy *et al.*, 2016; Vas *et al.*, 2015; Lyons *et al.*, 2017).

1.2 Volant animals - bats

Flying animals experience special challenges. Flight is the most energetically costly mode of locomotion (Shen *et al*., 2010). In addition, the aerosphere is more challenging and dynamic compared to terrestrial and aquatic environments (Kunz *et al.*, 2008). Atmospheric conditions and other physical factors (e.g., moon light, gravitational forces) are ever changing. For these animals, anthropogenic disturbances, such as buildings, lights and aircraft, further degrade and reduce space available (Kunz *et al*., 2008; Lambertucci *et al.*, 2015), and drones arguably represent an additional disturbance. Because drones usually fly in the same airspace as most flying animals (Lambertucci *et al.*, 2015), it is worth investigating their effect on animals while they are in flight.

I chose to investigate their impacts on bats because these impacts matter. Bats face a relatively high level of endangerment, with nearly one quarter of all species classified as near-threatened or at greater risk of extinction by the IUCN (IUCN, 2015). They play key ecological roles and provide critical ecosystem services, such as arthropod suppression, pollination and seed dispersal (Kunz *et al.*, 2011). In addition, most species (except most Old World fruit bats, i.e., Pteropodidae) have vocal echolocation, which they use for navigating and foraging. One of them being the aerial hawking species that echolocate and hunt on the wing. Because they forage in open to semi-open airspaces (Denzinger and Schnitzler, 2013), which are also where drones are used, drones might physically obstruct them or interfere with their echolocation, e.g., interfere with their ability to interpret returning echoes. This is in contrast to sit-and-wait, i.e., perch hunters, and gleaners, which detect prey by the sounds they emit and pick them off vegetation. Indeed, many studies reveal the negative impacts of anthropogenic noise on bats (e.g., Schaub *et al.* *(*2008)). Perhaps most importantly, the only studies on drones and bats have focused on the use of drones for bat population monitoring (Fu *et al.*, 2018; Kloepper and Kinniry, 2018), and so the impacts of drones on bats are totally unknown.

1.3 Singapore's context

In keeping with a global increase in drone activity, the number of consumer drones shipped into Singapore increased from 500,000 in 2013 to more than 4 million in 2015 (Ong, 2016). Members of the public fly drones for recreational purposes, e.g., photography and sport (racing), and various government agencies (e.g., National Parks Board, National Environmental Agency, Land Transport Authority and Singapore Post) use them to increase efficiency and reduce manpower needs (Ong, 2016; Ganesan, 2018).

Singapore's strict aviation laws (Civil Aviation Authority of Singapore, 2018b) restrict recreational drones to certain open and permitted regions (Fig. 1). Thus, the restrictions necessarily concentrate drone activity in a limited portion of Singapore's territory. This represents a potential problem because in this land-scarce and densely populated nation, these areas are inevitably close to spaces inhabited by bats. If drones are found to pose an added disturbance or source of mortality, then their presence could reduce the amount and quality of bat habitats. This could further threaten a taxon that has already suffered massive declines due to more than a century of deforestation and urban development (Pottie *et al.*, 2005; Lane *et al.*, 2006; Leong and Chan, 2011).

With Singapore recently designating One-North as a "drone estate", an area dedicated to developing urban drone uses (Civil Aviation Authority Singapore, 2018a). And developments such as shore-to-ship and commercial parcel delivery (Airbus, 2018), it shows Singapore's ambition of becoming a "drone hub" (Ong, 2016). As such, it is vital to minimise any negative impacts to its bats. I initiated this study hoping my findings might offer useful insight into how a novel source of disturbance affects bats in Singapore. But with the popularity of drones growing worldwide (Choi-Fitzpatrick *et al.*, 2016), my study has potentially wider implications.

1.4 Research objectives

I aimed to answer the question “Are bats affected by drones?”, by determining whether activity of insectivorous bats changes in the presence of drones by comparing bat activity:

1. between nights in presence and absence of drones, and
2. before, during and after a drone event.

Another goal was to determine whether drones affect foraging activity. I hypothesised that bats are disturbed by drones and predict that bat activity declines in the presence of drones as they avoid the disturbance. Foraging activity, similarly, will decrease in the presence of drones because drones are physical obstacles preventing foraging and the noise it produces might interfere with prey detection.

2. MATERIALS AND METHODS

2.1 Study sites

I conducted my study at two sites – Bishan-Ang Mo Kio (Bishan-AMK) Park and Old Holland Road (Fig. 1). Bishan-AMK Park is an urban park in central Singapore, with a canal that was recently de-concretised and rehabilitated (Public Utilities Board, 2018). The open field at Old Holland Road is near Ulu Sungei Pandan – another site whose canal is being rehabilitated. I chose these sites because they are both within the permitted areas for recreational drones (Civil Aviation Authority of Singapore, 2018b) and are popular spots for flying them. Also, I established that both sites are inhabited by aerial hawking bats by preliminary visits.

