The impact of anthropogenic light and sound on bat activity, foraging and communication

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By

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Declaration

The data collected in the field relating to sound recordings, canopy cover and tree density was collected collaboratively with Poorvi Ashok, as was the data gathered from deskwork for the distances to landscape features, the weather and sun and moon variables. Code to generate a heatmap was adapted from code written by Flavia Bellotto Trigo, acknowledged within the code supplied with this thesis.

All else, including invertebrate abundance fieldwork, all acoustic analysis and code, is entirely my own work, and any material that could be construed as the work of others is fully cited and referenced.

Signed

Name of student: Emma Little

Name of supervisor: Dr Cristina Banks-Leite

Acknowledgements

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Abstract

Bat behaviour is known to be affected by artificial light at night and noise in species-specific ways. Data on the effect of these two sensory pollutants acting together though is sorely limited, despite their frequent co-occurrence in the landscape. Using data from 47 acoustic monitors over two sites varying in their artificial light and noise levels, *P. pygmaeus* feeding rate was found to increase with light and decrease with noise. The increase with light was modulated by the level of noise, with light only having a strong effect when sound was low. This result suggests more research should focus on these sensory stressors simultaneously rather than independently, and has practical importance when planning lighting schemes.

1. Introduction

Artificial light is considered one of the top developing threats to biodiversity (Hölker et al., 2010), growing at a rate of c.2% per annum from 2012 to 2016 both in extent and radiance worldwide (Kyba et al., 2017). Within the UK, only one fifth of land is considered pristine in terms of light due to artificially lit residential, commercial and industrial buildings, transport networks and leisure facilities (Falchi et al., 2016). Anthropogenic noise is generated from a similar range of sources, though traffic noise is the component found to dominate urban landscapes (Botteldooren, De Coensel & De Muer, 2006), and is growing: while over the last two decades the UK road network grew less than 1% (Department for Transport, 2023), vehicle density increased 16.7% (Department for Transport, 2022). Globally these trends will be significantly amplified as less developed countries increase infrastructure and activities – road infrastructure alone is predicted to grow by a fifth by 2050 (Meijer et al., 2018). Despite how anthropogenic light and noise frequently co-occur in the landscape, their impact on the behaviour of animals is predominantly studied independently, with little attention afforded to their combined effect.

Impacts on animals from artificial light at night range from effects on foraging, drinking and temporal shifts in activities, to reproduction and species movements, as well as cascade effects through ecosystems (Gaston et al., 2013; Jägerbrand & Spoelstra, 2023). The effects can be direct through light avoidance, or indirect following, for example, the impacts of artificial light on prey abundance or distribution (van Langevelde et al., 2018). Noise can interfere with the way animals locate prey (Siemers & Schaub, 2010) or mates (Cunnington & Fahrig, 2013), and avoid predation (Shannon et al., 2014). Animals respond to noise to varying degrees

(Francis & Barber, 2013; Swaddle et al., 2015; Barber, Crooks & Fristrup, 2010), most commonly through increasing amplitude in their own calls (e.g. Brumm, 2004), as well as shifting frequency and changing call length or repetition rate (e.g. Slabbekoorn, 2013), and through sound-avoidance-led distribution changes (Gomes et al., 2021; Mejia, McClure & Barber, 2019). There may be negative impacts on fitness through these behavioural changes, as well as other physiological, developmental and genetic changes resulting from noise exposure (Kight & Swaddle, 2011). A study of the impact of light and noise simultaneously found evidence of an interactive effect in fifty species of birds, 40% of which were synergistic, or worse than the sum of the two effects individually (Wilson et al., 2021).

Insectivorous bat species are long lived for their size, with UK species living 15-40 years, they have a slow reproduction rate, are highly mobile and adapted to living in low light levels, using echolocation to navigate and forage (Jones et al., 2009; Russ, 2012). As such they make excellent case studies for responses to anthropogenic pressures, including artificial light at night and traffic noise (Jones et al., 2009; Russo & Ancillotto, 2015). Not only does their highly vocal nature lend themselves to assessment of activity levels using acoustic monitors, but thanks to diagnostic "feeding buzzes" within these calls (see Figure 3) we can also determine relative rates of feeding attempts (Fenton, 2003). Echolocating bats also provide an exquisite model in particular for investigating impacts of anthropogenic noise. They call across a wide range of frequencies and hear across an even wider range (Lattenkamp et al., 2021), and by definition their use of echolocation means they receive instant feedback from their self-communications, able to instantly monitor and respond to reflected echoes by adjusting pulse amplitude, frequency, length and or repetition rate (Luo et al., 2015).

Research into the impact of artificial light on echolocating bats has gained pace over the last fifteen years. Impacts on roosting (Rydell, Eklöf & Sánchez-Navarro, 2017), drinking (Russo et al., 2017), activity levels (Azam et al., 2016; Kerbiriou et al., 2020), foraging (Schoeman, 2016; Hooker, Lintott & Stone, 2022) and movement (Bhardwaj et al., 2020; Hale et al., 2015; Mathews et al., 2015; Stone, Jones & Harris, 2009) are all identified, as well as changes in physiology (Tomassini et al., 2014). Effects are species specific, resulting in changes at a community level (Azam et al., 2018; Salinas-Ramos et al., 2021; Stone, 2013) and can impact on trophic interactions between taxa: some bird species feed later in artificial light so increase the niche overlap with bats (Frey, 1993), and moths may not only be attracted to artificial light but once within it, they may cease avoiding bat echolocation sounds (Hügel & Goerlitz, 2020). The first decade or so of research built a picture of two main foraging guilds of bats (Schnitzler & Kalko, 2001) responding differently to artificial light: aerial hawkers like Pipistrelle species benefiting from invertebrate aggregations at lights, and gleaners like Myotis species and long-

eared bats negatively impacted (Stone, 2013). More resent research has started to question this generally accepted view: species previously considered to benefit from artificial light by taking advantage of invertebrate aggregations have since been found to experience negative impacts at larger scales (Azam et al., 2016; Barré et al., 2022; Pauwels et al., 2019). A study using experimentally increased artificial light along waterways found that feeding rates fell for bat species of both foraging guilds, and crucially were shown sometimes to fall despite no change in activity level (Hooker, Lintott & Stone, 2022). One cause may be that bats have been found to fly faster through artificial light (Barré et al., 2021), perhaps to reduce predation risk (Speakman, 1991), but may also compromise their ability to feed. Studies have frequently been confounded by focusing on bat activity rather than foraging itself (Russo et al., 2019), or measuring foraging rates but not disentangling the effect of invertebrate availability (Straka et al., 2019), despite the attraction of some invertebrates to some light types (Bruce-White & Shardlow, 2011).

