Pied tamarins change their vocal behavior in response to noise levels in the largest city in the Amazon

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Short title: Pied tamarin responses to anthropogenic noise

Abstract

Many animal species depend on sound to communicate with conspecifics. However, human-generated (anthropogenic) noise may mask acoustic signals and so disrupt behavior. Animals may use various strategies to circumvent this, including shifts in the timing of vocal activity and changes to the acoustic parameters of their calls. We tested whether pied tamarins (*Saguinus bicolor*) adjust their vocal behavior in response to city noise. We predicted that both the probability of occurrence and the number of long calls would increase in response to anthropogenic noise and that pied tamarins would temporally shift their vocal activity to avoid noisier periods. At a finer scale, we anticipated that the temporal parameters of tamarin calls (e.g., call duration and syllable repetition rate) would increase with noise amplitude. We collected information on the acoustic environment and the emission of long calls in nine wild pied tamarin groups in Manaus, Brazil. We found that the probability of long-call occurrence increased with higher levels of anthropogenic noise, though the number of long calls did not. The number of long calls was related to the time of day and the distance from home range borders - a proxy for the distance to neighboring groups. Neither long-call occurrence nor call rate was related to noise levels at different times of day. We found that pied tamarins decreased their syllable repetition rate in response to anthropogenic noise. Long calls are important for group cohesion and intergroup communication. Thus, it is possible that the tamarins emit one long call with lower syllable repetition, which might facilitate signal reception. The occurrence and quantity of pied tamarin' long calls, as well as their acoustic proprieties, seem to be governed by anthropogenic noise, time of the day and social mechanisms such as proximity to neighbouring groups.

Keywords: sound pollution, soundscape, urban ecology, primates, Amazon, *Saguinus bicolor*

Abbreviations

IUCN International Union for conservation of Nature
INMET Brazilian Institute for Meteorology
HR Home Range
DFT Discrete Fourier Transform
SISBIO/MMA (System in Biodiversity/ Ministry of Environment)

Introduction

Many animal species, especially those that live in social groups, depend on sound to communicate with conspecifics. Vocal communication is used to transmit information concerning essential social behaviors, such as cooperatively foraging for high quality food resources (Caine et al., 1995), defense against predators (Kirchhof & Hammerschmidt, 2006), territorial activities (Sobroza, Gordo, Barnett, et al., 2021), group cohesion (Kondo & Watanabe, 2009), assessment of competition (Benítez et al., 2017), and reproduction (Duarte et al., 2011). All these activities can be disrupted in noisy environments, via the masking of acoustic signals and/or the distraction of producers and receivers (Aaden et al., 2011; Allen et al., 2021; Brumm & Slabbekoorn, 2005; Buxton et al., 2020; Grabarczyk & Gill, 2019; Huet des Aunay et al., 2017). In recent decades, anthropogenic noise has increased worldwide, imposing new selective pressures on wildlife (Sih et al., 2011; Slabbekoorn et al., 2010; Swaddle et al., 2015). Responses to such disturbances have been reported across ecological scales, from individuals to populations, communities and cross-species interactions (Barbosa et al., 2020; Hubert et al., 2018; Slabbekoorn & Halfwerk, 2009; Soudijn et al., 2020).

Animals may use various strategies to avoid or reduce noise impacts (Brumm et al., 2004; Brumm & Slabbekoorn, 2005). Temporal displacement of vocal activity is a possible response to anthropogenic noise. For instance, a variety of bird species are known to shift the timing of their vocal activity from day to night as noise increases (Fuller et al., 2007; Gil et al., 2015). Such species naturally have peaks and troughs of vocal activity throughout the day, which may be related to social behavior as well as optimizing acoustic transmissibility (Pérez-Granados & Schuchmann, 2021; Waser & Brown, 1984). Such vocal activity peaks may also be timed to avoid overlap with periods when other species emit sounds (i.e., the acoustic niche hypothesis; Schneider et al., 2008). However, such diel patterns may also alter due to anthropogenic noise (Sierro et al., 2017).