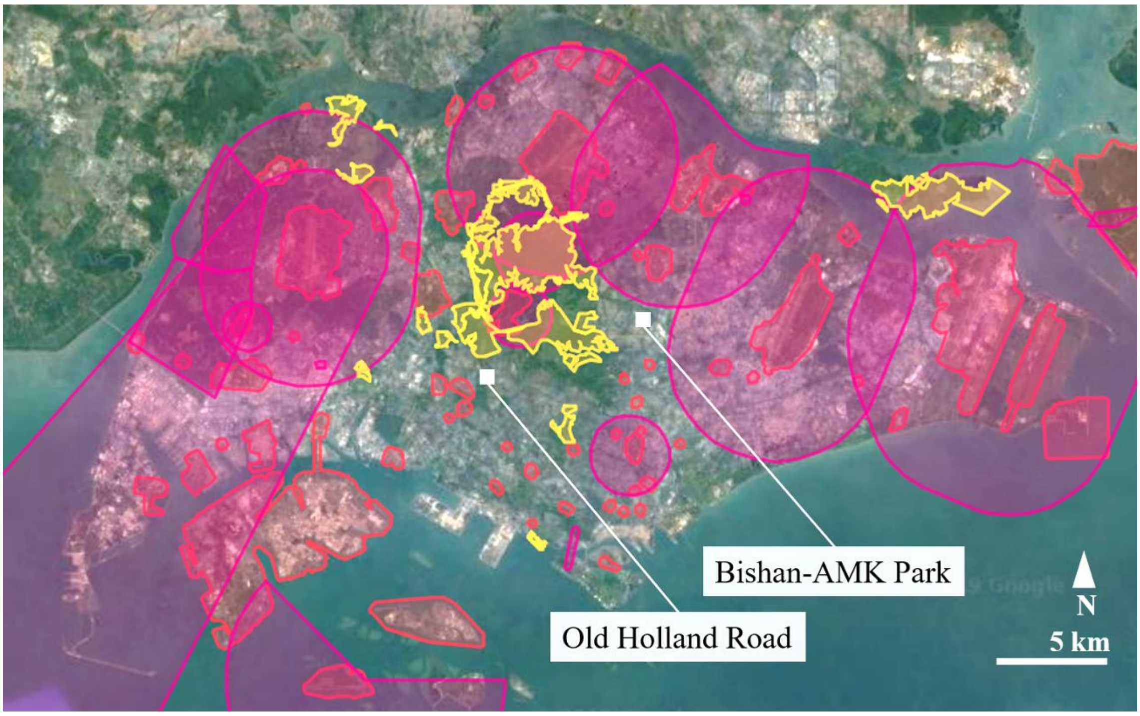

Fig. 1. Map of Singapore showing study sites and areas which prohibit drone flying (Garuda Robotics, 2019). Sites (white) at Bishan-AMK Park faces the stream and riparian vegetation while that of Old Holland Road is an open field. Regions marked red and yellow are “no-flying” zones. Red zones include areas within 5 km of an airport or airbase and restricted areas; yellow zones are parks and Nature Reserves that prohibit drone flying activities.

2.2 Acoustic recording

To measure bat activity, I conducted acoustic recording for an hour after sunset on nights without rain from October 2018 to March 2019. The hour after sunset is when bats are most active in Singapore (J Coleman, pers. comm.). It also coincides with the peak time for recreational drone use when they are used to photograph sunsets.

I used Anabat Express Passive Bat Detectors (Titley Electronics, New South Wales, Australia) to record bat echolocation calls by placing them at a 45^0 angle from the ground (Britzke *et al.*, 2010). I used the default sensitivity and data division ratio settings (both at 8). The device has a detection range from 10 to 150 kHz over 30 m, but this can vary depending on call frequency and distance of the bat to the omnidirectional microphone (Titley Electronics). Atmospheric conditions e.g., temperature and humidity will affect sound transmission (Lawrence & Simmons, 1982), and thus the quality of the recording.

Being an observational study, I took note of the presence of drones and categorised nights as with or without drones. Because I could not control the duration of the drones' flight, drone flight time i.e., the amount of time each drone stayed in the air, was also a variable. I also recorded abiotic variables such as temperature, wind speed, relative humidity and pressure every 15 minutes using a Kestrel 4000 weather meter (Nielsen-Kellerman, Boothwyn, Pennsylvania). In addition, I noted other anthropogenic activities such as the number of aircraft flyovers and the level of human activity. I categorised human activity level as "low", "medium" and "high" based on the number of pedestrians per five-minute period (< 15, 15-30 and > 30 pedestrians respectively).

The Anabat Express is designed to record high frequency sounds from bats. To better capture the noise produced by drones, which possibly includes lower frequency sounds (i.e., <10 kHz), I used a Zoom H5 Handy Recorder which records in full-spectrum (.wav) and analysed the recording in SongScope (Wildlife Acoustics) (Fig. 2).

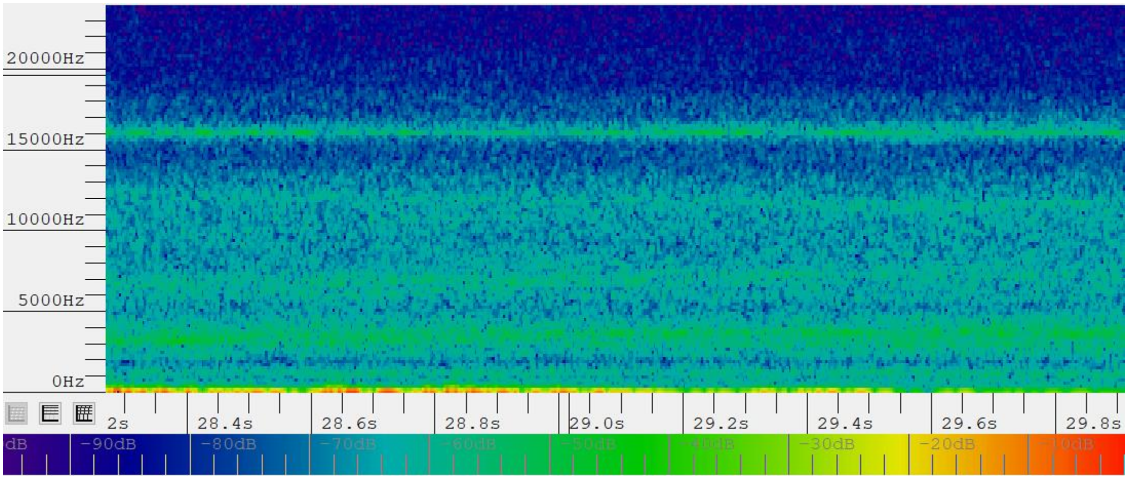

Fig. 2. Spectrogram of the sounds produced by a drone from one-meter distance. Low frequency sounds are the loudest (around 90 decibels) as shown in red, but drone noise reaches 16 kHz.

2.3 Quantifying bat activity

The Anabat Express uses zero-crossing analysis (ZCA) to visualise calls on a spectrogram (Baxter *et al.*, 2006). For this study, I used AnalookW (version 4.3x, Chris Corben) to do so. ZCA calculates certain key call parameters, but removes the amplitude component that “full spectrum” recorders include. In this way, it produces recordings that are lower in quality but easier to manage (given smaller file sizes), and the technology is much cheaper than full-spectrum machines.

These acoustic data cannot be used to directly quantify the number of bats present (i.e., bat abundance) because a single bat may call multiple times. Instead, they merely allow the researcher to calculate bat activity , and thus obtain an *index* of abundance. Following Hayes’ (1997) method, I used the number of bat passes per unit time, and defined a pass as a sequence of at least two search phase calls no more than one second apart (Fig. 3).