Research into the impacts of anthropogenic sound on bats is relatively recent and largely laboratory based (Allen et al., 2021; Bunkley & Barber, 2015; Currie et al., 2020; Luo, Siemers & Koselj, 2015; Siemers & Schaub, 2010), or in the field using transects from roads (Berthinussen & Altringham, 2012; Bonsen, Law & Ramp, 2015; Claireau et al., 2019; Pourshoushtari et al., 2018), and has had a heavy focus on gleaning bats (e.g. *Myotis spp.*) that use echolocation but also rely on listening for lower frequency prey sounds. Echolocating bats avoid noise even when the frequency does not overlap with bat echolocation calls (Allen et al., 2021; Luo, Siemers & Koselj, 2015), and when in noise their foraging rate and efficiency falls (Allen et al., 2021; Bunkley & Barber, 2015; Finch, Schofield & Mathews, 2020; Luo, Siemers & Koselj, 2015; Siemers & Schaub, 2010). Bats respond to louder noise levels with increased call amplitude (Currie et al., 2020; Lu, Zhang & Luo, 2020; Jiang et al., 2019; Tressler & Smotherman, 2009), especially when the noise frequency overlaps with the bats' own call frequency (Hage et al., 2013; Luo, Siemers & Koselj, 2015), and changes in spectral and temporal components of echolocation calls have been noted (Currie et al., 2020; Hage et al., 2013; Jiang et al., 2019; Song et al., 2020). The metabolic cost of louder calls (Currie et al., 2020) and an increased energy requirement as stress response genes upregulate when exposed to chronic traffic noise (Song et al., 2020), may lead to negative fitness implications. Crucially, the field studies have been unable to disentangle effects of habitat fragmentation, light, air pollution and edge and barrier effects from traffic noise alone, and the first experimental study in the field attempting to do so was only three years ago (Finch, Schofield & Mathews, 2020).

Alongside echolocation calls for navigation and foraging, bats also produce a range of, typically lower frequency, social calls that are used to communicate, largely with conspecifics (Fenton, 2003; Pfalzer & Kusch, 2003). While less well studied than echolocation calls, all species appear to have a range of calls with functions covering communication between mother and pup, claiming and defending foraging sites, attracting mates and relating distress (Pfalzer & Kusch, 2003). It is the most complex, song-like "D-type" social calls that appear to be used to announce presence and claim foraging sites (Budenz, Heib & Kusch, 2009; Götze, Denzinger & Schnitzler, 2020). The number of these calls has been shown to increase when there is increased competition for food, such as in areas of lower insect density, when temperature is cooler or during the middle of the night at the nadir of flying invertebrates (Downs & Racey, 2007; Russo & Jones, 1999), and can result in increased foraging success in the calling bat (Wright et al., 2014). With respect to anthropogenic noise, changes in amplitude and the complexity of social calls have been investigated (Jiang et al., 2019), but not, to the best of my knowledge, the call rate.

Very little attention has been given to assessing the impact of anthropogenic light and sound on bats simultaneously (Swaddle et al., 2015), despite how these sensory pollutants often co-occur in the landscape. One study considered light and sound together at an open-cast mine, but there was almost no variation in sound pressure level (dB) across the six noisy sample points (Cory-Toussaint & Taylor, 2022), so noise was effectively excluded from analysis. As opposed to the majority of studies that examine the impact of light and sound individually, I investigated their effects together in the field, both observationally and experimentally, accounting for habitat, flying invertebrate abundance and temperature. The aims of the research were to test 1) the accepted view of light attraction for aerial hawker *Pipistrelle spp.* and avoidance by gleaning *Myotis spp.* while controlling for habitat and flying invertebrate abundance*;* 2) whether enhanced activity levels around artificial light translate into enhanced feeding rates; 3) the impact of noise on activity, feeding and communication rates and 4) for an interaction between light and noise on the same responses. Given the research above I predict that 1) bat activity levels fall with increasing artificial light for *Myotis spp* and increase for aerial hawker *Pipistrelle spp.*; 2) species exhibiting increased activity levels around light do not have matching increased feeding rates; 3) activity and feeding rates of all species fall with increasing noise, while communication rate will increase to ensure their presence is announced effectively and 4) that anthropogenic noise and light interact synergistically with a negative effect on feeding rates.

2. Materials and Methods

A) Empirical Study

2A.1 Sites and sampling points

I made observations across two sites, each containing similar habitats but set within differing light and sound landscapes. Silwood Park near Ascot, Berkshire, consists of 100 hectares of ancient and secondary woodland, acid grassland, meadow and a lake. The majority of the site is categorised as being within 2-4 nanoWatts/cm^2/sr radiance of night lights shining up into the night sky, 4-16 nanoWatts/cm^2/sr for the south eastern corner (https://www.nightblight.cpre.org.uk/maps/). Barnes Common in South West London is 18 miles from Silwood Park, near enough to experience similar weather, sun and moon variation. Yet while it consists of similar habitats – with 50 hectares of woodland, acid grassland, meadows and a brook, the common falls into the 16-32nanoWatts/cm^2/sr radiance of night lights category, and is criss-crossed with lit roads, paths and a railway line, as well as surrounded by residential streets and a flood-lit sports facility.
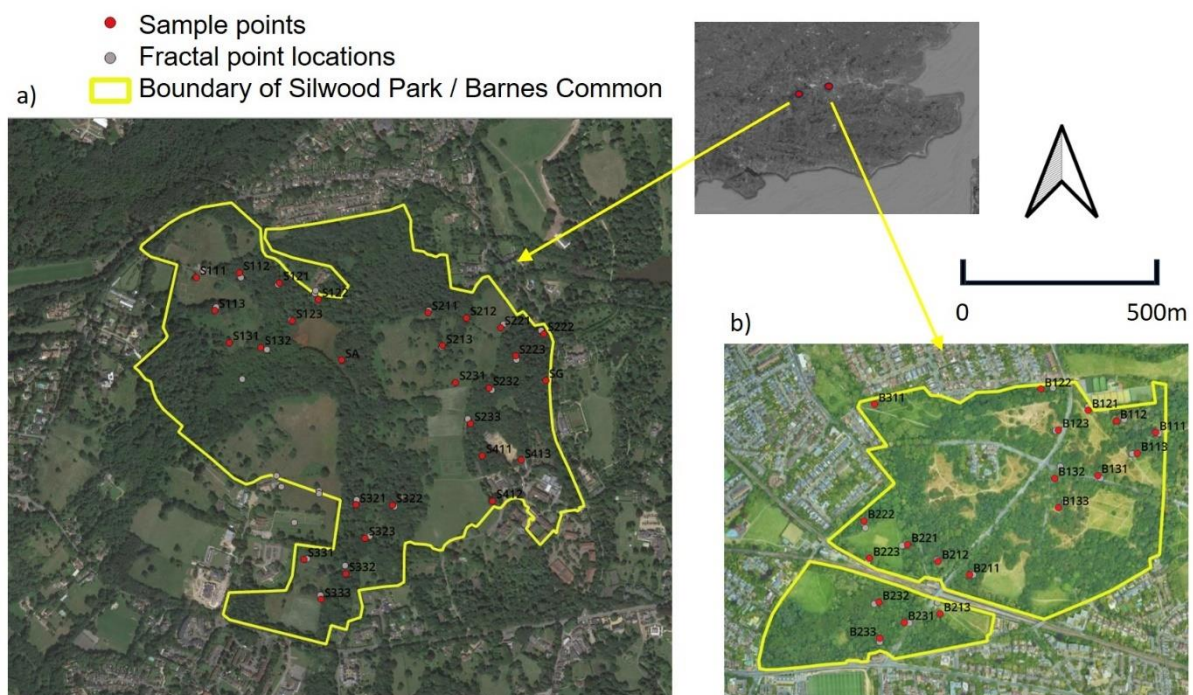

Figure 1: Map of the study areas in a) Silwood Park and b) Barnes Common, showing the 47 sample point and fractal point locations. Map created using QGIS v3.30.1 (http://www.qgis.org)

Silwood Park has an existing fractal sampling design as part of the Ecological Fractal Network (https://ecofracnetwork.github.io/), with sample points in 100m triangles, nested within 300m

triangles, nested within 900m triangles – providing differing spatial scales for analysis (Simpson & Pearse, 2021). I used these sample points, excluding four due to lack of safe access, and adding five to increase the light and sound gradient and exposure to the lake habitat (n=28; see Figure 1a). Two thirds of an equivalent fractal design (two 300m triangles) was used in Barnes Common, placed to optimise the light and sound gradient, with an additional point close to the brook (n=19; see Figure 1b). Acoustic recorders were placed as close to possible to the fractal points, depending on access and security from theft. I excluded one of these sample points (B131) as the AudioMoth failed to record on the analysed nights.

