EFFECTS OF ANTHROPOGENIC LIGHT AND NOISE ON ANTI-PREDATOR BEHAVIOUR AND REPRODUCTIVE SUCCESS OF AN URBAN NESTING PASSERINE

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ABSTRACT

Species inhabiting urbanized habitats are continually facing challenges as urbanization intensifies. For urban birds, noise pollution may affect acoustic communication, and light pollution may affect circadian rhythms, yet very little research has been conducted in these areas. I investigated the effects of noise and light pollution on daily nest survival and anti-predator behaviour of American robins (*Turdus migratorius*) Toronto, ON Canada over 2 summers by monitoring nests and by using an observational and experimental approach. Anti-predator behaviours were influenced by light and noise pollution, but nest survival was unaffected. Higher levels of anthropogenic light and noise had no effect on nest survival; even experimentally increasing light levels at nests had no effect. Higher light and noise pollution did increase the frequency of anti-predator behaviours by nesting birds. Lastly, in areas of higher noise pollution robins were less likely to respond to experimental predator calls.

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Introduction

Anti-predator behaviours

As predators evolve new hunting strategies over time, prey will respond and adapt more efficient anti-predator behaviours to increase their chances of survival (Dawkins & Krebs, 1979). This continuous evolution of predator and prey behaviour can be referred to as an "arms race" (Dawkins & Krebs, 1979). Improvement of attack strategies by predators will drive selection pressures forcing the evolution of anti-predator strategies in prey lineages (Dawkins & Krebs, 1979). Predator-prey interactions co-evolve over time due to various selection pressures such as environmental change. For example, a study conducted on grey wolves (*Canis lupus*) and moose (*Alces alces*) in Isle Royale, USA, showed that due to increasing snow cover, wolves adapted by hunting in larger packs, causing an increase in moose mortality (Post et al., 1999). Similarly, increasing temperatures are changing snowshoe hares' (*Lepus americanus*) distribution to colder areas (Wong & Candolin, 2015). As a result, their top predator, the Canada lynx (*Lynx canadensis*) is forced to hunt more of other prey species thus changing the predator prey dynamics (Wong & Candolin, 2015).

In birds, anti-predator behaviours such as escaping, aggressivity, or alarm calling have evolved in response to high predation risk. To detect an aerial predator, or after hearing an alarm call, birds will spend time skygazing to scan for dangers (Vanderhoff & Eason, 2009). Alarm calls can be generated by individuals to warn other birds of a potential threat (Keen et al., 2020). The intensity of these calls will suggest how

dangerous the threat may be and how vigilant the individuals need to be (Vanderhoff & Eason, 2009). During the breeding period, when an alarm call is detected, individuals tend to spend less time on foraging or resting and more on predator detection and avoidance (Vanderhoff & Eason, 2009). Flight is an efficient method to flee predators. Prior to escaping via flight, birds must assess predator size, distance from the predator, and the costs of escaping such as lost foraging opportunities or nest loss (Ydenberg & Dill, 1986). More aggressive anti-predator behaviours such as mobbing are also common and depending on the predator, can be an effective deterrent (Dutour et al., 2019). Individuals can also group together, otherwise known as flocking, to decrease an individual's chance of getting caught (Beauchamp, 2021). Anti-predator behaviours can vary depending on the season (i.e. breeding or non-breeding; Altmann, 1956). During the non-breeding season, escape via flight may be more common (Altmann, 1956), while during the breeding season, mobbing and attacking of a predator may be more common to protect the nest and young (Shedd, 1982).

Nest predation is the highest source of nesting mortality in birds (Agrawal et al., 2021), therefore, it is not surprising that birds have evolved a multitude of nest building strategies to protect their eggs and young from predation (DeGregorio et al., 2016). Passerines tend to conceal their nests by building in areas of dense vegetation or adding vegetation to imitate the appearance of debris (Collias & Collias, 1984). Some species such as the Blue Tit (*Cyanistes caeruleus*) that nest in cavities will further conceal the eggs using nest materials to reduce their visibility to predators (Saavedra & Amo, 2019).

Eggs can increase the visibility of the nest and concealing eggs help hide the nest from predators. The height at which the nest is built also plays an important role in reducing predation risk. Higher nests may be harder to reach by some predators that do not have the capacity to climb, but could be easier to reach by avian predators (DeGregorio et al., 2016). Building nests in human modified habitat is a strategy that may decrease predation from predators that do not tolerate urban areas (Collias & Collias, 1984).

Predator-prey dynamics in urban environments

The urbanization of natural landscapes began in the 18th century with industrialization when cities started to expand significantly (Isaksson, 2018). From 1985 to 2015, global urban areas expanded from 363,747 km^2 to 653,354 km^2 of land (Liu et al., 2020). Urban areas have continued to expand over the years, altering natural habitats and driving many species to adapt to this new environment (Isaksson, 2018). Though urbanization is considered a large threat to wildlife, some species such as Red-tailed Hawks (*Buteo jamaicensis*), Cooper's (*Accipiter cooperii*) and Sharp-shinned (*Accipiter striatus*) hawks' have become more abundant in urban areas due to increasing prey abundance and more nesting options with the use of manmade structures (Chace & Walsh, 2006; McCabe et al., 2018). Smaller bird species may also benefit from living in urban areas due to increasing food supplies and changes in predators (absence of larger predators) (Chace & Walsh, 2006). Predator communities have also adapted well to urban environments, but not without ecological modifications. Home ranges of predators, such

as coyotes (*Canis latrans*), racoons (*Procyon lotor*), and squirrels (*Siuridae*), are smaller compared to rural counterparts causing changes in their movements and distribution (Riley et al., 2003). Hunting strategies have also been modified in urban environments, for example by increasing foraging during the night (Green et al., 2022). Urbanization has been shown to change predator diets; coyotes in urban areas decrease their natural prey consumption and consume more anthropogenic food items (Larson et al., 2020). Predators such as coyotes, foxes, or hawks may be more abundant in urban areas (McCabe et al., 2018; Riley et al., 2003), which may affect levels of predation risk and alter predator-prey dynamics for urban nesting birds.

Regardless of their ability to adapt to urban environments, urban birds such as the European Robin (*Erithacus rubecula*) or the Eurasian Blackbird (*Turdus merula*) face specific anthropogenic disturbances such as new predators (e.g., domestic cats, *Felis catus*), building collisions, traffic, as well as light and noise pollution (Isaksson, 2018; Seress & Liker, 2015). Anthropogenic noise can complicate acoustic communication by decreasing transmission and perception of acoustic signals (Blumstein, 2014; Dooling, 2019). Acoustic signalling is particularly important for birds as it is an important process for reproduction and for inter and intra-specific communication, especially between chicks and their parents (Gil & Brumm, 2013). During reproduction, processes such as mate recognition and selection may be affected by anthropogenic noise as communication can be hindered (Gil & Brumm, 2013). In response to increased anthropogenic noise, some urban birds have changed their song frequencies, amplitude,

and length to be better heard (Nemeth et al., 2013), but these vocal adjustments are not without consequences. Changes in song frequency may increase difficulty in finding mates, competing with other individuals, and perceiving other important alarm or warning calls (Dooling, 2019; Gil & Brumm, 2013; Leonard & Horn, 2008; Patricelli & Blickley, 2006). Noise can mask signals, decreasing their ability to assess or be made aware of a potential danger, such as an approaching predator (Gil & Brumm, 2013). Due to this decreased auditory perception, some birds have adapted by increasing their attention to their surroundings and being more alert (Meillere et al., 2015). For example, female House Sparrows (*Passer domesticus*) exposed to experimentally increased traffic noise were more wary and flushed sooner from their nests (Meillere et al., 2015). Alternatively, in some cases, noise may decrease nest predation by repelling predators that have low levels of noise tolerance such as the Western Scrub Jay (*Aphelocoma californica*) (Francis et al., 2009).

In most large urban centres, birds experience bright nights due to high levels of anthropogenic light (Falchi et al., 2016). Similarly, anthropogenic light may also be a source of stress for birds. Birds have circannual (year) and circadian (day) rhythms that regulate the timing of important life processes such as when to start reproduction and migration etc. (Dominoni, 2015). These rhythms are greatly impacted by natural light which is processed by the multiple sensitive photoreceptors in the eyes, hypothalamus, and pineal gland (Dominoni, 2015). Birds have complex rhythms, potentially more so than other animals such as mammals, as the pineal gland receptors are more sensitive in

birds (Dominoni, 2015). Anthropogenic light at night may cause these photoreceptors to alter circadian and circannual rhythms in birds. Changes in circadian cycles have already been documented in some species, for example American robins have been singing at night, when they normally sing in the early morning (Dominoni, 2015). For circannual rhythm, the timing of reproduction in urban environments have also been advancing (i.e. having earlier lay dates or earlier gonadal development; Dominoni, 2015).

Multiple studies have looked at the effects of light pollution on bird migration or building collisions (Avery et al., 1976; La Sorte et al., 2017; Lao et al., 2020), but there are very few studies investigating the effects of light pollution on anti-predator behaviours of birds. One experimental study on peahens (*Pavo cristatus*) showed increased head movements when exposed to brighter light, and increasing vigilance to potential threats (Yorzinski et al., 2015). The few studies that have been conducted in the field show equivocal results. In American Robins (*Turdus migratorius*) Pharr et al. (2023) found an increase in apparent survival with increasing light pollution whereas Sanchez (2022) found that daily nest survival was not affected by light pollution.

Though it has been documented that anthropogenic light at night (Yorzinski et al., 2015) and anthropogenic noise (Dooling, 2019; Grade & Sieving, 2016) may negatively impact bird communities, few studies have looked at how these two factors combined affect nest survival and anti-predator behaviours of urban nesting birds in the field. The objective of my thesis is to investigate, using observational and experimental methods, how daily nest survival and anti-predator behaviours of nesting American Robins are

affected by anthropogenic light and noise pollution in a highly urbanized environment. Robins are a good study species for this research as they have adapted to urban environments and are therefore abundant in cities (Morneau et al., 1995). In addition, their bulky nests helped facilitate nest searching. The distinctive blue colour of their eggs also facilitate nest identification if the female is not incubating at the time the nest is found (Howell, 1942). Lastly, the reproductive ecology of robins is well documented as they have been extensively studied in suburban environments (Howell, 1942; Maiersperger, 2024; Morneau et al., 1995; Pharr et al., 2023; Yahner, 1983).