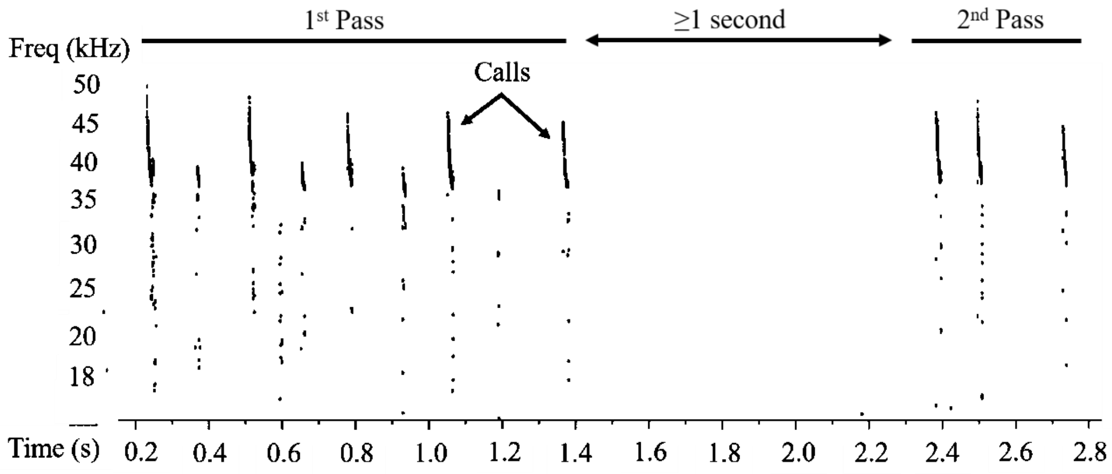

Fig. 3. Spectrogram showing two bat passes because search phase calls (Fig. 4) are separated by a second. Each individual line is an echolocation call, while a series of calls with less than a second apart makes up a bat pass.

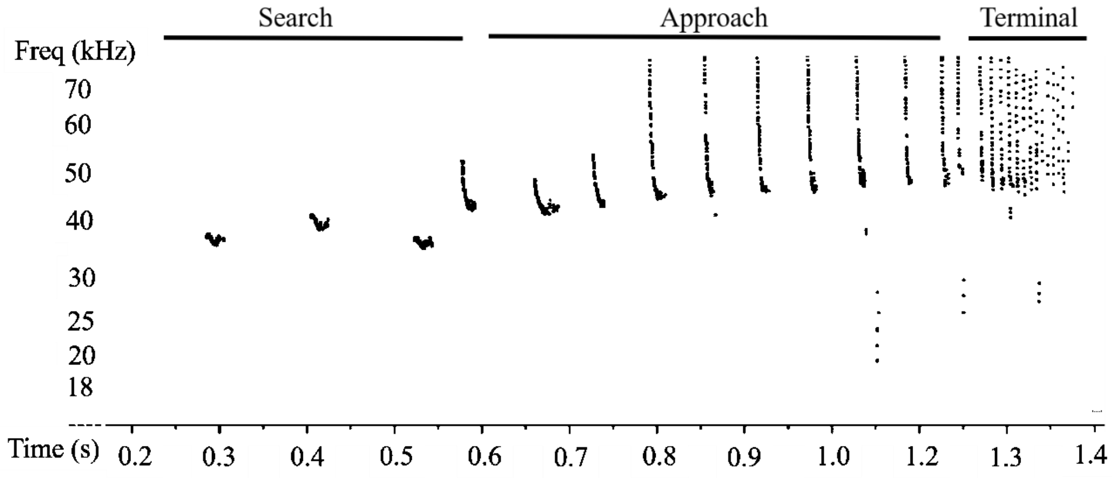

Fig. 4. Spectrogram showing the three phases of a bat pass – search, approach and terminal. A bat emits search phase calls when navigating or searching for prey. After detecting its prey, it emits approach calls which are at a more rapid rate to continuously determine the position of its prey in the air. Prior to capturing its prey, it produces a terminal buzz (Schnitzler and Kalko, 2001).

Quantifying foraging activity

I used the number of terminal buzzes per night as an estimate of foraging activity (Holderied *et al.*, 2008). A bat produces the terminal buzz (Fig. 4) when it zeroes in on its prey (Holderied *et al.*, 2008), thus, it is also termed the “feeding buzz”. However, the presence of a terminal buzz only implies a foraging attempt and cannot be used to measure successful prey capture (Britton and Jones, 1999).

The buzz ratio (terminal buzzes per pass) measures foraging effort per unit of flight activity (Vaughan *et al.*, 1997). It can also act as a proxy for insect activity (i.e., the higher the buzz ratio, the higher the insect activity) (Rowse *et al.*, 2016) and provide further information about habitat use.

2.4 Species identification

Although most of Singapore's echolocating bats are insectivores, there are two species of fruit bats, *Cynopterus brachyotis* and *Eonycteris spelaea*, that echolocate using their wings (Boonman *et al.*, 2014). The physiology and purpose of this adaptation remains poorly understood, and acoustic monitoring method may not apply to them.

Singapore lacks an echolocation reference call library and based on the only published study on echolocation calls of Singapore's bats (Pottie *et al.*, 2005), I only identified species that were easily distinguishable. Majority of calls had overlapping frequencies (see Appendix A) and similar shapes so I decided not to analyse the effect of drones on individual species. However, based on clearer recordings, the following are possible species that I have recorded (Fig. 5).

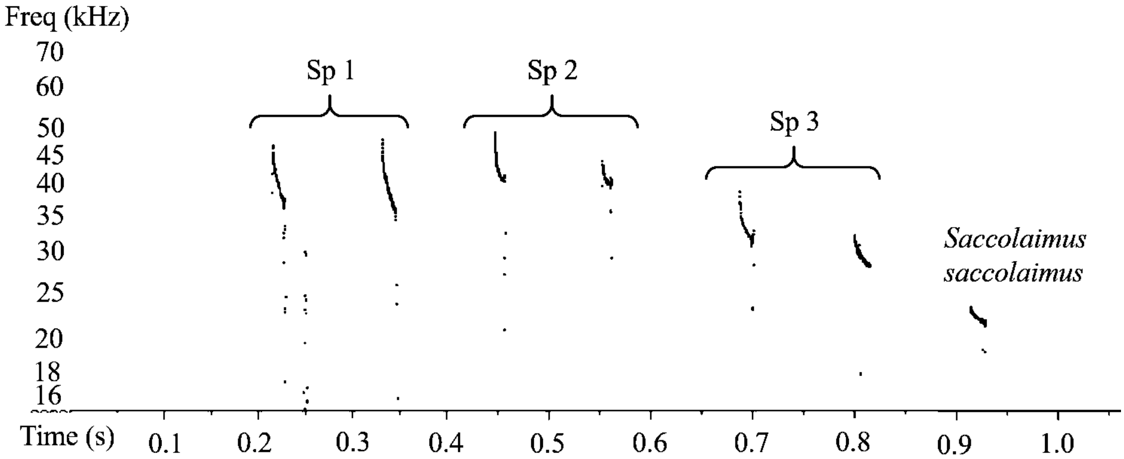

Fig. 5. Spectrogram of search phase calls observed. Echolocation calls that were not identified to species are labelled as unknown species (Sp). They are categorised based on similarity of call shape and frequency.