At a finer scale, some species also change the acoustic parameters of their calls, including frequency, time and amplitude (Brumm & Slabbekoorn, 2005). Doing this can potentially avoid obscuring spectral features and so enhance signal-to-noise ratio and signal audibility (Brumm & Slabbekoorn, 2005; Slabbekoorn & Peet, 2003). It has been suggested that some species may emit higher pitched calls to avoid spectral overlap with anthropogenic noise (Brumm & Bee, 2016; Roca et al., 2016; Slabbekoorn & Peet, 2003), as this often (though not always) has more energy at lower frequencies (Alquezar & Macedo, 2019; Caorsi et al., 2019; Gill et al., 2015). Such trends may be reversed when sound levels are extremely loud, and animal hearing is impaired (Wolfenden et al., 2019). In such cases, some animals, such as birds, find it difficult to detect higher frequencies and so may stop producing them largely or entirely; consequently, their calls become dominated by lower frequencies (Wolfenden et al., 2019). When facing intense noises, some fish and primate species also increase call duration and rate to increase detectability by the receptor (Brumm et al., 2004; Egnor et al., 2007; Picciulin et al., 2012; Santos et al., 2017). In contrast, other studies show that individuals cease calling when they are unlikely to be heard, presumably as a means of minimizing energy expenditure (Duarte et al., 2019; Kaiser et al., 2011).

Primates are ecologically important in tropical forests, especially because of their roles in seed dispersal and associated ecological processes such as forest regeneration and carbon storage (Fuzessy et al., 2016, 2021; Heymann et al., 2019; Peres et al., 2016). However, many primates are also threated by urbanization and its consequences, such as the risk of being run over by cars, attacked by domestic animals, electrocuted by power-lines, and by increased risks of disease transmission (Thatcher et al., 2023). Additional, indirect, threats, such as that of anthropogenic noise, may also play an important role in their daily lives. For instance, Black-tufted marmosets (*Callithrix penicillata*) prefer to use silent areas of their home ranges, even if they contain fewer food resources (Duarte et al., 2011). Black-fronted titi monkeys (*Callicebus nigrifrons*) residing in noisy areas near active mines, often reduce and change their daily patterns of vocal activity (Duarte et al., 2018). In contrast, Bolivian grey titi monkeys (*Plecturocebus donacophilus*) appear to be resilient to aural disturbance, and do not change their general activity budget or movement patterns in response to anthropogenic noise (Lineros et al. 2020). Therefore, primate behavioral responses towards anthropogenic noise appear to be predominantly species-specific.

Many primate species produce long distance calls (often termed “long calls”), that are usually high amplitude and often have multiple functions, including maintenance of group cohesion, delimiting territories, notification of food availability and mate defense (Dolotovskaya & Heymann, 2022; Hopkins, 2013; Snowdon, 2017; Wich & Nunn, 2002). For example, in southern brown howler monkeys (*Alouatta guariba*) vocalizations play an important role in intergroup competition, and long call emission tends to be spatially structured, with animals roaring more often at territorial boundaries (Da Cunha & Jalles-

Filho, 2007). However, long calls may also be important during intergroup encounters, as they can provide information on numerical odds (Kitchen, 2004).

Callitrichids are known for their intense vocal activity (Snowdon, 2001), they typically call when further apart (>15 m), but vocalization is also linked with interactions with extra-group individuals and intergroup encounters (Caselli et al., 2018; Snowdon, 2001). Nevertheless, such activity is also temporally structured, with animals calling more in the morning (Heymann, 1990; Norconk, 1990). Despite the importance of long calls to primate species, our knowledge of how, in the wild, their deployment is adjusted in response to anthropogenic noise, is limited (Duarte et al., 2011, 2018; Gómez-Espinosa et al., 2022; Lineros et al., 2020; Santos et al., 2017).