I hypothesize that both anthropogenic light and noise pollution will affect anti-predator behaviours and the reproductive success in urban-nesting American Robins. As anthropogenic light increases, I predict that nesting birds will a) exhibit an increase in vigilant behaviour, b) will flush from the nest sooner in the presence of a potential predator, and c) will experience reduced daily nest survival. In areas with higher noise pollution, I predict that nesting birds will a) exhibit an increase in vigilant behaviour, b) will flush from the nest **later** in the presence of a potential predator, and c) will experience reduced daily nest survival. In areas of higher noise pollution, I also predict that the likelihood to respond to experimental predator calls will decrease because noise makes it harder to detect predators. Light and noise are both a form of anthropogenic disturbance (i.e. changing circannual and circadian rhythms, hindering communication) which can have negative impacts on bird communities and their survival. These disturbances can also affect anti-predator behaviours by driving an increase in vigilance.

Methodology

Study site

The study was conducted within Downsview Park (43.7243° N, 79.3579° W) located in the city of Toronto, Ontario, Canada. Downsview Park is a dynamic urban park with a managed landscape characterized by small mixed forest patches of coniferous and deciduous trees, large open greenspace areas, naturalized meadows, and manmade stormwater ponds covering an area of approximately 81 hectares (Figure 1). The park is bordered by high circulation 4-lane arterial roads to the North and West, a new residential area to the South, and commercial and industrial buildings, including the Downsview Military Base and Airport (inactive) to the East. The park contains multiple action areas such as an enclosed dog park, a kids' play zone, and two urban farm lots. Due to its highly urban location, multiple events are hosted in the park including festivals, concerts, and educational activities (public nature walks, school visits etc.). Downsview Park is home to an abundance of nesting American Robins during the summer and home to a variety of predator species such as racoons, squirrels, snakes, and blue jays.

Figure 1. Map of Downsview park, Toronto, ON 2023. The red outline shows the study area, while the numbers indicate the approximate placement of the camera traps.

Study species

The American Robin (hereafter robin) is a common and widespread bird throughout North America. Although some populations migrate to southern North America during the non-breeding season, others may winter relatively close to the breeding grounds (Brown & Miller, 2016). Robins feed mostly on fruits during the fall and winter season and invertebrates (insects, worms) during the spring and summer

(Wheelwright, 1986). Chick diets are insect based then gradually change to a fruit based diet (Wheelwright, 1986).

Robins are monogamous with mate selection occurring based on male plumage colour, with brighter chest colours being preferred by females (Rowe & Weatherhead, 2011). Males will mostly be responsible for selecting and defending a nesting territory and females will breed in the same territory or close to the one chosen during the previous years (Howell, 1942). In temperate areas, the breeding season begins in April and ends in July with broods containing on average 4 eggs, 1 laid per day (Young, 1955). Nest building time can vary greatly but lasts on average 7 days (Young, 1955), and only the female build the nests (Howell, 1942). Robins will usually have a minimum of 2 broods per breeding season and the first nests will sometimes be reused for subsequent broods during the breeding season (Howell, 1942). Nests are most often found in trees with good foliage for concealment, such as spruce, and higher on the tree in urban habitats than rural areas to improve concealment (Morneau et al., 1995). Nests are mostly made of dead grass and some twigs held together with mud (Howell, 1942). Though robins nest in abundance in urban environments, they do not often nest on man-made buildings (Morneau et al., 1995). The female incubates the eggs for a period of approximately 11 days. Upon hatch, chicks remain in the nest and fledge approximately 11 days later (Turner et al., 2017). Females feed the chicks as well as themselves during the nestling stage and will therefore sometimes not be present on the nest (Howell, 1942). Common nest predators include Brown headed cowbirds (*Molothrus ater*), Blue jays (*Cyanocitta*

cristata), American crow(*Corvus brachyrhynchos*), and small mammals such as squirrels (*Sciuridae*) (Malpass et al., 2017).

Nest monitoring

I searched for robin nests in Downsview Park between May 4, and July 25, 2023, and from April 17 to June 12, 2024 for a minimum of 5 days per week from approximately 9am until 2pm. Nest searching was not conducted during inclement weather (i.e., heavy rain, extreme heat waves, etc.). Nests were found by searching for and observing adults that exhibited cues of reproductive activity (carrying material for nest building, territorial singing of males etc.) and watching them return to their nest (Morneau et al., 1995). Once a nest was found, its location was recorded using a handheld Garmin GPSMAP 65 (Garmin Ltd., Kansas, USA) and the nest was revisited every 3 or 4 days throughout the incubation and nestling stage to estimate daily nest survival. All attempts were made to reduce disturbance during nest visits. Whenever possible, a nest visit was conducted at a distance of 5m using binoculars to confirm the presence of adults and/or young in the nest. To count eggs and/or chicks, or if closer inspection was required, a pole with a mirror or phone was used to inspect nest contents and the time at the nest was minimized. A previous 3-year study on robins found no evidence of detrimental effects of nest visits on nest success, with or without handling of eggs (Ortega et al 1997).

At each nest visit, I estimated nest stage by noting the contents of the nest as follows: laying (increasing number of eggs on subsequent visits), egg incubation (same

number of eggs on subsequent visits), nestling stage (all nestlings present in nest) and fledging (some chicks out of nest but within vicinity). Nest age (in days) was estimated based on lay dates and/or hatch dates which were estimated using different methods depending on the stage when the nest was found. When found during laying, lay dates were estimated based on the number of eggs present in the nest and back calculating to the first egg laid given that 1 egg is laid per day (Howell, 1942). If the eggs were not visible or a complete clutch was present (4 eggs or more) lay dates were estimated based on known hatch dates and back calculating based on an incubation period of 11 days (Turner et al., 2017). When found after hatch, with chicks already present, hatch dates were estimated by assessing the age of the chicks via physical features (Howell, 1942). Chicks younger than 5 days old will generally still have their eyes closed most of the time, not raise their heads often, and have little plumage present (Howell, 1942). By day 9, the chicks should have a good amount of plumage present (Howell, 1942). When chicks were too old to assess age by the above characteristics, hatch dates were estimated based on the fledging date and back calculating based on a nestling stage of 11 days (Turner et al., 2017).

Behavioural observations

Behavioural observations of nesting females were conducted twice for each nest found, once during the incubation period and once during the nestling period when possible. Behavioural observations were 1 hour in length and occurred between 9am and

2pm on Tuesdays and Thursdays for logistical reasons. Only nesting females were observed; male and chick behaviour was not recorded. A maximum of 4 behaviour observations were performed on different nests on the same day to reduce observer fatigue. During observations, the observer and one assistant were hidden in a blind or behind trees and bushes at approximately 10 to 15m from the nest to minimize disturbance while maintaining good visibility of the incubating bird. Observations were made using a 20-60x Nikon spotting scope. Before observations began, after setting up the equipment, a 10-minute acclimation period took place (with no sound or movement) to ensure that the bird was not affected by the observers' presence during the first minutes of observations. The date, time, and number of chicks or eggs (if possible) were recorded at a distance during the time of the observations. At the end of each observation, flight initiation distance (FID) was also recorded (Morelli et al., 2022); the observer walked from the observation point to the nest in a straight line and stopped once the incubating bird flew away. The observer then measured FID as the distance between the point where the observer was positioned when the incubating bird fled and the nest using a tape measure.

Rates of incubation and anti-predator behaviours were estimated using a focal animal sampling method (Altmann, 1974). A list of pre-defined behaviours (Table 1) were recorded at one-minute intervals throughout the 1 hour observation period permitting a rate of behaviours per hour to be estimated by tallying observed behaviours.

Table 1: Ethogram of American Robin behaviours.

Behaviour Category	*Incubator Behaviour*	*Description*
Incubation/ nestling period	Rest	Eyes closed, no movement
	Sleepy	Appears to be falling asleep by closing and opening their eyes
	Stand 1	Stands up on nest
	Position change	Changes position on nest with no apparent reason (no alarm calls or evidence of predators)
	Incubation break - departure	Leaves nest for no apparent reason during incubation period (no alarm calls or evidence of predators)
	Incubation break - return	Returns to nest during incubation period for no apparent reason
	On rim	Standing on the rim of the nest
	Off nest	Off nest but within sight of observer
	Out of sight	Out of sight of observer
	Look away	Body or head is turned the other way, making it hard to see their face
	Bending down	Bending down towards the nest and fixing eggs or chicks
	Male visit	
	Male visit with food	
	Sitting on chicks	Female sits on the chicks
	No movement	Incubator does not move
	On nest but not visible	On the nest but view is being blocked (leaf, branch, other animal…)
	Feeding chicks	On the nest feeding the chicks
	Nest departure	Leaves nest during nestling period for no apparent reason, most likely to feed chicks during the nestling stage
	Nest return	Returns to nest during nestling period for no apparent reason
	Grooming	Grooming/ rubbing beak on stomach or wing
	Hatching	Moving body frequently likely due to chick hatch
Anti-predator	Alert robin call	Eyes open and raises its neck due to robin alarm call– no movement

Alert human	Eyes open and raises its neck due to humans– no movement
Alert (unknown)	Eyes open and raises its neck for unknown reason– no movement
Scan	Eyes open, turning head
Stand 2	Birds stands due to visible predator near nest
Flush - Robin alarm call	Flushes after a Robin alarm call
Flush - Bird alarm call	Flushes after alarm call of another bird species
Flush - Mammal alarm call	Flushes after alarm call of another mammal species
Flush - Researcher	Flushes due to researcher
Flush- Predator	Flushes due to predator
Flush- Human	Flushes due to human
Flush- Unknown	Flushes for unknown reasons
Alarm call	Produces alarm call *seet* calls (very high pitched)
Mobbing	Flies toward predator directly
Skygazing	Looking up at the sky to detect predators
Hide in nest	Tries to hide in the nest following a noise or alarm call
Raise feathers	Female raises tail and/or crown feathers

Reactions to experimental predator calls were recorded twice during every 60-minute behavioural observation by playing a predatory call over a period of 30 seconds, repeated once, 30 minutes apart. After the first 30 minutes of observation, a hawk call was played. At the end of the 60-minute period, a coyote call was played. These two predators were selected because they were abundant and the most vocal in this study area. The hawk called was found on the All about birds website (https://www.allaboutbirds.org/guide/Red-tailed_Hawk/sounds), and the coyote howl on

the Yellowstone national park website (https://www.nps.gov/yell/learn/photosmultimedia/sounds-coyote.htm). The sounds were played from the observation site (10 to 15 meters from the nest) using an iPhone 11 at full volume. These calls were only played for incubating females as female robins were rarely present on the nest during the nestling stage. No control playback (i.e. non-predator sounds) was performed.

Anti-predator behaviours were counted for each 1-hour observation separately for the incubation and nestling stage for each nest and then combined (incubation + nestling).