Sp 1 are most likely *Myotis* bats while Sp 2 are *Scotophilus kuhlii*. Call parameters of Sp 3 did not match any of those in Pottie et al. (2005). However, Sp 3 may be *Pipistrellus stenopterus*

(Kingston *et al.*, 2003) which was observed in Bukit Timah Nature Reserve (Leong *et al.*, 2010) but not documented by Pottie et al. (2005), or *Taphozous melanopogon* due to similar call frequencies and the inability of the zero-crossing recording to depict multi-harmonic calls (Adams, 2013). Ultimately, the only species I could confidently identify is *Saccolaimus saccolaimus* given its low average frequency (about 21 kHz).

2.5 Data analysis

I used R studio (version 1.1.463) to carry out all statistical analyses and assumed all data to be non-normal. I compared the mean number of passes, terminal buzzes and buzz ratio per night between nights with and without drones using the Wilcoxon signed-rank test, and tested for correlation between drone flight time and the number of bat passes using Spearman's correlation.

In addition, I visually inspected the spectrograms to assess the impact of drones on bat activity. I identified and counted "drone events", which were reflected in the spectrogram as instances when drone noise and bat calls were both present. I classified these drone events into three categories – according to if the drone caused an increase, decrease, or no change in bat activity. I then calculated the probabilities of each of the three drone events occurring. To determine the aftermath of the drone, I calculated the change in bat activity after the drone event using the mean number of passes per minute during and within five minutes after the drone had left:

$$Change\ (passes.min^{-1}) = \frac{(After - During)}{During}$$

To test the effect of drones and other variables on bat activity, I started with a saturated generalised linear model (GLM) and removed non-significant variables using the stepwise regression method. The model tested the effect of drone flight time, average temperature, the number of aircraft flyovers and human activity level on the number of bat passes per night. I excluded other abiotic variables such as average humidity, pressure, wind speed due to multicollinearity.

3. RESULTS

I recorded a total of 13,869 bat passes and 448 feeding buzzes over 55 nights, of which 27 had drone activity. There was bat activity on all nights but only 52 contained feeding buzzes.

3.1 Bat activity

Throughout the study, I observed only one drone at any one time. Bat activity did not differ on nights with and without drones (*P* = 0.76; Fig. 6a). There was also no correlation between bat activity and drone flight time (ρ = 0.20, *P* = 0.33; Fig. 6b).

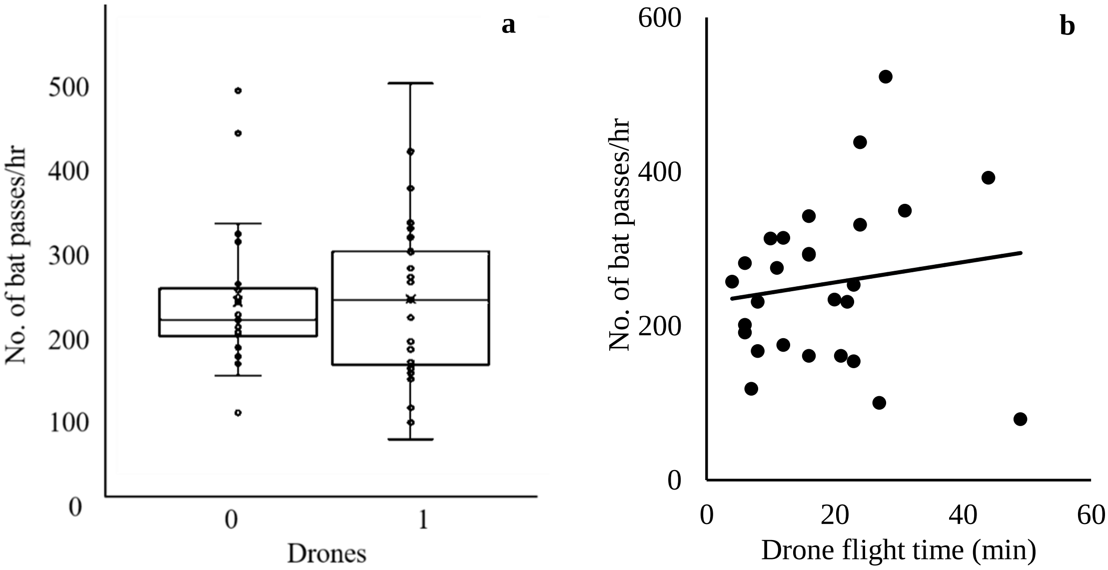

Fig. 6. (a) Comparison of bat passes between nights without (0) and with (1) drones. X denotes mean number of passes, 250.3 and 253.9 respectively. Both boxplots have similar mean and median values, however, nights with drones show greater variability. (b) Relation between number of bat passes per night and drone flight time. Line shows best-fit linear relation.

Through visual inspection of spectrograms, I identified 91 drone events (Fig. 7). Of these, 77 % showed a decrease in bat activity in the presence of a drone (Fig. 7a, b), 7 % increased (Fig. 7c) and the remaining showed no change. After the drone left, bat activity resumed 60 % of the time (Fig. 7d). Through calculations, I also found bat activity to increase after the drone event on 15 nights (n = 25, *P* = 0.01).