2A.2 Light and sound variables

I recorded illuminance (lux) and UV level (mW/m^2) at each sample point across the two locations on the same night, starting one hour after sunset on a clear night using a T-1 illuminance meter (Konica Minolta Sensing Inc, Osaka, Japan) and a RS Pro Mini Pocket UV AB Meter IM-213 (RS, New Taipei City, Taiwan). I held the meters horizontally, with the light sensitive sphere facing up, 2m above ground, and recorded the average of two readings. The illuminance measurements were repeated on a clear night at a similar moon phase approximately one month later with the light sensitive sphere directed instead towards the nearest source of light, an improved method for bat research (Azam et al., 2018), for all points in the Barnes site, and for those within 30m of a light source in Silwood Park. I recorded the distance to the nearest streetlamp, the distance to the nearest building, and the number of streetlamps within a 10m ,25m , 50m and 100m radius of each sample point using measurement tools on QGIS v3.30.1 (http://www.qgis.org), having obtained GIS layers of streetlamps from the relevant local borough councils. Sun and moon rise and set times, and moon illuminance at passing the meridian (percentage) data was taken from online resources (https://www.timeanddate.com; see metadata for location specific links).

I recorded a measure of noise for each sample point using Kaleidoscope Lite software v5.6.0c (Wildlife Acoustics; https://www.wildlifeacoustics.com/products/), by noting the mean sound pressure level (dB) of eleven recordings of sixty seconds taken over one hour, starting half an hour after sunset on the first night of the study. As sound proxies I also recorded the distance to the nearest road and railway line for each point using measurement tools in QGIS v3.30.1 (http://www.qgis.org).

2A.3 Flying invertebrate abundance

To account for variations in prey abundance, I set caged white sticky traps (see Figure 2) over two nights in May, when mean nightly temperature was over 10°C, no rainfall and little wind (Barnes Common: mean temperature 13.7°C, mean wind speed 2.9knots; Silwood Park: mean temperature 11.9°C, mean wind speed 0.2knots). The sticky traps measured 12.5cm by 10cm and were double sided, held in a cylinder of 2cm square plastic mesh, and placed at 1-2m height within 5m of the sample point. I recorded the count of invertebrates caught over twelve hours.

Figure 2: Flying invertebrate *sticky trap positioned at a sample point.*

2A. 4 Habitat analysis

I analysed each sample point for tree density using the point-centre-quarter-method (Cottam & Curtis, 1956), recording the distance to the nearest live standing tree with a stem of circumference 30cm or over at 130cm height, in each quarter. Density was calculated as the inverse of the squared mean distance to each tree, multiplied by 10,000 to provide trees per hectare. To assess canopy cover I took photographs using smart phones, 5m from the tree at each compass point, parallel and perpendicular to each compass direction. The phone was held horizontally, photographing upwards, as close to the ground as understorey cover would allow. Smartphone standard camera photographs have been shown to be suitable for quick assessments of canopy cover, using the total gap in the canopy layer as a proxy for the light availability within the habitat (Bianchi et al., 2017). I used the Fiji-ImageJ package (Schindelin et al., 2012) to analyse the total gap by adjusting the pixels to black and white. I also recorded

the distance to the nearest water body and woodland edge of each sample point using measurement tools on QGIS v3.30.1 (http://www.qgis.org).

2A.5 Weather variables

I obtained the mean nightly temperature (C), wind speed (knots) and rainfall (mm) from the Met Office Weather Observations Website, using weather stations within 2km of the sites (https://wow.metoffice.gov.uk; see metadata for location specific links).

2A.6 Bat Activity, Feeding Rate and Communication

I placed AudioMoth acoustic monitors (Hill et al., 2019) in protective cases at 2-4m above ground at each sample point, attached to a tree stem, branch or a pole. I set monitors to record one minute in every six (gain=Medium, sampling rate=250kHz), for fourteen nights from 2nd May to 16th May 2023, simultaneously for all sample points.
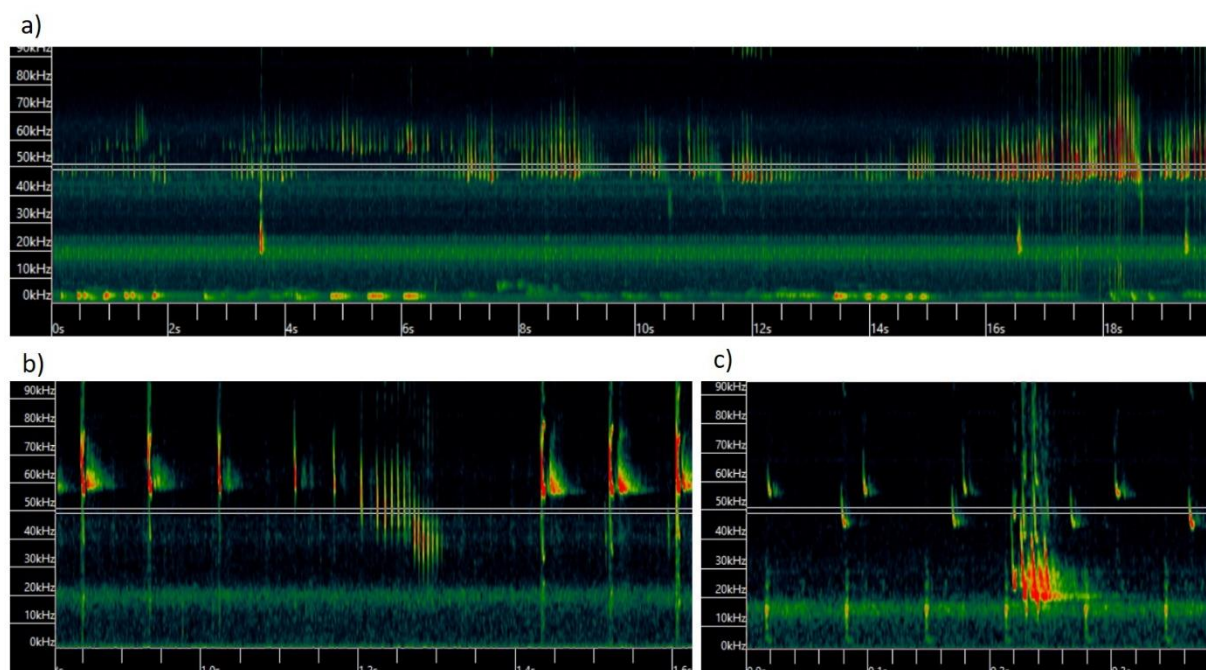
Figure 3: Spectrogram examples in bat acoustic analysis, showing a) a series of echolocation calls, feeding buzzes and social calls, and close up views of b) a feeding buzz and c) a D-type social call.