Environmental variables

Light and noise intensity

Light intensities during incubation and nestling periods were measured using HOBO pendant MX light data loggers (HOBO, Australia). Each light meter recorded light intensities up to 167,731 lux within 100ft (30.5m). Light meters were placed within 1 meter of the nest and were attached on a branch of the nest tree using a string. The light meters were directed towards the sky to ensure that the light levels obtained were similar to that experienced by the bird on its nest. When nests were located too high on a tree, the light meters were placed on the same tree in an area that best approximated (judged by eye) the light exposure of the nest during deployment. Light intensities were recorded for 2 consecutive days (2 nights) during the incubation stage or the nestling stage for each nest. When light intensity measures could not be gathered during the incubation or

nestling stage, light intensities were gathered within one week of the nest fledging or failure. All light data were downloaded and analysed using the HOBOconnect app (HOBO, Australia).

Ambient noise was recorded for 2 consecutive days (48 hours) and were started in the morning during both the incubation stage and the nestling stage for each nest by attaching SM4 bioacoustic recorders (Wildlife Acoustics, MA, USA) to the trunk of the nest tree. When two nests were located within 10 meters of each other, the same bioacoustics recorder was used for both nests. Sound pressure levels were recorded by the bioacoustic recorders every minute for 48 hours. Recordings were downloaded and analysed using the kaleidoscope pro 4 analysis software (Wildlife Acoustics, MA, USA). An average of the 48 hours of ambient noise was obtained for each nest.

Predation risk

To provide an index of predation risk for different habitats within the study area, we estimated predator activity per hour using camera traps. Camera traps were deployed for a period of 4 consecutive days, twice during the first field season and once during the second (June 19 to June 22, 2023, July 10 to July 14, 2023, and between June 5 and 27, 2024) at six sites throughout the park. The six sites were chosen to represent the diversity of nesting habitats located within the park (i.e., open field, forest area, etc.; Figure 1).

Camera traps (Reconyx PC900 and Reconyx Hyperfire 2: Holmen, Wisconsin, USA; Moultrie A-25i: Calera, Alabama, USA) were placed on trees at approximately 50 cm from the ground or higher when visibility was reduced by tall grasses or other

vegetation. The cameras were set on trigger only mode and were placed facing a trail, when possible, to catch human activity. The direction and placement of the cameras were changed between trapping sessions (within 10 m of previous placement) when the field of view was blocked or deemed insufficient (Figure 1). Images were taken both during the day and during the night during the 4-day period. The images were then examined by 2 observers to ensure that all wildlife photos were identified and counted correctly. If the same individual was present on camera for long periods of time, they were counted as a new interaction every 5 minutes. All predators (separated into species if identifiable) and humans present in the pictures within 30m were counted for each site. If the field of view was blocked for a certain period of time (i.e. fences being put up, truck blocking view, etc..) the data were excluded. Wildlife photos taken within 5 minutes of each other that could not be told apart were considered to be the same species and counted as 1. The relative activity rate per hour per species was then calculated for each site based on the average of the two sampling periods each year.

Habitat characteristics

To account for variation in habitat that could potentially influence anti-predator behaviours and nest survival (Gotmark et al., 1995), vegetation measurements were taken for each nest site. Nest and tree height (Reale & Blair, 2005) of each nest tree were estimated using a clinometer (Suunto PM-5 360 PC, Finland). Nest tree DBH, along with the diameter of the thickest branch of the nest tree (if possible) was gathered using a 1 meter long tree caliper (Yahner, 1983). If the nest height, DBH, or diameter of thickest

branch could not be measured, mean imputation was used for these nests (n=9). Canopy cover was measured using a spherical densiometer, placing the densiometer on top of the nest (Forest Suppliers Model C, Marianna FL). If nests were located too high and the foliage was not as dense, an estimate of the density was performed by eye or by using a densiometer on another, shorter tree with similar looking foliage density. Within a 10 x10-m quadrat centred on the nest tree, all trees and shrubs (taller than 1m) were counted (Holmes et al., 2020). Vegetation measurements were performed within one week after nest fledging or nest failure to decrease disturbance at active nests. The distance to nearest tree, and the distance from the nest to the trunk of the tree (Yahner, 1983) were then collected using a 50 m or 15 m tape measure.

To account for variation in indirect anthropogenic disturbance, we also estimated the distance to nearest road and the distance to nearest trail using a 50 m or 15 m tape measure. Direct activity rates of humans were estimated using the camera traps as described above.

Behavioural experiments

I manipulated overnight light levels at eight nests throughout the two seasons (three in 2023 and 5 in 2024). Nests were randomly selected, however, nests located in areas with high light pollution (near streets) or near areas located close to busy trails or roads were not manipulated to reduce the risk of equipment theft. Light manipulations consisted of placing a solar garden spotlight (Quntis IP65 Waterproof 2-in-1 solar

spotlights 24 LEDs) within 5 m of the nest as in Assadi & Fraser (2021). The light was turned on from sunset until sunrise for three consecutive days during the 11-day incubation period and again for three consecutive days of the 11-day nestling period. Behavioural observations, as described above, were taken the day after the 3rd night of light manipulations.

Statistical analysis

Daily nest survival

To estimate the effects of light and noise pollution on nest survival and nestling success, daily nest survival analyses were conducted using the program RMark (Laake, 2011). Whereas measures of apparent nest success indicate a simple proportion of nests that succeed (i.e. five nests out of 10 nests monitored = 50% nest success), daily nest survival analyses in RMark provide the probability of a nest surviving from one day to the next using a modified Mayfield method (Mayfield 1960). The Mayfield method incorporates the number of exposure days (number of days a nest is monitored) into estimates of daily nest survival, therefore a nest found later in the season (less exposure days) will have a higher probability of survival than a nest found earlier in the season (more exposure days and therefore more chances of depredation). The estimate of daily nest survival to the power of the number of incubation days then provides a much more informative measure of nest success.

Reducing multicollinearity in habitat variables

As 12 habitat variables were collected, a principal component analysis (PCA) was performed using the *psych* package (v.1.8.4, Revelle 2018) in the program R (v. 3.5.1, R Core Team 2018) to produce synthetic orthogonal (non-correlated) variables representing habitat. This was conducted for the 2023 and 2024 data combined. Rotated components (RC) were retained based on eigenvalues >1 (Abdi & Williams, 2010).

Explaining variation in daily nest survival.

Twenty-two *a* priori models were generated to test different hypotheses regarding the effects of light and noise on daily nest survival (Table 2). Akaike's Information Criterion corrected for small sample sizes (AIC_c) was used to select the model that best explained variation in daily nest survival (Burnham and Anderson 2002). The model with the lowest AICc was selected as the top model based on the principle of parsimony (Burnham and Anderson 2002). Model selection occurred using two steps in order to determine whether I needed to control for the two experiments and an effect of year in all the models. First, models 1 to 4 were run alone to determine if any of these variables described the variation in daily nest survival better than the null model. The light experiment and year did not explain the variation in the dataset better than the null model, therefore these variables were not included to each model. The stage (stage found for survival analysis and observation stage for anti-predator behaviour analyses) was included to each model.

Table 2: List of a-priori hypotheses and corresponding models required to test them. Stage was added to each model to control for it.

Hypothesis	*Model*
1 Null	1 Intercept only
2 Experiment	2 Intercept + experiment
3 Stage	3 Intercept + stage
4 Year	4 Intercept + year
5 Light	5 Intercept + light + stage
6 Noise	6 Intercept + noise + stage
7 Light and Noise	7 Intercept + light + noise + stage
8 Habitat only	8 Intercept + habitat variables + stage
9-11 Habitat	9-11 Intercept + light OR noise OR light + noise + habitat variables + stage
12 Anthropogenic variables alone	12 Intercept + anthropogenic variables + stage
13-15 Anthropogenic variables	13-15 Intercept + light OR noise OR light + noise + anthropogenic variables + stage
16 Predators alone	16 Intercept + predators + stage
17-19 Predators	17-19 Intercept + light OR noise OR light + noise + predators + stage
20-22 Interaction with stage	20-22 Intercept + light * stage OR noise * stage OR light + noise * stage

Habitat variables = tree height, nearest tree, # of trees, # of bushes, canopy cover, DBH, nest height, thickest branch, distance from nest to trunk
Anthropogenic variables = nearest road, nearest trail, human activity

Explaining variation in anti-predator behaviours

To estimate the effects of light and noise pollution on anti-predator behaviours, generalized linear models were conducted. Twenty-two *a* priori models were generated to test different hypotheses regarding the effects of light and noise on a) all anti-predator behaviours, b) alert behaviours, c) scanning behaviours and d) skygazing behaviours (Table 2). Model selection followed the two-step method described above to make sure that any experimental and/or year effects were included in all models if necessary.

Callback experiment

To assess the effects of anthropogenic noise on responses to experimental callbacks, a logistic regression was performed. A 0 or 1 was used to note whether the birds exhibited an antipredator behaviour during the callback in response to a) hawk calls, b) coyote calls or c) both regardless of species. The model with the lowest AIC score was selected as the top model.

All analyses were conducted in the program R (v. 3.5.1, R Core Team 2018). All means are presented ± SD unless otherwise noted.

Results

Nest monitoring

A total of 49 robin nests were monitored during the summer of 2023 and 2024; 29 between May 4 and July 25, 2023, and 20 between April 17 and June 12, 2024. In 2023, eight nests were found during the nest building stage, 11 during the incubation stage, and 10 during the nestling stage. Fourteen of these nests successfully fledged at least one chick (48%), while 15 failed (52%). In 2024, three nests were found during the nest building stage, most nests were found during the incubation stage (12), and five during the nestling stage. Of these nests, half survived (50%) while the other half failed (50%).

Behavioural observations

A total of 41 one-hour behavioural observations were performed throughout the three-month period (26 in 2023, 15 in 2024); 12 during the incubation stage and 14 during the nestling stage in 2023 and seven during the incubation stage and eight during the nestling stage in 2024. A total of nine different types of anti-predator behaviours were recorded during all observation sessions (Table 3). The three most common anti-predator behaviours during incubation and the nestling stages were alert (41% of total observations in 2023, 39% in 2024), scanning (39% of total observations in 2023, 32% in 2024), and skygazing (2% of total observations in 2023, 15% n 2024; Table 3). No

analysis to compare FID was conducted as there was zero variation in FID; i.e, FID was 0m for all nests.

Table 3: Average anti-predator behaviours observed per hour per nest during incubation, nestling and both stages combined.