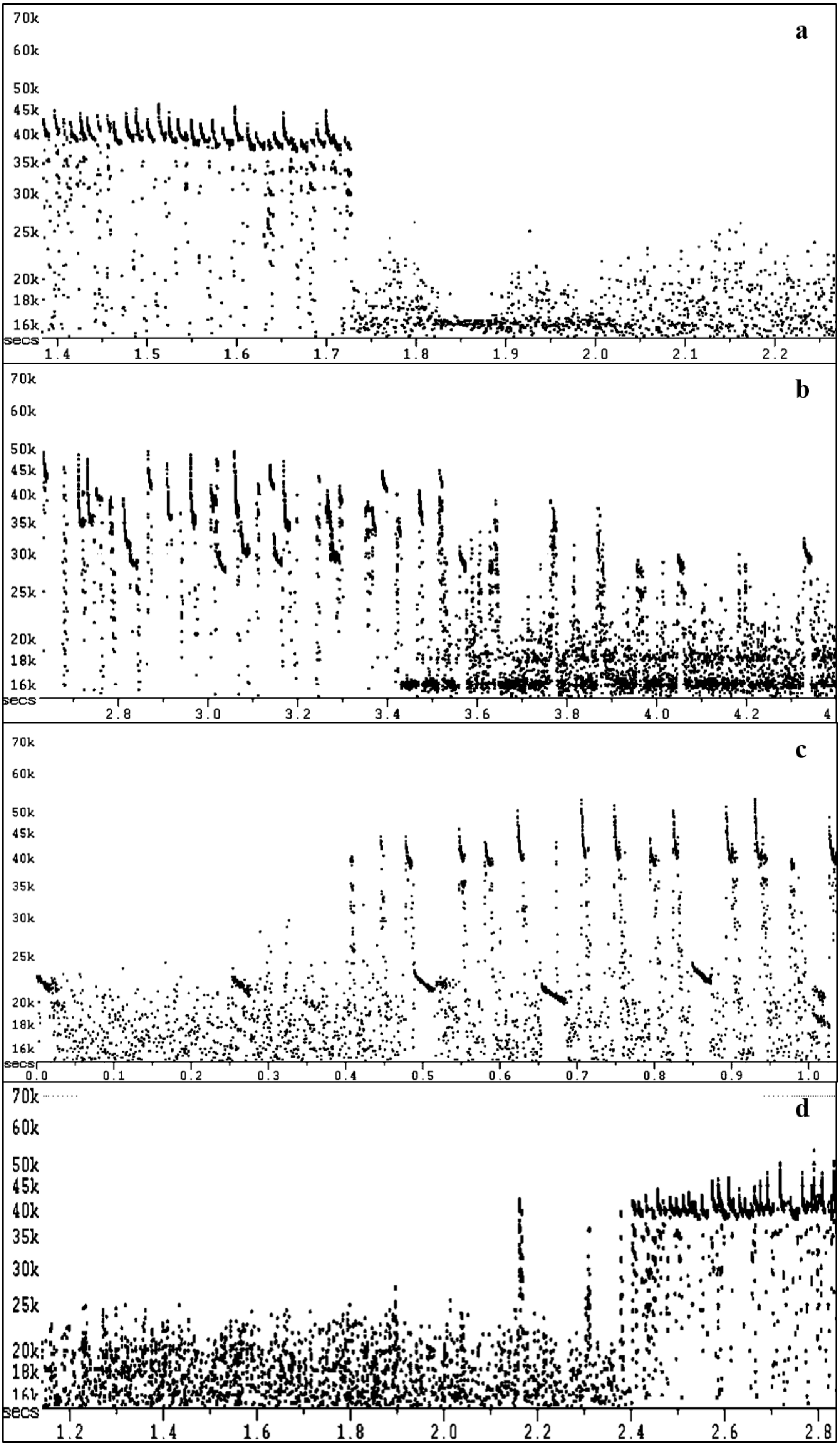
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Fig. 7. Spectrograms used for qualitative analysis. (a) Bat calls disappeared with the appearance of drone – an outcome counted as a “decrease” (b) Bat activity decreasing from three individuals calling simultaneously to one that remained in presence of drone activity – an outcome counted as a “decrease” (c) Bat calls persisting, and the number of individuals increasing from one to two – an outcome counted as an “increase” (d) Bat calls resuming after drone left.

Despite no correlation between drone flight time and bat activity, GLM results found bat activity to be influenced by drone flight time, human activity level and average temperature (*P* = 3.09e-06). Bat activity differed at various human activity level (Kruskal-Wallis: *P* = 0.003; Fig. 8a) and had a negative relationship (Table 1). Temperature, similarly, had an inverse relationship with bat activity (Table 1, Fig. 8b). There was an interaction between drone flight time and human activity.

Table 1. Effect of variables on the number of bat passes per night.

	Estimate	Std. Error	t-value	Pr(> |t|)
(Intercept)	1360.02	418.17	3.25	0.002 **
Drone flight time	9.26	2.57	3.61	0.0007 ***
Human activity level	-22.44	16.77	-1.34	0.19
Average temperature	-37.69	14.87	-2.53	0.01 *
Drone flight time : Human activity level	-3.54	1.12	-3.16	0.003 **

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’