I analysed the sound files for bat echolocation calls in Kaleidoscope Lite software v5.6.0c (Wildlife Acoustics; https://www.wildlifeacoustics.com/products/), identifying calls from four nights using their call shape, end frequency and the peak frequency (Russ, 2012). Calls were manually identified as automated software was found frequently to miss bat calls and is not

yet able to detect social calls (see supplementary information for comparison analysis). I analysed recordings from 30 minutes before sunset to 30 minutes after sunrise, recording the number of bat passes, terminal feeding buzzes and D-type social calls (see Figure 3). A single bat pass was defined as one or more calls within two seconds of each other, with a maximum duration of ten seconds. I classified bat passes and feeding buzzes to species level for *Pipistrelle spp.* where possible. Given the difficulty of separating out some species from echolocation calls alone, *Nyctalus spp.* and *Eptesicus spp.* were grouped together, and *Myotis spp.* were grouped together.

2A.7 Statistical Analysis

All analysis was carried out using R software v.4.2.2 (R Core Team, 2021) with packages "psych" (Revelle, 2023), "usdm" (Naimi, 2023), "MASS" (Ripley et al., 2023), "lme4" (Bates et al., 2023), "DHARMa" (Hartig & Lohse, 2022), "performance" (Lüdecke (@strengejacke) et al., 2023), "stargazer" (Hlavac, 2022) and "ggeffects" (Lüdecke et al., 2023). To assess the effect of light and noise on total bat activity, feeding and communication by species/genera I used generalised linear models, with a negative binomial distribution of errors to account for overdispersion issues under poisson. To assess total bat activity I used a generalised linear mixed model, with negative binomial distribution of errors and species/genera grouping as a random effect (1|Species) to account for different base rates of activity between species/genera. For bat activity the response variable was the count of bat passes, overall as well as separately for species/genera groupings. To analyse feeding rate the response variable was the count of feeding buzzes, separately modelled for *P. pipistrellus and P. pygmaeus*, with an offset to account for differential bat activity by species at different locations on different days. Similarly for assessing the effect on communication rate, the response variable was the count of social calls, again with an offset to account for differential total bat activity levels, to effectively create a communication rate measure.

The fixed effects were illuminance (lux), amplitude, distance from water body, canopy cover, invertebrate abundance and temperature, as well as an interaction term between light and sound. All fixed effects were z-scaled. Little to no UV light was detected, there was very low wind (always <0.5knots) and no rainfall on any of the nights, so these variables were excluded. Canopy cover and distance from water were chosen as variables to account for habitat as they have previously been shown to be important for bat activity and foraging (Laforge et al., 2019; Straka et al., 2019). The surfeit of distance measures recorded to cover a variety of light and sound variables ultimately lead to models not converging, and they were excluded to

focus on the two light and sound parameters I anticipated being most imperative; see model design below.

Activity level: $bat\ passes \sim lux\ +\ amp\ +\ lux * amp\ +\ distance\ from\ water\ +$
$canopy\ cover\ +\ Invertebrate\ count\ +\ temperature$

Feeding rate: $bat\ feeding\ buzzes \sim lux\ +\ amp\ +\ lux * amp\ +\ distance\ from\ water\ +$
$canopy\ cover\ +\ Invertebrate\ count\ +\ temperature\ +\ offset(species\ passes)$

Communication rate: $bat\ social\ calls \sim lux\ +\ amp\ +\ lux * amp\ +\ distance\ from\ water\ +$
$canopy\ cover\ +\ Invertebrate\ count\ +\ temperature\ +\ offset(total\ passes)$

B) <u>Experimental Study</u>

2B.1 Site and Sampling points

I set up a light and sound experiment in Nash's Copse, Silwood Park, for twelve nights between 18th May to 8th June 2023. The experiment consisted of three repeats of four nights, varying the location by c.25 meters to reduce localised factors affecting the results. A control site 200-250m from the treatment sites was also monitored over the same period, to enable a before-after-control-impact design (see Figure 4).
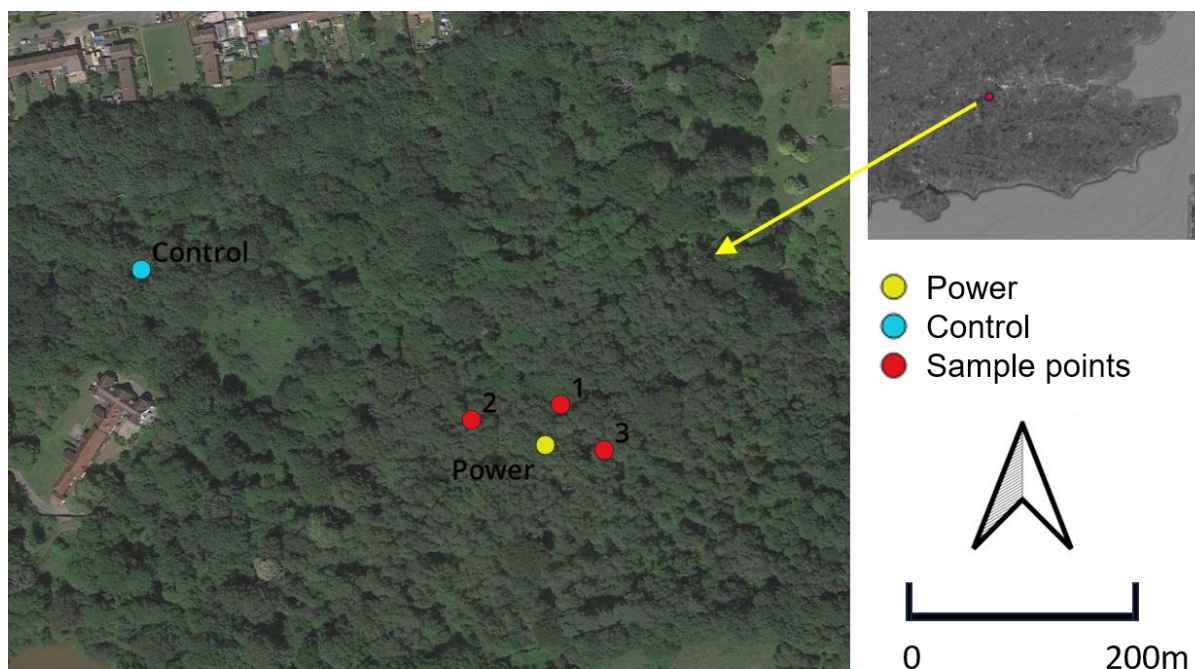

Figure 4: Map of the study areas in Nash's Copse, Silwood Park, showing the 5m and 100m sample points by transect, the control sample point and the location of the power supply. Map created using QGIS v3.30.1 (http://www.qgis.org)

2B.2 Light and Sound Treatments

Each experimental location had one control night (when light and sound equipment were set up but not in use), one night of light treatment, one night of sound treatment, and one night of both light and sound treatment. Light treatment was provided by one 100W Aigostar LED Work Light (8,800LM, 6,500K Cold White), placed at 2-3m height, and switched on 1.5-2 hours before sunset and off two hours after sunrise. I used an RS Pro Mini Pocket UV AB Meter IM-213 (RS, New Taipei City, Taiwan) to confirm the light produced no UV, and by recording and analysing sound files on an AudioMoth acoustic monitor (Hill et al., 2019) I further confirmed no ultrasonic noise production. The light does attract flying invertebrates: 3.8 times as many were caught on average by sticky traps in light treatment when traps were set over six nights with alternating light and dark treatment. Sound treatment was produced by continuous playback of traffic noise (BBC Sound Effects Library: London Traffic - Heavy Passing Traffic (Shepherd's Bush, London); https://sound-effects.bbcrewind.co.uk/search), through a W-King 30W Portable Loud Speaker, starting 1.5-2 hours before sunset and ending at the same time the following day.