	2023			*2024*		
Behaviour	*Incubation*	*Nestling*	*Total*	*Incubation*	*Nestling*	*Total*
Alert	8.42 ±4.42	3.71 ±2.79	5.89 ±4.28	6.86 ±2.55	4.13 ±2.36	5.40 ±2.75
Scanning	6.83 ±2.44	4.79 ±3.68	5.73±3.28	5.29 ±3.30	3.75 ±2.05	4.47±2.72
Skygazing	2.33 ±2.27	1.36 ±1.69	1.81 ±2.00	2.57 ±1.51	1.63 ±0.92	2.07±1.28
Hiding in nest	0.83 ±1.59	0.07 ±0.27	0.42 ±1.14	1.57 ±1.27	0.50 ±1.41	1.00 ±1.41
Raising feathers	0.25 ±0.87	0.00 ±0.00	0.12 ±0.59	1.29 ±1.60	0.38 ±0.74	0.80 ±1.27
Standing	0.42 ±0.67	0.07 ±0.27	0.23 ±0.51	0.71 ±1.11	0.14 ±0.38	0.13 ±0.52
Flush- predator	0.00 ±0.00	0.07 ±0.27	0.04 ±0.20	0.00 ±0.00	0.25 ±0.71	0.00 ±0.00
Flush- unknown	0.00 ±0.00	0.07 ±0.27	0.04 ±0.20	0.00 ±0.00	0.00 ±0.00	0.00 ±0.00
Flush-human	0.00 ±0.0	0.14 ±0.37	0.08 ± 0.2	0.00 ±0.00	0.00 ±0.00	0.00 ±0.00

Environmental variables

Light Intensity

Light intensity at nests varied from 0 to 1.57 lux in 2023 (0.21±0.39, n=27) and from 0 to 11.30 lux in 2024 (0.43±1.64, n=20). At several nests light intensities were measured at 0 (n=12 in 2023, n=1 in 2024). Only one nest had a light intensity measure above 1 lux in 2023 (Nest 24).

Noise intensity

In 2023, the noise pollution at nests varied from 16.19± 5.34 dB to 37.33± 3.08 dB (n=29). The average noise pollution in 2023 was 21.00± 4.75 dB. In 2024, noise pollution levels varied from 18.32± 3.81 dB to 37.28± 2.60 dB (n=20). The total average noise pollution for all nests in 2024 was 23.23± 5.38 dB. Most nests were located in areas over 20 dB (n=29) for 2023 and 2024 data combined.

Nest site characteristics

In 2023, nests were located in trees with an average height of 6.56± 2.92m and the average nest height was 3.59± 1.71m. Nests were located on trees with an average DBH of 17.75± 23.82cm. The average diameter of the thickest nest branch was 4.10± 2.16cm (n=17). Nests were located at an average distance of 39.70± 57.74cm from the trunk of the tree and the average canopy cover was 65.58± 22.45%. Robin nests were located on both deciduous (n=17) and coniferous trees (n=12). Within the 10 x10m quadrat, the average number of trees around the nests was 7±5.03, and the average number of shrubs was 2±4.08. Lastly, nests were located on average 1.86± 3.55m away from the closest tree.

In 2024, the average height of the nests was 1.92 ± 1.14m, situated on trees that averaged 3.85 ± 1.73m in height. These nests were found on trees with an average diameter at breast height (DBH) of 22.91 ± 36.71cm. The thickest nest branch had an average diameter of 5.31 ± 3.86cm. Nests were typically located at an average distance of 14.37 ± 31.93cm from the trunk of the tree, and the average canopy cover was 80.01 ± 23.12%. Robin nests were observed on both deciduous (n = 2) and coniferous trees (n = 17), and on buildings (n=1). Within a 10 x 10m quadrat, the average number of trees surrounding the nests was 6 ± 3.67, while the average number of shrubs was 2 ± 2.37. Additionally, nests were located an average of 1.46 ± 1.12m away from the nearest tree.

Principal component analysis of habitat variables

Four rotated components (RC) were retained from the principal component analysis (PCA). Combined these 4 RC accounted for 100% of the variation in the habitat variable dataset. The first factor (RC1), had high positive loadings of nest and tree height (Table 4), therefore high levels of RC1 indicate increased nest and tree height. The second factor (RC2), had high positive loadings of distance to the nearest tree and the distance of the nest from the trunk along with strong negative loadings of the number of trees within the 10x10m quadrat (Table 4). Therefore, high levels of RC2 indicate a lower density of trees around the nest and the nest being located far from the main trunk on the branches of the nest tree. RC3 had high positive loadings of DBH and nest branch diameter (Table 4); high levels of RC3 indicates nests on larger trees. Finally, RC4 had

high loadings of bushes in the 10x10m quadrat (Table 4) therefore high levels of RC4 would indicate a shrubbier nest area.

Table 4: List of habitat covariates and the 4 rotated components (RC). High loadings, above 0.70 are in bold.

Covariate	*Loadings*			
	RC1	RC2	RC3	RC4
DBH	0.18	0.32	**0.77**	0.00
Canopy	-0.40	0.07	0.39	0.59
Thickness of branch	0.16	-0.18	**0.87**	-0.11
Distance from nest to trunk	0.47	**0.73**	0.19	0.21
Tree height	**0.88**	0.06	0.16	-0.10
Nest height	**0.91**	-0.01	0.15	-0.02
# trees	0.26	**-0.72**	0.02	0.34
# bushes	0.02	-0.15	-0.23	**0.81**
Nearest tree	0.05	**0.90**	0.01	-0.05
Proportion explained	0.30	0.29	0.24	0.17
Cumulative variance	0.30	0.59	0.83	1.00

Predator activity rates

In 2023, a total of 722.35 hours were recorded in total for all six sites and 1303.68 hours in 2024. Potential predators detected included squirrels (*Sciuridae*), raccoons (*Procyon lotor*), coyotes (*Canis latrans*). The most common potential predators were coyotes in 2023 (n=2) and squirrels in 2024 (n=12). In 2023, hourly predator activity rates were consistently low across sites, ranging from a low of 0 at sites 4 and 5 to a high of 0.019 at site 3. Sites 4 and 5 had the lowest rates of 0.00 predators/hour and site 3 had

the highest predator rates (0.2 predators/hour). Predators observed in site 3 were coyotes (n=2). Site 5 had the lowest rates of human activity (0.25 humans/hour) and the highest human activity rates were located at site 3 (3.17 humans/hours). In 2024, site 1 had the lowest predator rates (0.00 predators/hour) and site 6 had the highest predator rates of 0.047 predators/hour including squirrels (n=12) and raccoons (n=4). Human activity rates, however, were the lowest at site 6 with a rate of 1.02 humans/hour and the highest at site 1 (4.684 humans/hour).

Effects of light and noise on daily nest survival

Variation in daily nest survival was best explained by the nest stage model with daily nest survival higher during the incubation stage than during nesting (Table 5, Figure 2) however the null model fell within two AICc (Table 5). Daily nest survival overall (both years combined) was 0.91, and raised to the power of 22, (number of exposure days), nest success for the population was low at 0.13 (13%).

Table 5: Model selection results for daily nests survival showing AICc and ΔAIC.

#	*Model*	*k*	*AICc*	*ΔAIC*
3	Intercept + stage	**1**	**95.89548**	**0.000**
1	**Intercept**	1	97.87311	1.9776
2	Intercept+ experiment	2	99.44193	3.5464
20	Intercept + light * stage	3	99.54025	3.6448
6	Intercept + noise	2	99.59657	3.7011
21	Intercept + noise * stage	3	99.65394	3.7585
16	Intercept + predators	2	99.80834	3.9129
5	Intercept + light	2	99.88464	3.9892
4	Intercept + year	2	99.88736	3.9919
18	Intercept + noise + predators	3	101.51091	5.6154
7	Intercept + light and noise	3	101.51711	5.6216
22	Intercept + light * stage and noise * stage	4	101.57255	5.6771
17	Intercept + light + predators	3	101.84836	5.9529
12	Intercept + anthropogenic variables	5	103.28197	7.3865
19	Intercept + light and noise + predators	4	103.47920	7.5837
14	Intercept + noise + anthropogenic variables	5	104.62789	8.7324
13	Intercept + light + anthropogenic variables	5	105.36561	9.4701
8	Intercept + habitat variables	10	105.67872	9.7832
15	Intercept + light and noise + anthropogenic variables	6	106.51042	10.6149
10	Intercept + noise + habitat variables	11	107.36119	11.4657
9	Intercept + light + habitat variables	11	107.48757	11.5921
11	Intercept + light and noise + habitat variables	12	109.19169	13.2962

Habitat variables = tree height, nearest tree, # of trees, # of bushes, canopy cover, DBH, nest height, thickest branch, distance from nest to trunk
Anthropogenic variables = nearest road, nearest trail, human activity

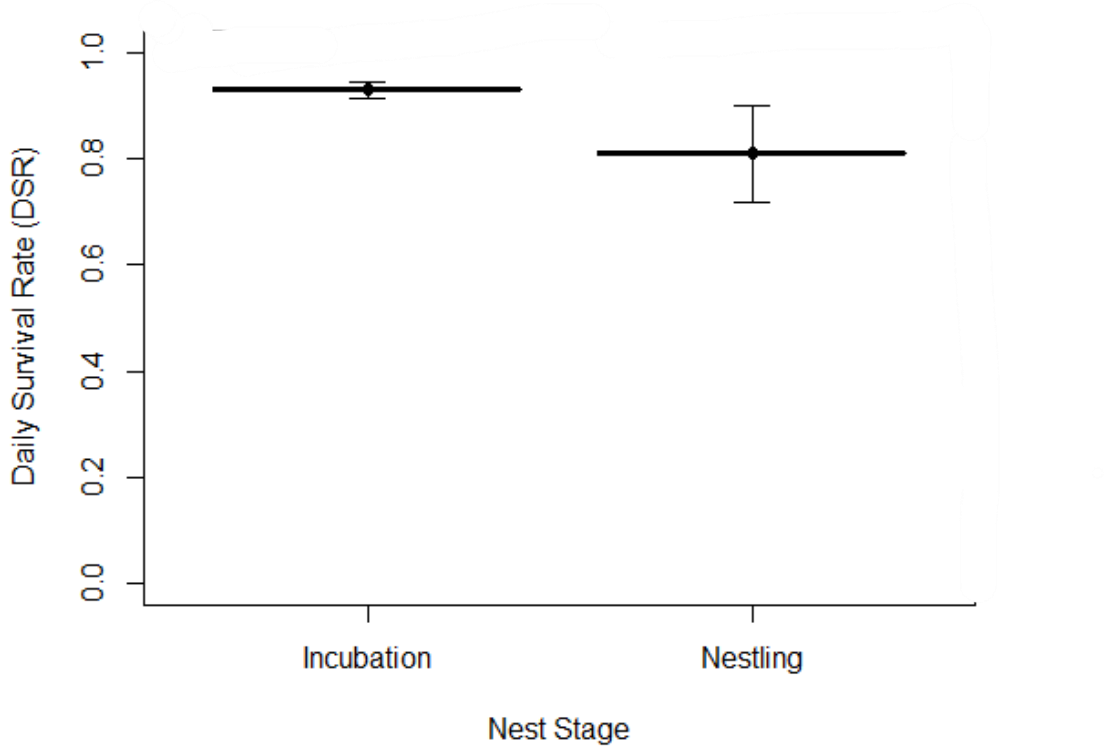

Figure 2: Box plot of top model for daily nest survival including standard error for the 2 seasons, n=34 nests for incubation and n=15 for nestling.