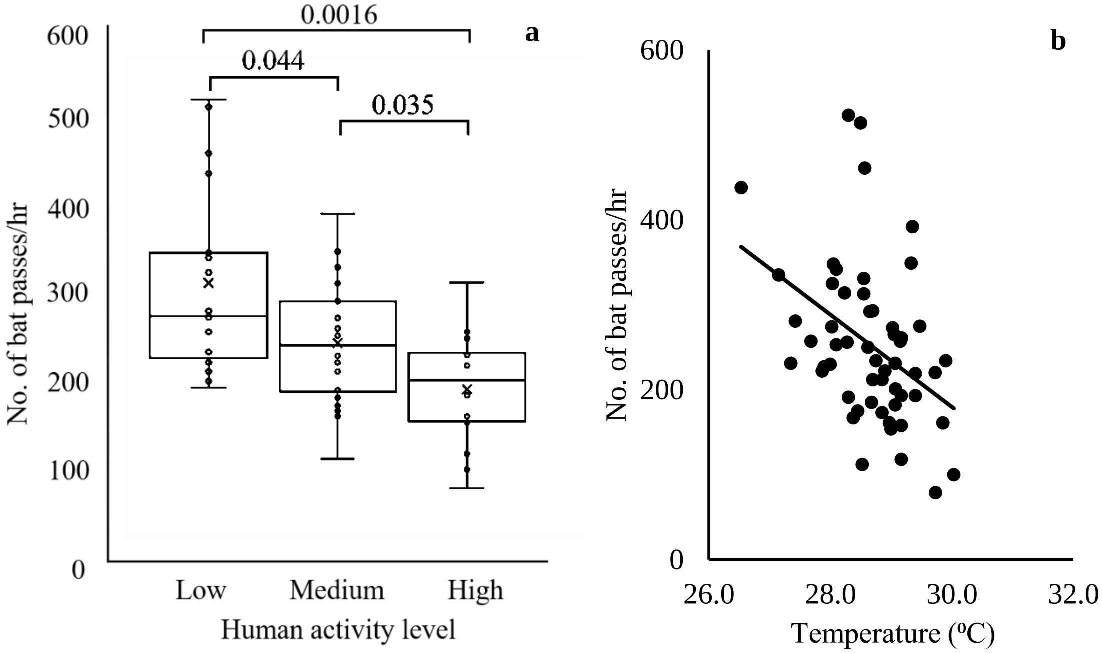

Fig. 8. (a) Comparison of bat activity at various human activity levels at the study sites. X denotes the mean number of bat passes. Pairwise tests indicate bat activity differs between the various human activity levels. (b) Correlation between number of bat passes and temperature (ρ = -0.40, *P* = 0.003). Line is best-fit linear line.

Foraging activity

The mean number of terminal buzzes (Fig. 9a) and buzz ratio (Fig. 9b) did not differ in the presence and absence of drones. I recorded an average of 7.6 and 8.6 buzzes per night in the presence and absence of drones respectively. The number of terminal buzzes recorded were relatively little compared to bat passes, thus buzz ratio was close to zero.

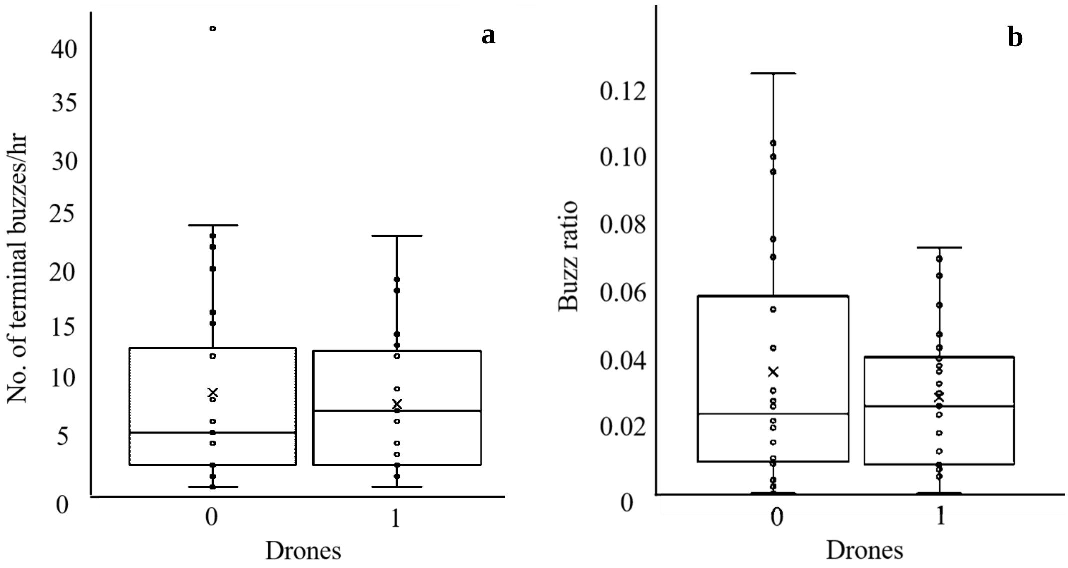

Fig. 9. Comparison of (a) terminal buzzes (foraging activity) and (b) buzz ratio in presence (1) and absence (0) of drones. X denotes means. There was no effect of drones on the number of terminal buzzes and buzz ratio.

Other findings – temporal variation

Bat activity is known to vary throughout the night (Hayes, 1997). But temporal variation is not well-studied in bats in the tropics. In Singapore, bats are most active during the hour after sunset (J Coleman, pers. comm.) and so I assumed activity within the hour of recording to not vary greatly. However, after processing the recordings, I found bat activity to peak around 10 minutes after sunset and decrease from the 20th-minute (Fig. 10). There was no statistical difference between passes/min for drone and non-drone samples.

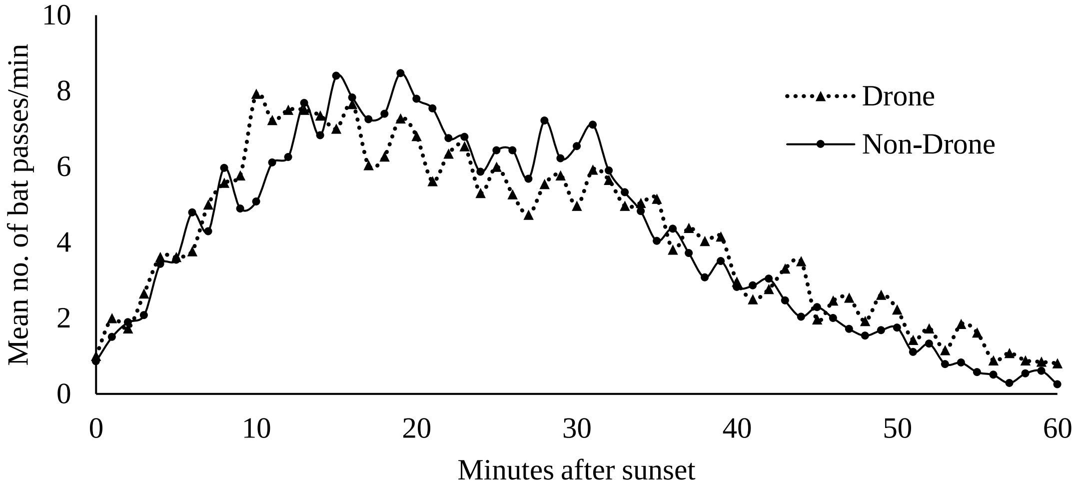

Fig. 10. Temporal variation in activity of all species. Mean number of bat passes per minute was calculated using the whole dataset for nights in the presence (Drone) and absence (Non-Drone) of drones.

4. DISCUSSION

Almost nothing is known about the effects of drones on animals while in flight, and bats, especially, depend heavily on the aerosphere. My results suggest that bats are affected by the presence of drones, however, only for a short period.

4.1 Effect on bat activity

I predicted that bat activity declines in the presence of drones because bats avoid them. Although that is not what my comparison of nights with and without drones revealed, visual examination of my spectrograms revealed that bat calls most often declined in the presence of the drone. Bat calls even increased after the drone left, possibly indicating a resumption of bat activity and thus, a disturbance.