2B.3 Other Variables

I recorded the illuminance with and without light treatment, and bat calls as previously described for the empirical study. I recorded an average sound pressure level (the Equivalent Continuous Sound Pressure Level; dB) over thirty seconds at waist height using the National Institute for Occupational Safety and Health (NIOSH) Sound Level Meter App (EA Lab, Slovenia), with and without sound treatment. Light and sound measurements were taken at the site of the treatment, as well as 5m, 10m, 20m, 50m and 100m from the treatment site, and the control site. Bat calls were recorded at 5m from the site of treatment, and at the control site.

2B.4 Statistical Analysis

All analysis was carried out using R software v.4.2.2 (R Core Team, 2021) with packages as previously listed. I carried out one-way ANOVAs to compare the illuminance and sound pressure level under different treatment types at set distances from the treatment point. I modelled each treatment type (sound, light, and both together) separately against the control treatment night and control location, using a before-after-control-impact (BACI) design, using a generalised linear model with poisson distribution of errors. The response variable was total

count of bat passes, and the fixed effects were temporal (control versus treatment nights), spatial (control versus experimental locations) and their interaction term.

3. Results

A) <u>Empirical study</u>

3A.1 Bat monitoring

Across the 46 sample points I manually analysed 18,258 one minute sound recordings, 3,574 of which contained bat calls. I recorded 8,729 bat passes, 791 attempts at feeding and 6,734 social calls. Bat passes were identified as P. pygmaeus (n=4,247), P. pipistrellus (n=3,713), other pipistrelle species and pipistrelle calls I was unable to identify to species level (n=285), Myotis spp. (n=270), grouped Nyctalus spp. and Eptesicus spp. (n=158), and unidentified species (n=56). All but two feeding attempts were from Pipistrelle spp., with P. pygmaeus (n=429) again the largest share, followed by P. pipistrellus (n=347) and feeding attempts unable to be identified to a species level between the two (n=13). Species recorded in the grouped data were *Pipistrellus nathusii*, *Myotis nattereri*, *Myotis daubentonii*, *Nyctalus noctule*, *Nyctalus leisleri*, and *Eptesicus serotinus*.

3A.2 Light and sound effects on bat activity level and feeding rate

When controlled for habitat, flying invertebrate abundance and temperature, the effects of light, noise and their interaction were found to be insignificant with respect to overall bat activity level. While light, noise and the interaction between light and noise were all found to impact upon the feeding rate of *P. pygmaeus*, none had an effect on the feeding rate of *P. pipistrellus*, which was influenced only by the distance from water and canopy cover. The model predicts that the rate of feeding attempts by *P. pygmaeus* would increase by a factor of 5.82 (CI: 2.56-13.20) with one standard deviation increase in illuminance (lux), and reduce by a factor of 0.68 (CI: 0.48-0.96) per standard deviation increase in amplitude (see Figures 5 and 6 and Table 1). The effect of light and sound together dampens the positive effect of light independently, and increases the negative effect of noise independently (p-value <0.001; see Figures 5 and 6, and Table 1). When both illuminance and amplitude increase by one standard deviation simultaneously the increase in feeding rate would be expected to increase by a factor of 1.45, rather than the 3.95 expected if they acted independently. The pseudo-R^2 of 0.26 suggests the model has moderate explanatory power.
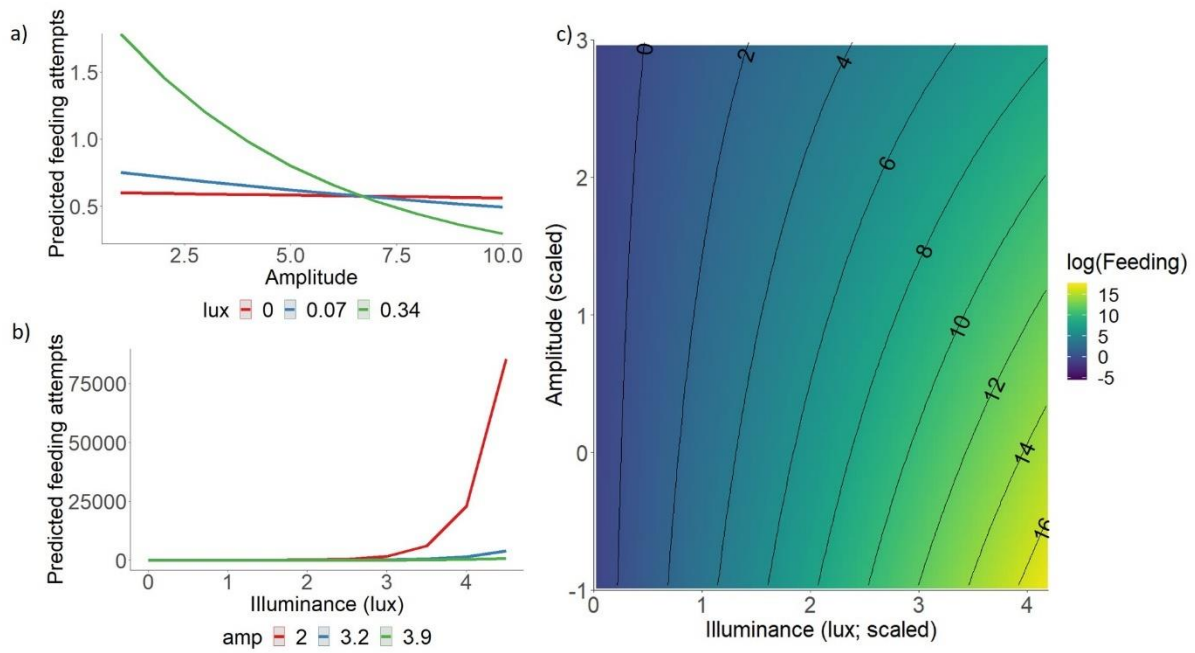
Figure 5: a) Predicted counts of feeding attempts of P. pygmaeus against amplitude for three levels of light (first quartile, third quartile and mean of the lux observations), and b) against illuminance (lux) for three levels of amplitude (the first quartile, mean and third quartile of amplitude observations). c) the log of predicted counts of feeding buzzes as they vary with light and sound (both scaled).