Effects of light and noise on anti-predator behaviours

All anti-predator behaviours

Variation in all anti-predator behaviours combined was best described by a model including noise, habitat variables and nest stage (Model 10, Table 6). An increase in anti-predator behaviours occurred with increasing noise pollution (Table 7, Figure 3A). An increase in RC1 also showed an increase in anti-predator behaviours (Table 7, Figure

3B). However, decreasing RC2, RC3, and RC4 values showed an increase in anti-predator behaviours (Table 7, Figure 3 C,D,E). Anti-predator behaviours also differed by nest stage with more anti-predator behaviours exhibited during incubation (Table 7, Figure 3F).

Table 6: Model selection results for total anti-predator behaviours.

#	*Model*	*k*	*AIC*	*ΔAIC*
10	**Intercept + noise + habitat variables + stage**	**12**	**291.3709**	**0.000**
3	Intercept + stage	2	293.1478	1.7769
12	Intercept + anthropogenic variables + stage	5	293.3014	1.9305
11	Intercept + light and noise + habitat variables + stage	13	293.3703	1.9994
6	Intercept + noise +stage	3	293.7322	2.3613
8	Intercept + habitat variables + callback	11	294.3010	2.9301
14	Intercept + noise + anthropogenic variables + stage Intercept + light + stage	6	294.6946	3.3237
5	Intercept + predators + stage	3	294.8857	3.5148
16	Intercept + noise + predators + stage	3	294.9236	3.2527
18	Intercept + light + anthropogenic variables + stage	14	295.2247	3.8538
13	Intercept + noise * stage	6	295.2877	3.9168
21	Intercept + light and noise + stage	3	295.2883	3.9174
7	Intercept + light + habitat variables + stage	4	295.6927	4.3218
9	Intercept + light + predators + stage	12	296.3008	4.9299
17	Intercept + light and noise + anthropogenic variables + stage	4	296.5896	5.2442
15	Intercept + light * stage	7	296.6151	5.2442
20	Intercept + light and noise + predators + stage	3	296.7636	5.3927
19	Intercept + light * stage and noise * stage	5	297.1585	5.7876
22	Intercept	4	299.1304	7.7595
1	Intercept + year	1	330.0297	38.6588
4	Intercept +experiment	2	331.8571	40.4862
2		2	331.8697	40.4988

Habitat variables = tree height, nearest tree, # of trees, # of bushes, canopy cover, DBH, nest height, thickest branch, distance from nest to trunk
Anthropogenic variables = nearest road, nearest trail, human activity

Table 7: Parameters of the top ranked model explaining variation anti-predator behaviours.

Parameter	*Estimate*	*SE*	*z-value*	*p-value*
Intercept	2.510752	0.182816	13.734	< 2e-16
Noise	0.017613	0.007856	2.242	0.0250
RC1	0.087687	0.040409	2.170	0.0300
RC2	-0.121668	0.049876	-2.439	0.0147
RC3	-0.020358	0.03995	-0.510	0.6103
RC4	-0.020786	0.054597	-0.381	0.7034
Stage	-0.558923	0.090152	-6.200	5.65e-10

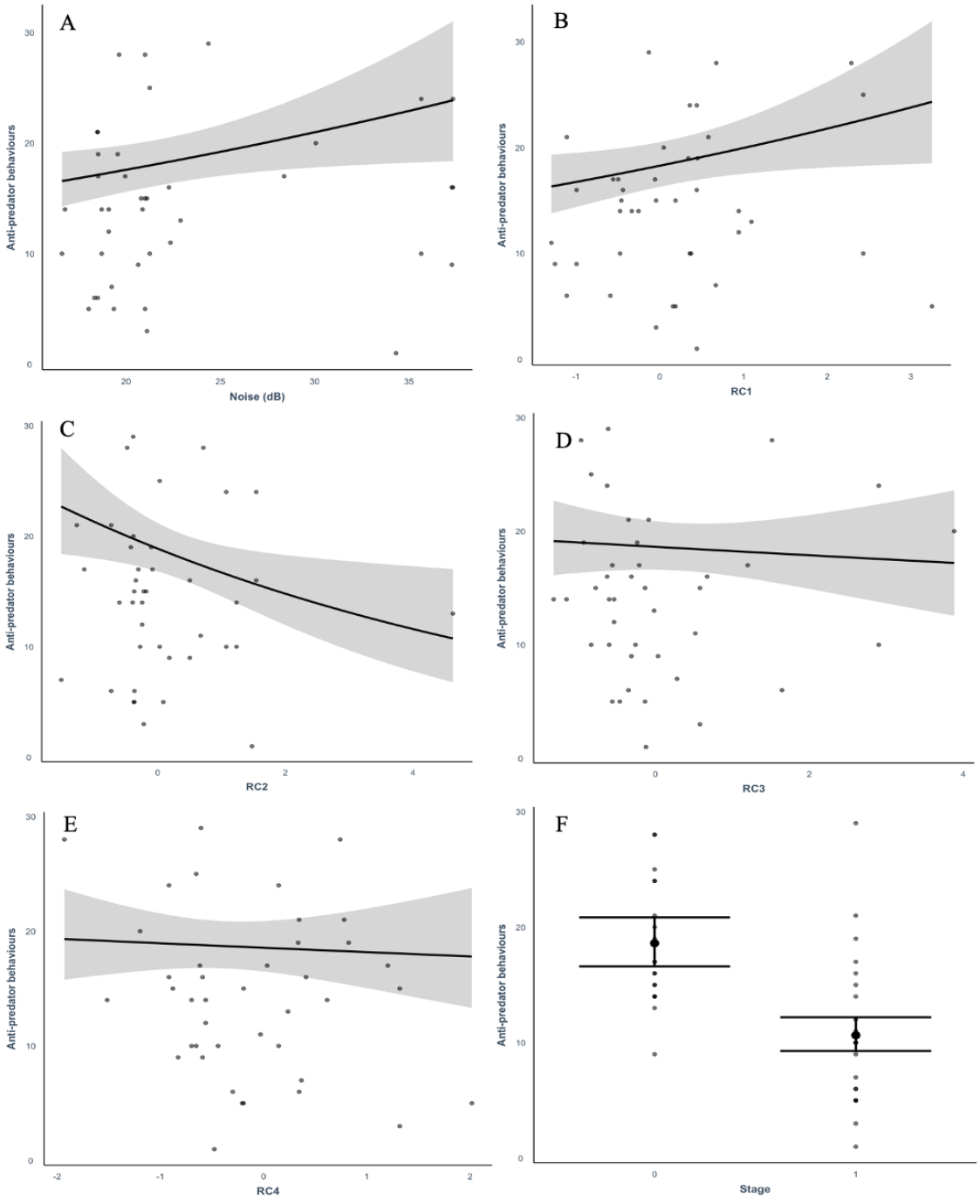

Figure 3. Graphs of top model (model 12) of effects of noise and habitat variables on all anti-predator behaviours per hour. RC1- positive loadings of nest and tree height, RC2-

positive loadings of distance to the nearest tree and the distance of the nest from the trunk along with strong negative loadings of the number of trees within the 10x10m quadrat, RC3- nests on larger trees, RC4 – positive loadings of bushes in the 10x10m quadrat. Zero indicates incubation and 1 the nestling stage.

Alert behaviours

Variation in alert behaviour was best described by a model that included nest stage alone (model 3, Table 8). Nests that had observations taken during the incubation stage had higher rates per hour of alert responses compared to nests that were observed during the nestling stage (Table 9, Figure 4). Four competing models included the stage in addition to 1) a negative effect of light pollution (model 5), 2) a negative effect of noise (model 6), and 3) a negative effect of predators (model 16; Table 8).

Table 8: Model selection results for alert behaviour (AL).

#	*Model*	*k*	*AIC*	*ΔAIC*
3	**Intercept + stage**	**2**	**222.0118**	**0.000**
5	Intercept + light + stage	3	222.8769	0.8651
6	Intercept + noise + stage	3	223.2540	1.2422
16	Intercept + predators + stage	3	223.8123	1.8005
20	Intercept + light * stage	3	223.8553	1.8435
7	Intercept + light and noise + stage	4	224.5218	2.5100
17	Intercept + light + predators + stage	4	224.5321	2.5203
18	Intercept + noise + predators + stage	4	224.8749	2.8631
21	Intercept + noise * stage	3	225.0912	3.0794
19	Intercept + light and noise + predators + stage	5	226.0482	4.0364
12	Intercept + anthropogenic variables + stage	5	226.6053	4.5935
13	Intercept + light + anthropogenic variables + stage	6	227.1344	5.1226
9	Intercept + light + habitat variables + callback	12	227.1899	5.1781
8	Intercept + habitat variables + callback	11	227.3668	5.355
22	Intercept + light * stage and noise * stage	4	227.3674	5.3556
14	Intercept + noise + anthropogenic variables + stage	6	227.6220	5.6102
15	Intercept + light and noise + anthropogenic variables + stage	7	228.5648	6.553
11	Intercept + light and noise + habitat variables + stage	13	228.8391	6.8273
10	Intercept + noise + habitat variables + callback	12	228.9747	6.9629
1	Intercept	1	240.8270	18.8152
4	Intercept + year	2	240.9436	18.9318
2	Intercept+ experiment	2	242.4340	20.4222

Habitat variables = tree height, nearest tree, # of trees, # of bushes, canopy cover, DBH, nest height, thickest branch, distance from nest to trunk
Anthropogenic variables = nearest road, nearest trail, human activity

Table 9: Parameters of the top ranked model explaining variation alert behaviours.