The spectrograms showed a clear tendency for bat activity to decline when a drone appeared. And because bat calls were visible immediately before the drone appeared, the most logical interpretation is that the disappearance of bat calls is linked to the appearance of the drone. However, the disappearance of calls could indicate that the bat left the immediate area (avoidance) or that it stopped echolocating – two alternatives that are impossible to distinguish by the methods I used.

An animal responds to a disturbance by tolerating or avoiding. And to make this decision, the animal will have to weigh the costs and benefits of these two options (Beale, 2007). If the costs of remaining at the disturbed habitat (e.g., reduced foraging space, stress, noisy environment) are greater than the benefits of doing so, the animal leaves the area. However, if the opposite occurs (i.e., benefits are greater than costs of remaining), the animal tolerates the disturbance and remains.

Bats are able to fly without echolocating – a strategy that they may employ to avoid signal interference (sonar jamming) from conspecifics, whose calls and returning echoes can provide enough useful information for them to continue navigating the night sky (Chiu and Moss, 2008). This occurs more frequently when the conspecific has similar calls. Perhaps bats in my study stopped echolocating in the presence of drone noise to avoid excessive auditory information (possible overlap in frequency range of drone noise and bat calls), while remaining in the area.

I also observed that bat activity tended to increase immediately after a drone event. This outcome could reflect a resumption of bat activity, i.e., following an initial decline in echolocation in response to a drone. If so, then this says something about the importance of both echolocation and the foraging area.

Bats are nocturnal, and their food intake is constrained by the availability of insect prey, which peaks early in the night. Foraging habitats of bats have been found to be heavily influenced by distribution of insect prey (Gonsalves *et al.*, 2013), especially for urban bats (Krauel and LeBuhn, 2016). In other words, bats have a limited amount of time each night to hunt, using a mode of locomotion that is energetically costly, and so they need to begin foraging shortly after emerging from their roosts. And although aerial hawking bats may be able to fly without echolocating, they certainly cannot hunt without echolocating (Schnitzler and Kalko, 2001).

Therefore, any reduction in their echolocation calls, whether it represents their departure from a site or the temporary cessation of echolocation, represents an energetic cost to the animals.

Furthermore, many bat species fly “a beat”, meaning they return to the same foraging site every night and fly the same route (Rainho and Palmeirim, 2011). If the increase in calls after a drone event really is indicative of a resumption of foraging activity, then this suggests that these sites may be part of these bats’ “beats”. If so, then in the long run, increasing drone activity in these sites could therefore represent an important degradation of habitat quality and be detrimental to fitness (Beale, 2007). The bat may also decide to switch its foraging site, if the cost of tolerating the disturbance exceeds the benefits of using a new habitat (Bejder *et al.*, 2006).

Despite spectrograms indicating an effect of drones on bats, it should be noted that change was absent in overall bat activity between nights with and without drones. And there might be a few reasons to this.

The decrease in bat activity caused by the drone’s presence could have been compensated for by other times with high activity. Drones flew for an average of 18 minutes per night and this is only a portion of the hour of recording. I had assumed bat activity to be constant throughout the hour. However, I found bat activity to decline even within the hour of recording. If baseline bat activity differs over the course of an hour, then a drone flying in the first 10 minutes after sunset might have different effects compared to a drone flying in the last 10 minutes of the hour. Furthermore, during peak bat activity periods, the aerosphere is more crowded, and the introduction of a drone might have greater effects.

A second possible explanation for the lack of change could be habituation, increasing tolerance levels towards a disturbance that results in weaker behavioural response (Bejder *et al.*, 2009). The mean noise level in Singapore is 69.4 decibels (Ng, 2017) while that of the drone was around 80 decibels. If background noise is fairly loud, then short exposures to loud sounds (despite drone noise having a slightly different profile than other urban noise (Christian and Cabell, 2017)) might have minimal impact on bats. Because my study sites are also frequently used by drone users, it is also possible that bats in these locations have interacted with drones before. Over time, individuals might learn that there is no adverse effect of the drone (i.e., direct collision) and continue to utilise the area (Bejder *et al.*, 2006). That said, in my study, drones were not present every night, and those that were did not fly a fixed route each night. So, even if habituation were possible, it might be difficult for a bat to predict and strategically avoid the disturbance while foraging in the area (Bejder *et al.*, 2009).

Finally, I examined the effect of drones on all bats in my sites, when the effects could easily be species-specific. In other words, if detrimental effects are limited to one species that is comparatively rare in a site, then it could be masked by the lack of effect on more abundant species. Calls of *Saccolaimus saccolaimus* (of lower frequency) may be more affected by the presence of the drone (Bunkley *et al.*, 2015), but because it is only 2.35 % of the total number of calls recorded, changes may not be detectable.

Effect on foraging activity

I predicted that foraging activity decreases in the presence of drones because drones interfere with prey catching. Quantitative results indicate no difference in the number of terminal buzzes and buzz ratio between nights with and without drones. This could be because of the relatively few terminal buzzes recorded as compared to bat passes. The Anabat is less sensitive to terminal buzzes than search and approach phase calls (Adams *et al.*, 2012). Furthermore, aerial hawking bats might prefer to hunt at higher altitudes i.e., further distance from the detector, reducing the ability of the detector to pick up these terminal buzzes (Griffin, 1971; Gorresen *et al.*, 2008). Therefore, the use of the number of terminal buzzes might have underestimated foraging activity.

There is also a possibility of the study sites not used extensively as feeding grounds. The presence of bats (indicative by bat passes) in these areas can simply mean that the study site is part of their route to other foraging sites or drinking sites (Rainho and Palmeirim, 2011).

Influence of other variables

GLM results indicate that drone flight time, human activity level and average temperature influence bat activity. Contrary to predictions, bat activity was positively related to drone flight time. The sounds produced by flying drones may be similar to those produced by insects (Islam *et al.*, 2017), eliciting the curiosity of bats.

Another interesting find was the negative relationship between bat activity and human activity level. There are many studies about human disturbance on wildlife because of the rise in outdoor recreation and the proximity of humans to wildlife (Fernandez-Juricic and Telleria, 2000; Tablado and Jenni, 2017). But most research on human-bat interaction are about the response of hibernating bats to visitors in hibernacula (Thomas, 1995; Frick *et al.*, 2016). For my study, noise could be a possible reason for lower bat activity at higher human activity levels. The availability of insect prey might also be affected by the number of visitors because of the use of insect repellent. However, my study is unable to accurately determine the exact mechanism and relationship (correlation or causation), and more needs to be done.