3A.3 Light and sound effects on bat communication rate

The effect of light and sound together dampens the effect of light and noise independently on bat communication rate (p-value <0.05), although the underlying main effects of each independently were insignificant (see Figure 6 and Table 1). When both illuminance and amplitude increase by one standard deviation simultaneously the model suggests the communication rate would reduce by a factor of 0.67 (CI: 0.45-0.99). The pseudo-R^2 of 0.08 also suggests the model is only weakly explanatory.
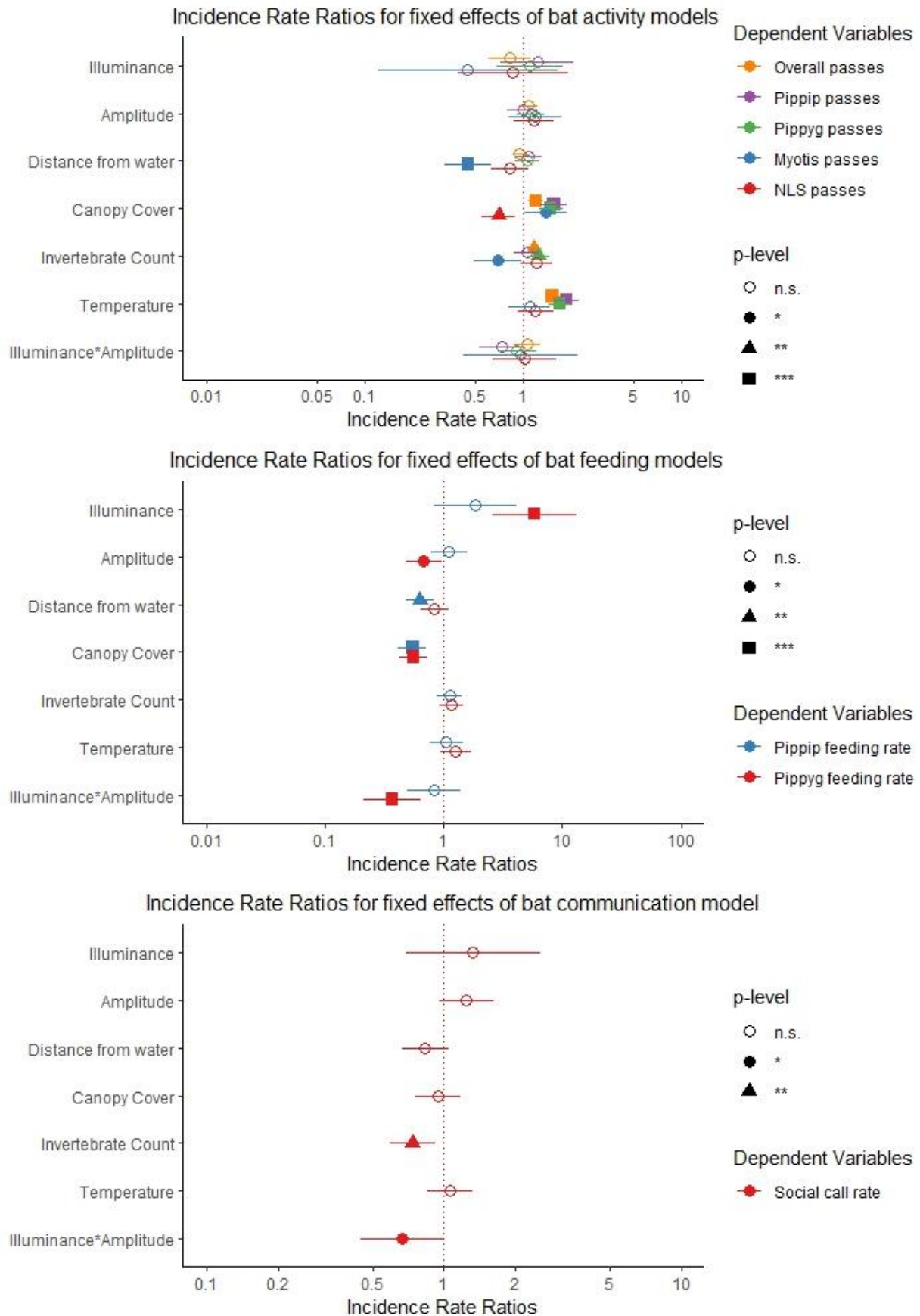
Figure 6: Incidence Rate Ratios (IRR) for all models by fixed effect. p-level: n.s. p-value not-significant, * p<0.05, ** p<0.01, *** p<0.001.

Table 1: Parameters, standard errors in parentheses and significance levels (* p<0.05, ** p<0.01, *** p<0.001) from all final models. Pippyg: P. pygmaeus; Pippip: P. pipistrellus; NycEpt: Nyctalus and Eptesicus species. Estimates show the effect of illuminance and other variables on the bat passes, feeding rate or social call rate

|	*Dependent variable:*							
	Overall passes	Pippyg passes	Pippip passes	Myotis passes	NycEpt passes	Pippyg feeding	Pippip feeding	Social calls
	generalized linear mixed-effects	negative binomial	negative binomial	negative binomial	negative binomial	negative binomial	negative binomial	negative binomial
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Illuminance (lux)	-0.182	0.097	0.215	-0.804	-0.144	1.761***	0.607	0.285
	(0.158)	(0.245)	(0.273)	(0.667)	(0.408)	(0.418)	(0.406)	(0.330)
Amplitude	0.090	0.113	0.004	0.181	0.159	-0.388*	0.104	0.219
	(0.067)	(0.104)	(0.114)	(0.195)	(0.150)	(0.178)	(0.176)	(0.136)
Distance from water	-0.046	0.065	0.081	-0.804***	-0.192	-0.184	-0.465**	-0.183
	(0.051)	(0.088)	(0.097)	(0.172)	(0.135)	(0.141)	(0.142)	(0.116)
Canopy Cover	0.191***	0.407***	0.449***	0.333*	-0.354**	-0.587***	-0.608***	-0.060
	(0.058)	(0.087)	(0.094)	(0.161)	(0.123)	(0.137)	(0.139)	(0.112)
Invertebrate count	0.165**	0.226**	0.056	-0.357*	0.203	0.143	0.118	-0.305**
	(0.052)	(0.085)	(0.093)	(0.177)	(0.118)	(0.116)	(0.126)	(0.112)
Temperature	0.434***	0.537***	0.635***	0.093	0.187	0.231	0.054	0.058
	(0.054)	(0.085)	(0.093)	(0.152)	(0.132)	(0.153)	(0.161)	(0.111)
Lux*Amplitude	0.054	-0.083	-0.314	-0.033	0.028	-1.005***	-0.186	-0.407*
	(0.099)	(0.146)	(0.165)	(0.421)	(0.236)	(0.289)	(0.263)	(0.204)
Intercept	0.230	2.991***	2.974***	-0.115	-0.248	-2.312***	-2.744***	-0.157
	(0.784)	(0.114)	(0.125)	(0.264)	(0.182)	(0.183)	(0.186)	(0.151)
Observations	1,253	179	179	179	179	179	179	179

Note: *p<0.05; **p<0.01; ***p<0.001

B) Experimental study

3B.1 Bat monitoring

Across the four treatments over twelve nights I analysed 2,304 one-minute sound recordings, only 92 of which contained bat calls. I recorded 120 bat passes, 50 of which were marked as "distant" or "very distant". Only 1 attempt at feeding (*P. pygmaeus*) and 37 social calls were recorded. Bat passes were identified as *P. pipistrellus* (n=44), *P. pygmaeus* (n=27), *Myotis spp.* (n=24), grouped *Nyctalus spp.* and *Eptesicus spp.* (n=20), and other (n=5).