Parameter	*Estimate*	*SE*	*z-value*	*p-value*
Intercept	2.04599	0.08248	24.806	< 2e-16
Stage	-0.59374	0.13206	-4.496	6.93e-06

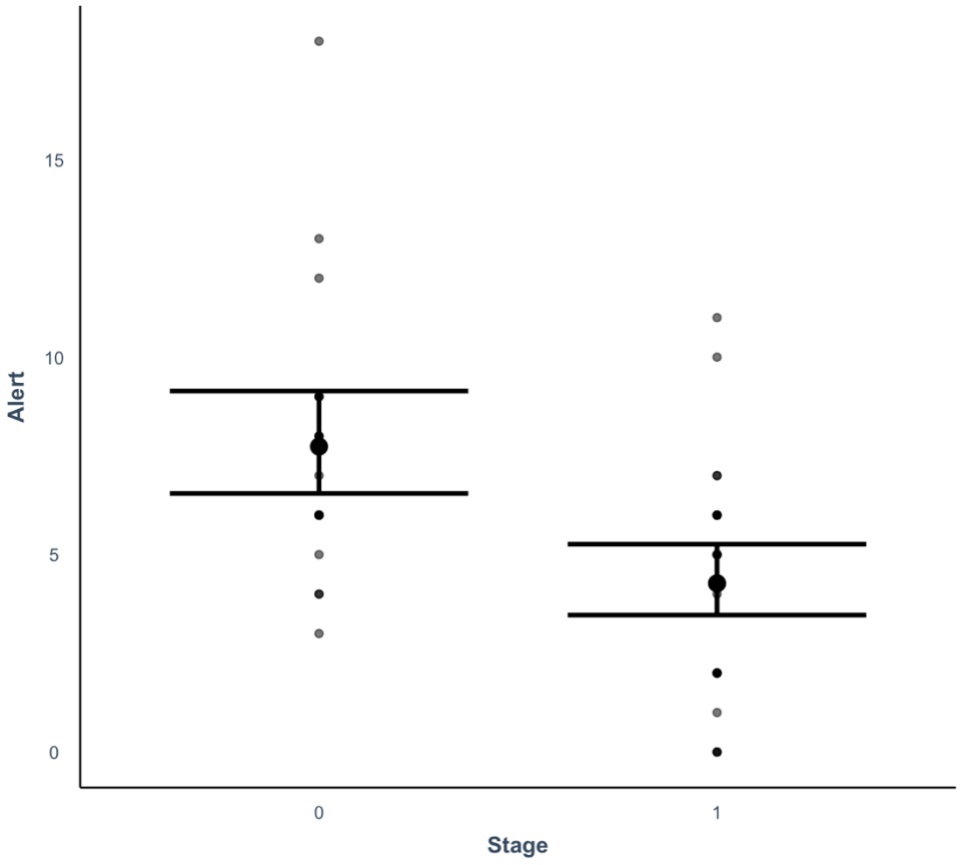

Figure 4. Boxplot of top model (model 3) showing effects of callback on alert behaviours. Zero shows the incubation stage, while 1 shows the nests where observations were performed during the nestling stage.

Scanning behaviour

Variation in scanning behaviours were best described by model 11, which included a positive effect of light and noise pollution (Table 10, Figure 5 A, B). As light and noise pollution increased, the scanning behaviours increased (Table 10, Figure 5 A, B). The model also included a positive effect of RC1 (Table 11, Figure 5 C), a negative effect of RC2, RC3, and RC4 (Figure 5 D, E, F). Scanning behaviours also changed depending on the stage (Figure 5 G).

Table 10: Model selection results for scanning behaviour (SC).

#	*Model*	*k*	*AIC*	*ΔAIC*
11	**Intercept + light and noise + habitat variables + stage**	**13**	**200.5554**	**0.000**
9	Intercept + light + habitat variables + stage	12	201.3808	0.8254
5	Intercept + light + stage	3	201.9590	1.4036
17	Intercept + light + predators + stage	4	202.3091	1.7537
7	Intercept + light and noise + stage	4	202.7063	2.1509
20	Intercept + light * stage	3	203.4154	2.8600
19	Intercept + light and noise + predators + stage	5	203.4432	2.8878
10	Intercept + noise + habitat variables +	12	205.2075	4.6521
6	stage	3	205.3417	4.7863
18	Intercept + noise + stage	4	205.6929	5.1375
16	Intercept + noise + predators + stage	3	205.8807	5.3253
15	Intercept + predators + stage	7	206.1276	5.5722
21	Intercept + light and noise + anthropogenic variables + stage	4	206.2896	5.7342
8	Intercept + light * stage and noise * stage	11	206.3776	5.8222
3	Intercept + habitat variables + stage	2	206.4019	5.8465
13	Intercept + stage	6	206.5577	6.0023
22	Intercept + light + anthropogenic variables + stage	3	207.1446	6.5892
14	Intercept + noise * stage	6	207.7073	7.1519
2	Intercept + noise + anthropogenic variables + stage	2	208.7465	8.1911
4	Intercept+ experiment	2	209.6567	9.1013
12	Intercept + year	5	209.6968	9.1414
1	Intercept + anthropogenic variables + stage Intercept	1	209.7021	9.1467

Habitat variables = tree height, nearest tree, # of trees, # of bushes, canopy cover, DBH, nest height, thickest branch, distance from nest to trunk
Anthropogenic variables = nearest road, nearest trail, human activity

Table 11: Parameters of the top ranked model explaining variation scanning behaviours.

Parameter	*Estimate*	*SE*	*z-value*	*p-value*
Intercept	1.19243	0.29478	4.045	5.23e-05
Light	0.11464	0.04490	2.553	0.0107
Noise	0.02117	0.01248	1.696	0.0899
RC1	0.10351	0.06648	1.557	0.1195
RC2	-0.04876	0.07976	-0.611	0.5410
RC3	-0.17945	0.09335	-1.922	0.0546
RC4	-0.05449	0.10234	-0.532	0.5944
Stage	-0.27676	0.14913	-1.856	0.0635

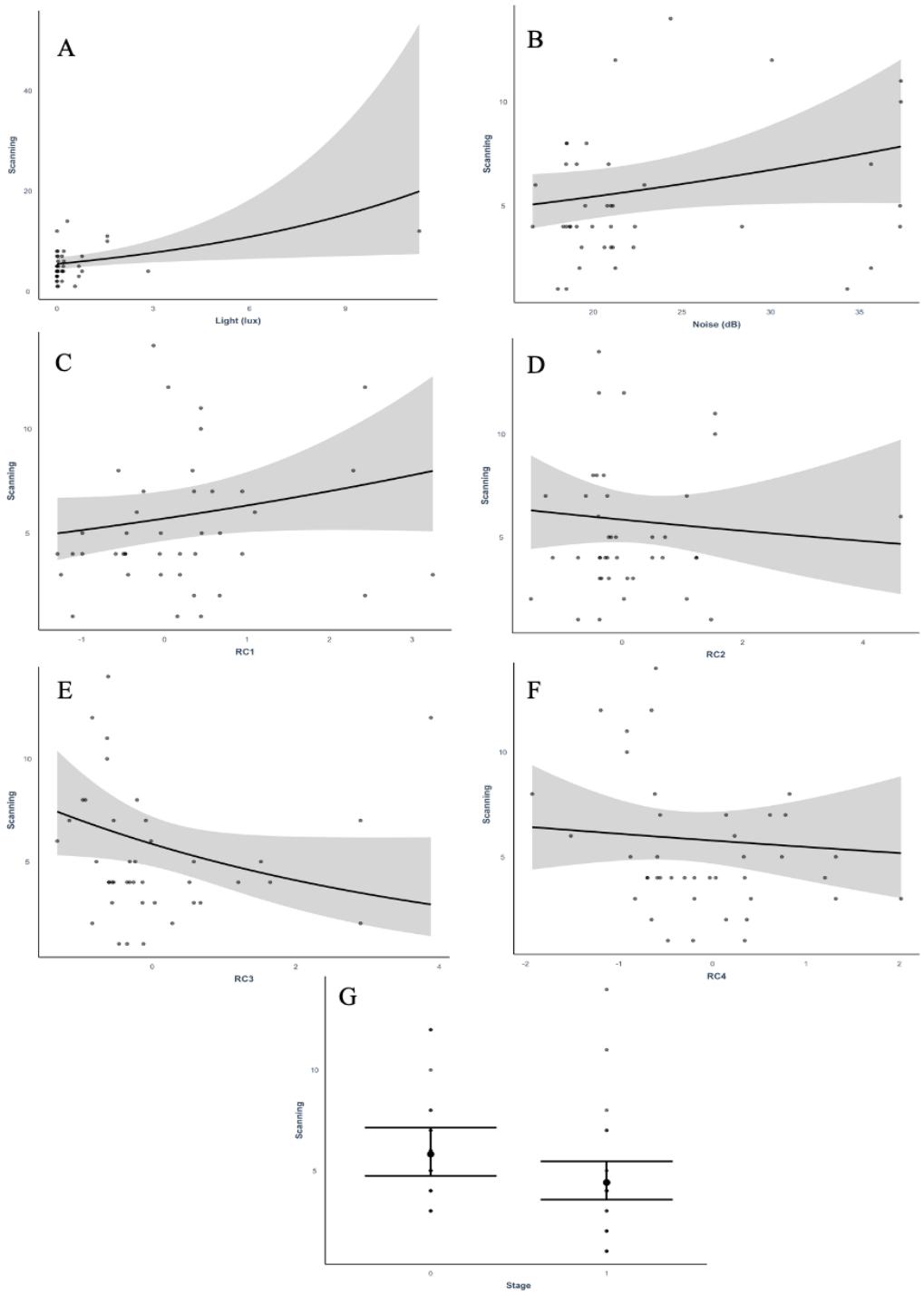

Figure 5. Graphs of top model (model 11) showing effects of light, noise and habitat variables on scanning behaviours per hour. RC1- positive loadings of nest and tree

height, RC2- positive loadings of distance to the nearest tree and the distance of the nest from the trunk along with strong negative loadings of the number of trees within the 10x10m quadrat, RC3- nests on larger trees, RC4- positive loadings of bushes in the 10x10m quadrat. Zero indicates incubation and 1 the nestling stage.

Skygazing behaviour

Variation in skygazing behaviours were best described by a model with anthropogenic variables and the nest stage (model 12, Table 12). As the distance from the roads and trails to the nest increases, the skygazing behaviours decreased (Table 13, Figure 6 A, B). As human activity decreased, skygazing behaviours decreased (Table 13, Figure 6 C). Skygazing behaviours also increased during incubation (Table 13, Figure 6 D). A slight positive effect of light and noise were found in competing models (13 and 14).

Table 12: AIC of all models for skygazing anti-predator behaviour (SG).

#	*Model*	*k*	*AIC*	*ΔAIC*
12	**Intercept + anthropogenic variables + stage**	**5**	**147.8712**	**0.000**
13	Intercept + light + anthropogenic variables + stage	6	149.2752	1.404
14	Intercept + noise + anthropogenic variables + stage	6	149.4271	1.5559
15	Intercept + light and noise + anthropogenic variables + stage	7	151.1890	3.3178
6	Intercept + noise + stage	3	151.9778	4.1066
3	Intercept + stage	2	152.1782	4.307
10	Intercept + noise + habitat variables + stage	12	152.3533	4.4821
18	Intercept + noise + predators + stage	4	152.7639	4.8927
21	Intercept + noise * stage	3	152.9590	5.0878
16	Intercept + predators + stage	3	153.5916	5.7204
11	Intercept + light and noise + habitat variables + stage	13	153.7729	5.9017
7	Intercept + light and noise + stage	4	153.9765	6.1053
5	Intercept + light + stage	3	154.0016	6.1304
8	Intercept + habitat variables + stage	11	154.7387	6.8675
19	Intercept + light and noise + predators + stage	5	154.7489	6.8777
20	Intercept + light * stage	3	155.2717	7.4005
17	Intercept + light + predators + stage	4	155.3147	7.4435
22	Intercept + light * stage and noise * stage	4	156.2667	8.3955
9	Intercept + light + habitat variables + stage	12	156.2872	8.416
1	Intercept	1	157.5290	9.6578
4	Intercept + year	2	158.9585	11.0873
2	Intercept+ experiment	2	159.5042	11.633

Habitat variables = tree height, nearest tree, # of trees, # of bushes, canopy cover, DBH, nest height, thickest branch, distance from nest to trunk
Anthropogenic variables = nearest road, nearest trail, human activity

Table 13: Parameters of the top ranked model explaining variation skygazing behaviours.