Bat activity is known to be highly influenced by temperature. Metabolic rates of bats are eight to 15 times higher while flying than at rest (Voigt and Lewanzik, 2011). In addition to endogenous heat, their dark coloured body (which was evolved to evade predation) absorbs heat from the environment (Voigt and Lewanzik, 2011). Therefore, bats may reduce activity at higher temperatures to prevent hyperthermia. This could also be a driver of nocturnal activity.

4.2 Limitations and future research

I relied on recreational drones being flown by the public, as opposed to carrying out a proper experiment, because the study took place in parks. Given the projected increase in drone activity in Singapore and other jurisdictions, I strongly recommend a controlled experiment, in which the experimenter can manipulate presence/absence, numbers, types, flight paths and flight times of drones, especially given that flight pattern (i.e., how the drone flies) may be biologically important to animals (Mulero-Pazmany *et al.*, 2017; Chabot and Bird, 2015). Study area can be reduced to maximise the bat detection and ensure that bats within the study area are exposed to drones.

A limitation of this study was the inability to determine if the absence of echolocation calls on the spectrogram was due to the absence of bats or that the bats had stopped echolocating. Future studies should incorporate visual recordings such as thermal imaging to determine the presence of bats (Hristov *et al.*, 2008). High-speed videography can also be used to identify the position of the bat and its immediate response to the drone (Holderied *et al.*, 2008).

This study was also limited by literature available on local bat species and their call parameters. The lack of an echolocation reference call library prevented me from using the automated species identification function in AnalookW. Furthermore, the only published study on echolocation calls of Singapore's bats (Pottie *et al.*, 2005) provides no useful information because it used full-spectrum detectors. Besides, echolocation calls vary in several parameters among microhabitats (Surlykke and Kalko, 2008) and even within a pass (Schnitzler and Kalko, 2001). The bottom line is that researchers must make their own reference call libraries or use others produced in the same habitat under study to reliably identify species (J. Coleman, pers. comm.). Without doing so, the effect of drones on bats cannot be certain. Drones might affect certain species and not others. The activity of unaffected species may mask the change caused by drones, thus affecting quantitative data.

Unable to use the automated identification system, I carried out manual inspection and counting of bat calls on spectrograms. However, manual processing tends to be subjective and highly dependent on individual experience. There is also bias towards more easily identifiable calls (Aodha *et al.*, 2018), such as *Saccolaimus saccolaimus* which has a much lower call frequency range. As such, automated identification of acoustic recordings should be used in the future with the call reference library set up.

Zero-crossing recording has its benefits and limitations. As mentioned, it is less able to depict multi-harmonic calls and terminal buzzes. For future studies using the Anabat Express, if time permits, recordings should be converted to audio (.wav or MP3) and the experimenter should listen for terminal buzzes (see Appendix B).

5. CONCLUSION

Drones will become more common in our airspace because of its many uses. However, they are relatively novel stimuli with unknown effects on volant animals, such as bats. This study aimed to determine the effect of drones on bats in Singapore and found that drones brought short-term changes to bat activity. With the increase of drones in Singapore, more needs to be done to minimise the impact of drones on bats and other wildlife. Current drone flying regulations in Singapore lack guidelines on approaching animals, therefore, this study hopes to gather more attention and research to this issue. Furthermore, scientific research on bats in Singapore are lacking, and more information on ecology and behaviour are required to make better suggestions.

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7. APPENDICES

Appendix A

Table 2. Echolocation call parameters used for species identification. Duration – the length of a call; call structure – shape and pattern of a call; maximum frequency – the highest frequency of a call; minimum frequency – the lowest frequency of a call; peak frequency – the frequency of maximum energy i.e., loudest. Call structures: FM – frequency-modulated; CF – constant-frequency; st – steep; sh – shallow.

Species	Location	Duration (ms)	Call structure	Maximum frequency (kHz)	Minimum frequency (kHz)	Peak frequency (kHz)	References
Scotophilus kuhlii	Singapore	4.01 ± 0.03	st-FM-CF	84.9 ± 2.25	36.6 ± 0.46	43.3 ± 0.16	Pottie *et al.*, 2005
	Lombok, Indonesia	2.3 - 3.2	st-sh-FM	51.2	40.6 - 41.2	41.6 - 42.2	McKenzie *et al.*, 1995
Myotis adversus	Singapore	4.68 ± 0.10	FM	82.5 ± 0.71	30.4 ± 0.36	46.2 ± 0.31	Pottie *et al.*, 2005
	Australia	5.14 ± 0.84	FM	80.18 ± 3.5	31.16 ± 2.99	46.49 ± 4.3	Jones and Rayner, 1991
Myotis muricola	Singapore	4.98 ± 0.07	st-FM-CF	79.9 ± 1.02	53.7 ± 0.48	57.2 ± 0.01	Pottie *et al.*, 2005
	Malaysia	2.14 ± 0.29	FM	126.07 ± 3.37	50.29 ± 2.39	64.39 ± 1.33	Yoon and Park, 2016
Saccolaimus saccolaimus	Singapore	12.2 ± 0.08	Multi-harmonic	23.5 ± 1.32	21.8 ± 1.42	22.6 ± 0.42	Pottie *et al.*, 2005
	Thailand	3.85 ± 2.11	-	60.25 ± 12.09	17.75 ± 0.98	32.03 ± 8.85	Hughes *et al.*, 2011
Taphozous melanopogon	Singapore	10.43 ± 0.06	Multi-harmonic	28.7 ± 1.24	25.2 ± 0.82	27.9 ± 0.56	Pottie *et al.*, 2005
	Thailand	6.02 ± 3.4	-	76.15 ± 20.18	20.37 ± 6.2	29.71 ± 2.67	Hughes *et al.*, 2011
Pipistrellus stenopterus	Pahang, Malaysia	13.8 ± 0.42	-	42.8 ± 2.01	28 ± 0.4	31 ± 0.49	Kingston *et al.*, 2003
	Pahang, Malaysia	9.7 ± 0.21		56 ± 1.81	32.9 ± 0.28	37 ± 0.38	Kingston *et al.*, 2003

Appendix B

Recording of terminal buzz is available here: https://www.youtube.com/watch?v=KResesI4YQc