3B.2 Light and sound effects on bat activity, foraging and communication

Light and sound treatments did not impact on the illuminance and noise levels at the control location, 250m from the treatment site (see Figure 7a and b). One way ANOVA revealed there was no statistically significant difference in illuminance across the four treatment types by 20m from the treatment site (F=1.93; D.F.=3,8; p-value=0.20) and none in sound pressure level by 100m from the treatment site (F=3.90; D.F.=3,8; p-value=0.06).
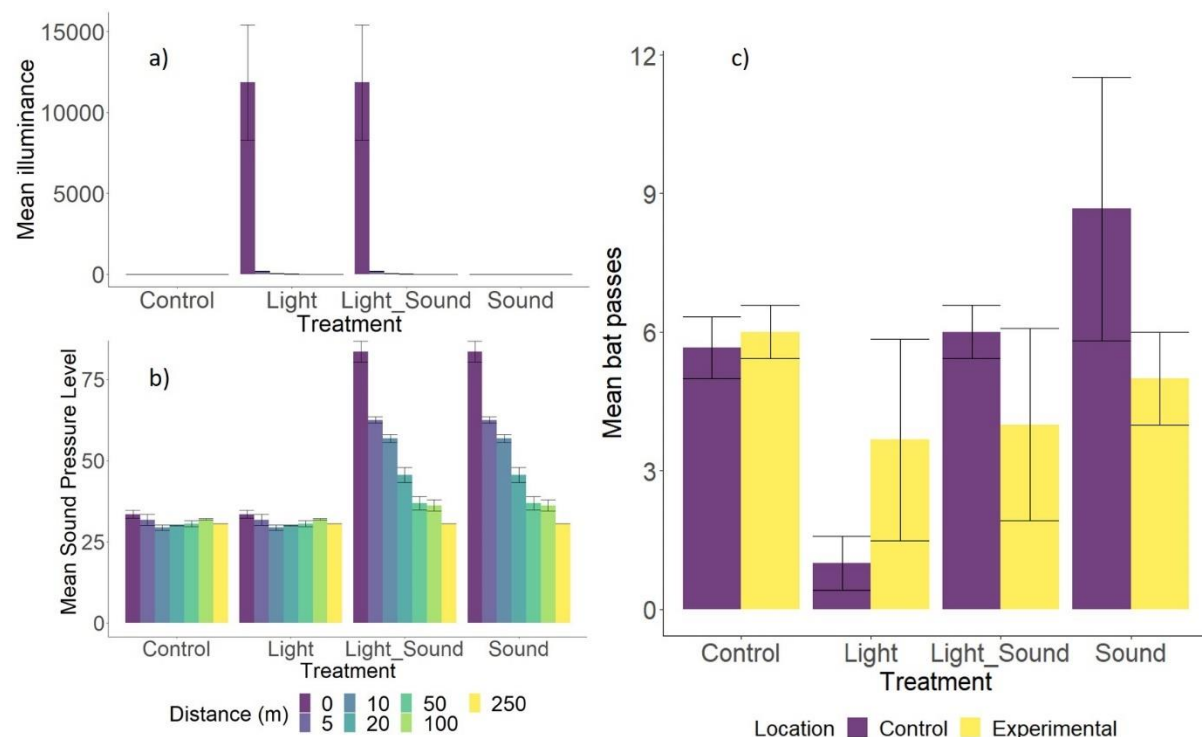

Figure 7: Boxplots of a) mean illuminance and b) mean sound pressure level, both by distance from treatment site (m) and by treatment type; and c) mean total count of bat passes by treatment, at control and experimental locations

The number of bat passes by species/genera, feeding attempts and social calls were all too low to analyse. For each of the three treatments, the overall count of bat passes recorded at Experimental versus Control locations did not differ significantly between the control and treatment nights (interaction term p-values for light = 0.09, sound = 0.20, light and sound = 0.36; see Figure 7c).

4. Discussion

The observational field data in this study provided support to my prediction that when studied together, anthropogenic light and noise would interact synergistically with a negative effect on the feeding rate of bats. It also added support to the effects of light and noise being species-specific, finding feeding of *P. pygmaeus* increased with light and fell with noise, but no such effect was found on *P. pipistrellus* despite being of the same foraging guild and even overlapping niches. Much of the research into the effect of light and sound on bats is carried out individually and experimentally, introducing light or sound into areas that are otherwise dark and quiet (Finch, Schofield & Mathews, 2020; Hooker, Lintott & Stone, 2022), and studies into the effect of light and noise together are very few (Cory-Toussaint & Taylor, 2022). The frequent co-occurrence of these two sensory stressors in the landscape and the result of an interaction between the two suggests research should shift focus from investigating each independently, to simultaneously. Similarly, their interaction should be taken into account when planning lighting schemes.

When controlling for habitat and invertebrate abundance there was no effect from light or noise on bat activity levels, but the feeding rate of *P. pygmaeus* was impacted by all three. The assumption has been that species active around artificial lights will benefit by feeding on aggregations of flying invertebrates, although some studies have shown negative impacts on feeding from artificial light despite unchanged activity levels (Hooker, Lintott & Stone, 2022), and also that bats may fly through artificial light at speeds too fast for foraging (Barré et al., 2021). This study found that the feeding rate increased for *P. pygmaeus* with increasing light, and fell with increasing noise. Although past studies have been mixed on the impact of light on *P. pygmaeus* activity level (Straka et al., 2019; Hooker, Lintott & Stone, 2022), the result is contrary to my predictions specifically for feeding rate, based on the hypothesis that increased flight speeds in artificial light would reduce the feeding efficiency. The reduction in feeding rate in noise was as predicted, and supports the growing evidence that noise negatively impacts feeding rates for bat species across foraging guilds, and not just for the gleaning bats that listen for lower frequency prey sounds. This study has provided new information

regarding the impact of light and noise on bat feeding rates when they co-occur. Investigating the model's predictions for feeding attempts in light and noise it is clear that noise had a greater impact in highly lit areas (see Figure 5a and c), and that light had a greater effect when noise was low (see Figure 5b and c). The implication is that the increased feeding in lit areas is significantly diminished by the presence of noise: the accepted view that some bat species benefit by feeding around streetlamps may not be supported when those streetlamps are lighting roads, railways or other noisy sites – as they frequently do. Most bat species have shown declines in activity and or feeding with increasing light, and if further research showed this interaction effect could be extrapolated to them, amplifying the negative effects of light and noise alone, then budget-restricted councils upgrading lighting schemes could focus their bat-sensitive plans around the noisiest spaces.

Although the light and noise interaction term was found to have a significant negative effect on bat communication rate, with the underlying main effects being insignificant the discussion of that interaction is moot. Bat social calls are not well studied, and the increasing use of automated-filtering and identification software to manage large datasets may worsen the situation until social calls libraries are improved. Only four nights of data were manually analysed due to its laborious nature, and perhaps trends would reveal themselves when more data is analysed (see Supplementary Information for manual and automated filtering comparison).

The aim of the experimental study was to test for the effects of light and noise in the absence of these factors intrinsic to the observational study of lit roads and other structures, such as edge effects and pollution. Unfortunately, advised against using a generator due to theft risk, the study site was chosen for the source of power available. The area of ancient woodland around the power source was very dense, and although woodland-adapted species, such as *Myotis Nattereri, Nyctalus noctule,* and *Plecotus auratus*, were all present in the area their numbers were too low for sufficient data. Over 40% of the bat passes recorded were marked as distant, suggesting they were tens of meters from the treatment site, so possibly out of range of treatment impact. Results were insignificant, though arguably a trend to fewer passes under light or light and sound treatments is apparent (see Figure 7c). This study should be repeated when a site with power is located that has less dense woodland, or ideally an edge habitat to incorporate the *Pipistrellus spp.*

Whilst acoustic monitoring is able to unobtrusively survey bats, the detectability of different species varies widely (Dekker et al., 2022). Most pertinently for this study, the most hard to detect species are likely those most affected by light – some of the *Myotis* species – and by

sound – gleaning bats including most notably the long-eared bats, that call very softly and rely more on listening for prey (Marimuthu, 1997; Siemers & Swift, 2006). With the disturbance or handling of bats requiring a licence under EU law, unobtrusive measures are needed, and perhaps as eDNA analysis of air advances this could become useful for analysing these softly spoken bats.