Parameter	*Estimate*	*SE*	*z-value*	*p-value*
Intercept	1.575402	0.305592	5.155	2.53e-07
Nearest road	-0.006101	0.017629	-0.346	0.729300
Nearest trail	-0.044704	0.014925	-2.995	0.002741
Human rate	-0.048821	0.093114	-0.524	0.600059
Stage	-0.794550	0.241244	-3.294	0.000989

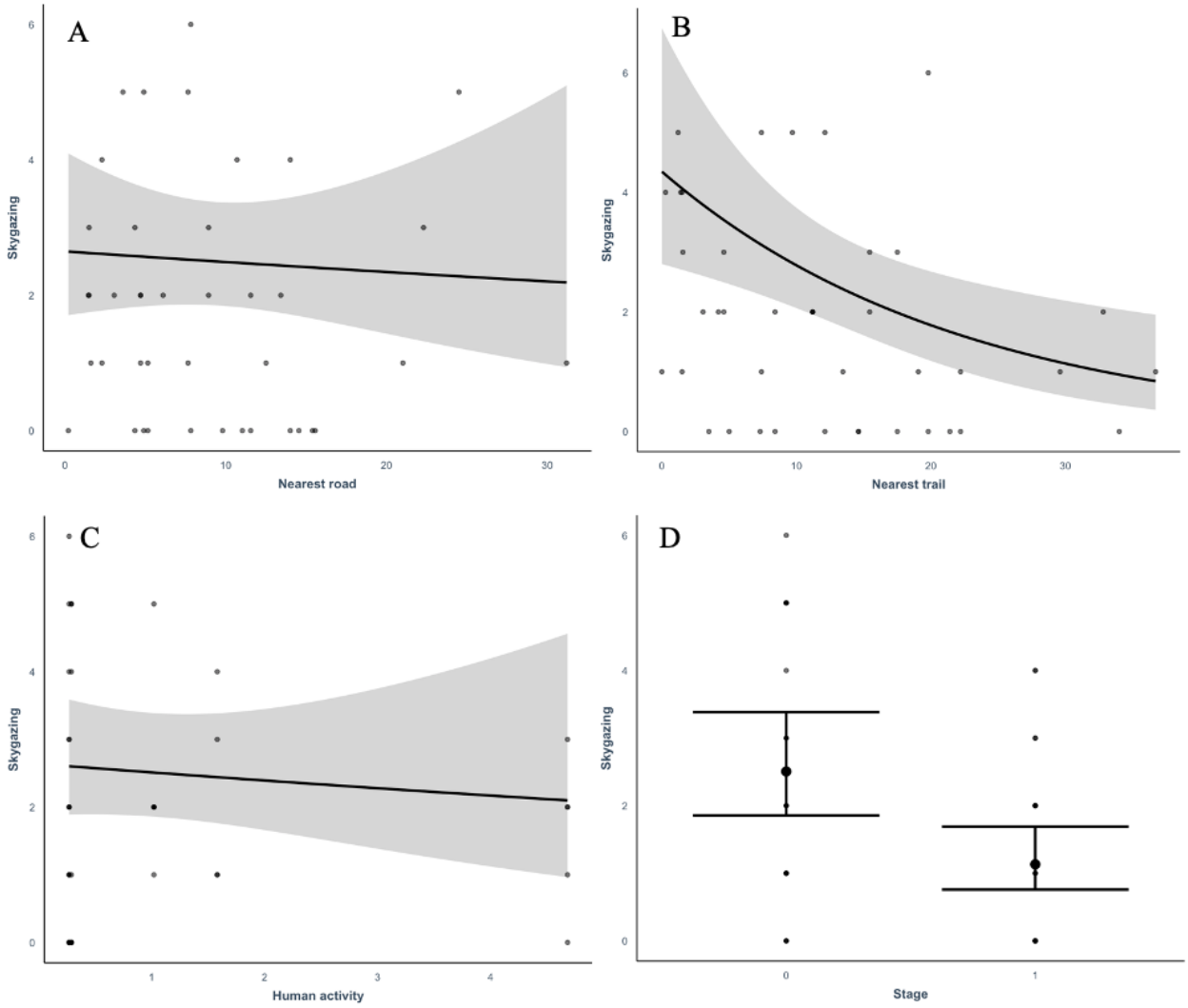

Figure 6. Graphs of top model (model 12) showing the effects of anthropogenic variables (nearest road, nearest trail, and human activity) on skygazing behaviours per hour.

Callback experiment

During the callback experiment, noise alone best explained the variation in the likelihood that a robin would respond to experimental calls (Table 14). Birds were more

likely to respond when ambient noise was lower (Table 15, Figure 7). The type of predator played (coyote or hawk) did not affect the likelihood of response (Table 14).

Table 14: Model selection table for predator callback experiment.

#	*Model*	*k*	*AIC*	*ΔAIC*
3	**Intercept + noise**	**2**	**35.229**	**0.000**
2	Intercept + noise + predator type	3	37.032	1.803
1	Intercept	1	46.316	11.087
4	Intercept + predator type	2	48.185	12.956

Table 15: Parameters of the top ranked model explaining response to callbacks.

Parameter	*Estimate*	*SE*	*z-value*	*p-value*
Intercept	21.659	7.796	2.778	0.00547
Noise	-1.013	0.373	-2.717	0.00659

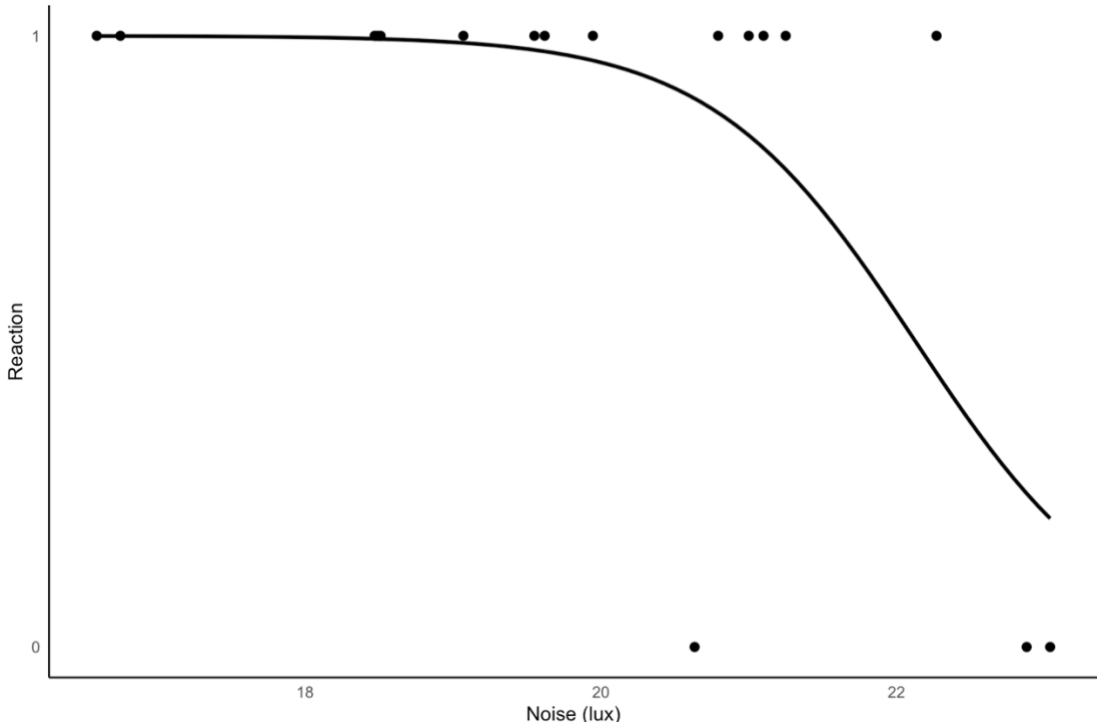

Figure 7. Graph of top model of logistic regression for callback experiment (model 3) showing effects of noise on the robin's presence or absence of reaction to callback.

Discussion

In this study, I aimed to investigate the impacts of light and noise pollution on daily nest survival and anti-predator behaviours of American Robins. I hypothesized that both anthropogenic light and noise pollution would affect anti-predator behaviours and the reproductive success in urban-nesting American Robins. Contrary to my predictions, increases in anthropogenic light and noise had no effect on nest survival. The experimental increasing of light levels at nests also showed no effect. Nest stage

(incubation or nestling) alone was the factor that best described variation in daily nest survival, where nests had higher daily survival rates during incubation than during the nestling stage. Across both stages, daily nest survival was relatively low at 0.91 (13% nest success). Nest stage was also an important factor describing variation in anti-predator behaviours (alert, scanning, skygazing and all combined), with a lower frequency of anti-predator behaviours occurring during the nestling stage for all analyses. Light and noise pollution, in addition to direct and indirect human activity and habitat, however, were also important predictors of anti-predator behaviours; as predicted, in most cases, light and noise pollution were associated with an increase in anti-predator behaviours. Lastly, noise pollution had an important effect on the likelihood that robins responded to experimental predator calls (both coyote and hawk); in areas of higher noise, robins were less likely to respond to predators.