Bats in the UK provide important pest control services, and conservation efforts have stabilised their population numbers after decades of declines. With anthropogenic light and noise levels continuing to grow, more research into their impact on bat behaviour is required. The results of this study add support to a body of literature regarding species-specific impacts of light and noise on bat behaviour. Future work could include a more nuanced measure of noise, such as its variance, given that chronic noise and unexpected sudden noise may be perceived very differently, with the former enabling tolerance or adaptations to build (Gallego-Abenza, Mathevon & Wheatcroft, 2020; Russo & Jones, 1999) and the latter perceived as a threat (Francis & Barber, 2013). This study should be expanded then to incorporate a greater number of sites to expand the light and noise gradients under analysis, and include a measure of noise variance. The synergistic interaction of light and noise on the feeding rate of *P. pygmaeus* found in this study should urge future bat research to shift focus to studying these pollutants together rather than individually, and similarly planning for lighting schemes should pause to consider whether areas of greater noise level may require more sensitive plans to accommodate bats.

Data and Code Availability

All raw data and code used to generate this report are available at GitHub using the following link:

https://github.com/emmallittle/Little_EEC_MSc_00556901.git

Original sound recordings are not available at the above archive due to the accidental recording of personal conversations contained within. The recording of personal conversation by members of the public without their permission is legal provided it was for my own use, but the distribution of those recordings to a third party is in breach of the Regulation of Investigatory Powers Act 2000 (https://www.legislation.gov.uk/ukpga/2000/23/section/21) and the Data Protection Act 2018 (https://www.legislation.gov.uk/ukpga/2018/12/contents).

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Supplementary Information

The impact of auto-filtering software on bat research

<u>Introduction</u>

Technological advances have led to the use of machine-learning software to automate the location of sound files containing bat calls. This can be taken further, to use automated species identification, though of the primary research cited in this document, none relied on the latter and always manually checked suggested identifications either at random (e.g. Barré et al., 2022) or in full (e.g. Pauwels et al., 2021). This poses the question of how auto-filtering is affecting the quality of bat research.

This additional study aims to compare manual and automated filtering of bat calls to identify impacts on bat research. Given that machine-learning improves with the size of call libraries, I predict that different species will be filtered out at differential rates (automated filtering of less common species less efficient than for more common species), impacting upon the identified relative activity levels.

<u>Methods</u>

I manually analysed the sound files from the first night of the empirical study (n=4,692; >78 hours of sound recordings) for bat passes, and used Kaleidoscope Pro v5.6.0c (Wildlife Acoustics; www.wildlifeacoustics.com) and Sonobat Batch Scrubber 5.7 (SonoBat; sonobat.com) software packages to automatically filter the files for bat passes. I chose the most lenient setting offered by Sonobat (high tolerance for noise and poor call quality). For auto-identification of species I used Kaleidoscope Pro, with a granularity of ten seconds (splitting each recorded file into ten second sections for single species identification). These datasets were then compared to find a false negative rate for the software packages (bat passes found manually but missed by the software), and the impact on relative species activity levels.

Results

Kaleidoscope Pro and Sonobat missed 24% and 11% of the bat containing sound recordings respectively (false negatives; see Figure 5). Using the most tolerant setting to minimise false negatives from Sonobat did though result in incorrectly filtering 68% of the files as containing bats (false positives; see Figure 5).
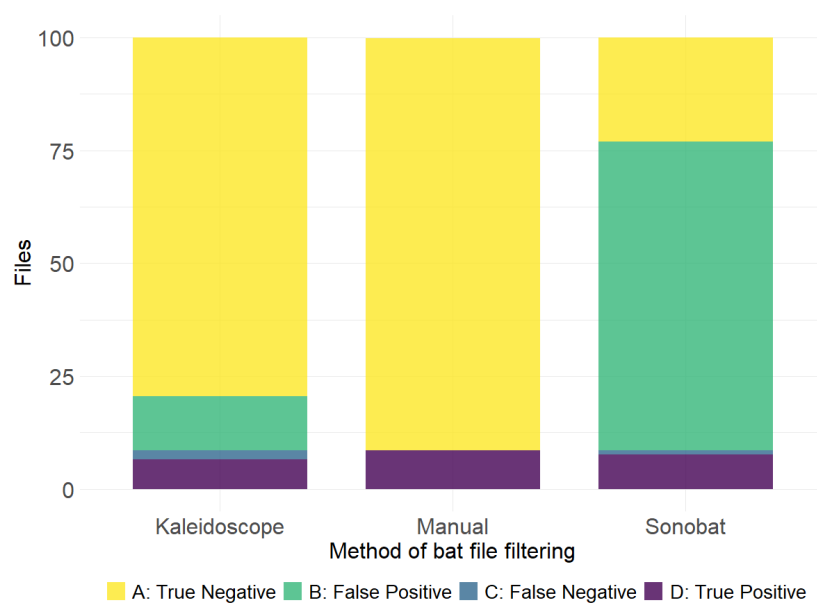

Figure 8: Proportion of files filtered out to contain bats correctly (True Positive) and incorrectly (False Positive), and those filtered out as noise correctly (True Negative) and incorrectly (False Negative), manually and by two auto-filtering software packages

Kaleidoscope Pro found 94% of files containing *P. pipistrellus* and 81% of those containing *P. pygmeaus*, but only 53% of those containing *Myotis spp.*, such that the rarer *Myotis spp.* reduced as a proportion of relative activity when using auto-filtering followed by manual identification from 5% to 3% (see Figure 6).
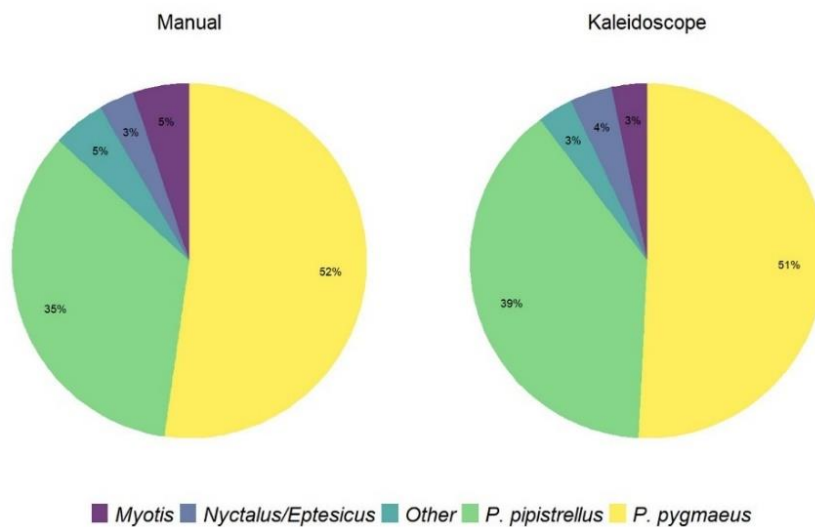
Figure 9: Variation in relative activity level by species/genera, by method of filtering.

Discussion

The use of automated filtering, whilst time saving, not only missed nearly a quarter of the bat files (when not so low tolerance that excessive false positives are produced) but also missed the rarer Myotis spp. more often, as predicted, distorting the relative activity levels by species/genera. Quieter calls tended to be the ones missed, which suggests that species with typically softer calls would also be missed more frequently (eg long-eared bats). Further to these effects on less common species, automated processes are yet to identify multiple bats overlapping, reducing the bat pass counts compared to manual analysis, and are only just starting to automate feeding buzz counts and social calls. Auto-analysis software saves a great deal of time if looking for presence or absence of species, but for now the manual analysis of sound recordings will produce more robust activity level, feeding and communication rate data.