Contrary to my initial predictions, noise pollution did not appear to influence nest survival in urban nesting robins. Effects of noise pollution on nest success of passerines, though not extensively studied, appear to vary considerably by species. One study performed on Western Bluebirds (*Sialia mexicana*) and Ash-throated Flycatcher (*Myiarchus cinerascens*) on a university campus located in a suburban area that experiences low levels of anthropogenic noise, found that nest success did not decrease for the Western Bluebird but did for the Ash-throat Flycatcher due to nest abandonment (Mulholland et al., 2018). The authors suggested that Ash-throated Flycatchers may be more sensitive to noise than Western Bluebirds (Mulholland et al., 2018). As a highly

ubiquitous urban bird, robins may already be well habituated to noise levels in urban areas. To my knowledge, only a few other studies have investigated effects of noise on nest survival or adult survival of robins. Sanchez (2022) found no negative impacts of noise pollution on the nest success of robins nesting in a recently urbanized county (Weld County, Colorado, USA). Pharr et al. (2023) found that noise pollution had no effect on adult annual survival of seven bird species (including robins) nesting in the highly urbanized Washington DC, USA. It is possible that noise levels were not high enough to disturb nesting birds at my study site. In 2017, noise levels in urban areas of Toronto were reported to range from 50.4 to 78.3 dB (Drew et al., 2017). Drew et al. (2017) measured noise levels at 220 sites in Toronto with high human activity (ex. near roads, railways, and high human density). Sanchez (2022) also used wildlife song meters and found an average noise pollution level of 46.9 dB/ 61.5 dB (Sanchez, 2022). In contrast, our study site, despite being located close to areas of high human activity (larger roads), had considerably lower noise pollution levels, ranging from 16.19 and 37.33 dB but averaging 18 – 20 dB each year. Even in our noisiest areas (ex. Dog park), our values were completely outside of the lower range of Drew et al. (2017). Drew et al. (2017) used a Noise Sentry RT sound level meter data logger to measure noise pollution levels. In my study, bioacoustic recorders were used, but both instruments were able to get sound pressure level with an A weighted ban, which adjusts sound to better fit human hearing. Despite the lower-than-usual noise levels at my site, the results align with the only other

available studies on robins, which also found no effects on nest survival or adult survival even at higher noise levels (Sanchez 2022 and Pharr et al. 2023).

As predicted, light pollution did not appear to influence nest survival in urban nesting robins either. My results do align with the only other study that specifically looked at the effects of light pollution on robin nest survival (Sanchez, 2022). Using Sky Quality Meters to measure light at nests, Sanchez (2022) found that daily nest survival was not affected by light pollution, however, they did find that nests located in brighter areas were associated with higher survival. Our results differ from those found for some passerines. Barn Swallows (*Hirundo rustica*) nesting on buildings in Taipei City, Taiwan experienced increased nest success with increasing light pollution levels (Wang et al., 2021). Wang et al., (2021) measured light using a light meter and found light pollution levels ranged between 0 lux to >10 lux across their sites. Light pollution levels in Toronto were found to be around 16 lux in Nathan Phillips Square (Thurairajah et al., 2023). Light pollution within my study site, which is located in the suburbs of Toronto, ON, was consistently low throughout the two-year study period (0.21±0.39 in 2023 and from 0.43±1.64 in 2024). Again, as for noise pollution, it is possible that light pollution levels within the park were too low to observe any significant effects on nest survival. Light pollution may need to reach a certain threshold level before it affects nest survival, however, the fact that Sanchez (2022) also found no effect, provides support to our findings of no effect. Sanchez (2022) also suggested that light pollution could potentially increase nest survival, as certain predators may avoid brighter areas during the night,

reducing predation risk for nesting birds. Pharr et al., (2023) also looked at the effects of light pollution using data from the second world atlas of artificial night sky brightness on adult survival and found that light pollution increased adult survival in robins. Regarding the methods used in this study, the light data logger proved to be a useful tool for measuring light pollution levels, although proper placement of the illuminance meters is crucial for obtaining accurate data (Mander et al., 2023). In this study, the placement of the light meters may have affected the accuracy of the light measurements, potentially influencing the results. However, the light data logger remains a good tool for such measurements and could be optimized in future studies by ensuring more precise placement.

Variation in daily nest survival was best explained by nest stage; nests had higher daily survival rates during incubation than during the nestling stage. These results are not surprising as during the nestling stage, there is much more activity at the nest, with the adults departing on foraging breaks and chicks begging and competing for food upon their return. Nest predators may use these cues during the nestling phase to locate nests. By playing recordings of begging chicks at artificial nests in Red-whiskered Bulbul (*Pycnonotus jocosus)*, Liu et al., (2022) demonstrated that the sounds of begging chicks increased the frequency of predator visits to nests during the nestling period. Despite the differences in nest survival between incubation and nestling periods, overall daily nest survival was very low across both years, with daily nest survival estimated at 0.91, resulting in nest success of only 13%. One recent study found that urban nesting robins

also had relatively low nest survival (0.92, nest success of 25%; (Maiersperger, 2024) whereas previous studies have found higher nest success in urban environments (41.2% to 75%; (Morneau et al., 1995; Yen et al., 1996). Though outside the scope of this study, this apparent decrease of nest survival over time in urban birds is worth investigating. I did not detect any effects of predator activity rates or habitat on daily nest survival, despite these variables being documented as important predictors of nest success in numerous studies (DeGregorio et al., 2016; Sanchez, 2022; Vazquez et al., 2021). One potential explanation for the lack of observed effects from predators in this study could be that the cameras did not detect avian predators well, therefore predator activity rates may have been underestimated. There were also a limited number of cameras deployed (6 cameras for 30 nests/year), which may have muted any actual differences in predation risk experienced between nests.

Contrary to the lack of effects on nest survival, light pollution did result in an increase in all anti-predator behaviours in robins as predicted. Effects of light pollution on anti-predator behaviours of birds have not been greatly studied. Most studies have focussed on the effect of light on other aspects such as bird migration patterns (La Sorte et al., 2017). Yorzinski et al., (2015) documented increased vigilance rates (head movements) in peahens while experimentally increasing light levels at night (0.75 to 1,260 lux) in a controlled laboratory setting. Yorzinski et al. (2015) suggested that an increase in vigilant behaviours in areas of higher light pollution may occur due to increased predation risk in brighter areas, causing birds to increase vigilance to better

detect predators. Like Yorzinski et al., (2015), I documented an increase in vigilant behaviours (scanning and alert) at higher light levels, even though my range of light levels was much lower (maximum of 11.3 lux). It is possible that increased vigilant behaviours in areas of higher light could compensate for any potential effects of light on nest survival, potentially explaining the lack of effects of light on nest survival. This explanation is only possible if the physiological costs of the additional vigilant behaviour is not too high, and, of course, if the increased vigilance is actually successful in detecting or deterring predators.

Surprisingly, the experimental addition of light did not have an effect on anti-predator behaviours. This could be because only 8 nests were able to be used for this experiment. Additionally, the lights were turned on for 2 nights only, and if left for more nights, an effect may have been noticed. The lights used could have also have been a limitation as in the regular observations, birds exposed to light were usually exposed to larger light poles as well as other sources of light (such as cars, buildings, etc.), rather than just a garden spotlight. Anthropogenic light at night is typically considered dim when it ranges from 5 to 10 lux, although many organisms are more often exposed to light levels of up to only 2 lux (Alaasam, 2022).

My results show that areas with higher noise levels also had an increase in overall anti-predator behaviours. Sweet et al. (2022) performed an experiment on 27 Song Sparrows (*Melospiza melodia*) and looked at how noise pollution affected their vigilant behaviours. Roadway traffic noises were played in a room and sound levels were played

at 55, 61, and 68 dbA. Their results showed an increase in vigilance and a decrease in foraging behaviour with increasing noise levels. Similarly, in this study vigilant behaviours increased in areas of increasing noise pollution levels. Environments with high noise level can interfere with auditory signals such as alarm calls approaching predators, causing birds to have to increase their vigilant behaviours to better detect potential threats (Sweet et al., 2022). Indeed, these findings were supported by the callback experiment. The callback experiment indicated that higher anthropogenic noise levels resulted in a decrease in the birds' ability to respond to predators. When hawk or coyote calls were played during behavioural observation periods, birds were less likely to exhibit anti-predator behaviour when located in areas of higher noise pollution. Based on these results, the experimental predator calls were likely masked by increased noise pollution; the birds did not appear to detect the predator calls and therefore, did not display any anti-predator behaviours in response. No control sound (i.e. non-predator) was played.

Anti-predator behaviours were also affected by nest, habitat, and human activity rates. Environmental characteristics such nest concealment have been shown to affect nest success in passerines such as the White-crested Elaenia (*Elaenia albiceps*) in Patagonian temperate forests (Vazquez et al., 2021), therefore, vigilance is likely to increase in areas where nests are more open and easier to find for predators. In my study, vigilance increased as nest and tree height increased (high RC1). This makes sense as higher trees can allow for nests to be built higher, and higher nests may be more exposed

to avian predators (Colombelli-Négrel & Kleindorfer, 2009). Vigilance decreased in areas where nests were located closer to the trunk (high RC2). Nests located closer to the trunk could provide greater concealment, and greater concealment protect birds from predation allowing them to decrease their vigilance (Colombelli-Négrel & Kleindorfer, 2009). Vigilance also decreased in areas with less trees (low RC2). Areas with less trees could be located closer to areas where less predators are present (roads), or that the trees are larger allowing for less space to have too many trees. Areas where trees were larger (high RC3) had lower vigilance, probably due to the fact that larger trees will have greater canopy cover and greater concealment. Lastly, areas with more bushes showed less vigilance (high RC4). A study on the Superb Fairy-wren (*Malurus cyaneus*) in four conservation parks in South Australia found that nest height and concealment played key roles in nest predation (Colombelli-Négrel & Kleindorfer, 2009). Nests that were better concealed were less visible to predators relying on visual cues, therefore reducing predation risk (Colombelli-Négrel & Kleindorfer, 2009). This suggests that robins nesting in more concealed locations would exhibit lower vigilance, as they would be better concealed from predators compared to those in more exposed nests.

Surprisingly, my results showed a decrease in antipredator behaviours when human activity was higher. One potential explanation for this result is that increasing human activity could scare predators away. Additionally, areas with increasing human activity are usually closer to human infrastructure (roads, buildings, playgrounds) and therefore larger predators will be less likely to approach these areas (Chace & Walsh,

2006). Research has shown that human activity increases vigilance in non-urban birds (Xu et al., 2020). A study in urban and rural areas of the Katmandu Valley, Nepal found that FID of 33 species was shorter for urban birds (Nepali et al., 2024). Urban birds may therefore be more used to seeing humans and are able to tell predators and humans apart. This could lead to decreased vigilance in areas of high human activity.

In all models describing variation in anti-predator behaviour, nest stage was an important factor, with the incubation stage showing increased rates of anti-predator behaviours. In this study, more anti-predator behaviours were noticed during the incubation stage likely because the incubating female was on the nest for longer periods during incubation as opposed to the nestling period.

In conclusion, this study provides valuable insights into the effects of light and noise pollution on anti-predator behaviours and daily nest survival of American Robins. Even though no direct impacts of light or noise were detected on nest survival, light and noise pollution were both important predictors of increased vigilant behaviours in robins. High noise pollution possibly masked predator calls, interfering with the robins' ability to hear and respond to predator calls. Indeed, to my knowledge, this study is one of the first field studies to document the effects of light and noise on anti-predator behaviours of an urban nesting passerine. Future research should explore the potential cumulative effects of both light and noise pollution over longer periods across different seasons and life stages of other urban nesting birds so to greater insights into the long-term impacts of urbanization on bird behaviour.

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