Pied tamarins (*Saguinus bicolor)* are Amazonian callitrichids with a highly restricted geographic range encompassing a total of just 7,500 km², much of which occurs in urban and peri-urban areas of Manaus, the largest city in the Brazilian Amazon (Gordo et al., 2013, 2017). Urbanization has restricted individual groups to isolated forest fragments, and these are surrounded by a noisy urban matrix (Gordo et al., 2013). Mainly due to fragmentation and its consequences (e.g., road-kill, electrocution, and attacks from domestic animals), the species is considered Critically Endangered by the IUCN (Gordo et al., 2019). The species has 12 identified call types in its vocal repertoire, which includes long calls (Sobroza et al. 2017). Pied tamarin long calls are signals composed of variable number of syllables (not more than 8) with a ∩−shaped spectral signature and relatively constant interval between syllables (Sobroza, Gordo, Pequeno, Dunn, et al., 2021a). They are emitted during inter- and intra-group interactions, such as territorial defense, group movement and cohesion (Sobroza et al., 2017; Sobroza, Gordo, Pequeno, Dunn, et al., 2021a). While noise levels in captivity are known to have a low impact on pied tamarins feeding and vigilance behavior (Steinbrecher et al. 2023), little is known about the impact of noise on pied tamarin vocal behavior in the wild.

The current study aimed to evaluate whether pied tamarins alter their communication behavior in response to urban noise. For this, we followed nine wild pied tamarin groups from urban and peri-urban areas and assessed whether their vocal behavior was related to variation in anthropogenic noise (Brumm & Slater, 2006; Deoniziak & Osiejuk, 2016). When faced with high intensity noises, some animals cease calling (Vargas-Salinas & Amézquita, 2014). Therefore, we analysed both long call occurrence, i.e. decisions of individual animals to call or not (binary data) and the number of long calls (count data) separately. We predicted that both the occurrence and number of long calls would increase with an increase in anthropogenic noise, such that signal content would become redundant and more likely to reach the receiver (Brumm & Slater, 2006; Deoniziak & Osiejuk, 2016). We also predicted that long call occurrence and the number of long calls would increase in response to increased noise levels. Many primate species have a peak of vocal activity in the morning (do Nascimento et al., 2021; Ravaglia et al., 2023), though, we predicted that pied tamarins would shift such a pattern to avoid the noisiest periods of the day. At a finer scale, we tested whether temporal parameters of the acoustic features of the tamarin long calls (duration and syllable repetition rate) would increase with noise amplitude. At the same time, we predicted that the dominant and lowest frequencies would remain similar, as pied tamarin long calls are high-pitched, ranging from 6 to 9 kHz (Sobroza et al., 2017), and in primates frequency features are expected to be less likely to be modulated than temporal features (Janik & Slater, 1997).

Methods

Study area

The current study was conducted in the central Brazilian Amazon, in the city of Manaus, Amazonas State, Brazil (Figure 1). Manaus is an industrial city that has expanded in a disorderly and poorly-regulated way since the 1970s (Coelho et al., 2018). Consequently, while the city houses more than 2-million people, it also contains over 900 forest fragments of different shapes and sizes (Coelho et al., 2018). The average temperature during the sampling period was 27.7 Cº (SD= ± 2.6), and average relative air humidity was 73.27% (SD = ± 13.94) (Brazilian Institute for Meteorology INMET- station A101). The distance from the sampling areas to the meteorology station varied from 3.04 to 14.71 km (mean = 4.98, SD = ± 4.33). Our study sites comprised five forest fragments ranging from 24 to ~700 ha managed by different organizations (private, municipal, state, and federal - including one military area). The fragments have been isolated for between 30 and 68 years (Gontijo, 2008), and each is surrounded by asphalted roads. Nine groups of pied tamarins were followed in five forest fragments of the city of Manaus and one in a continuous forest area at the city's periphery (Table 1) (Figure 1).

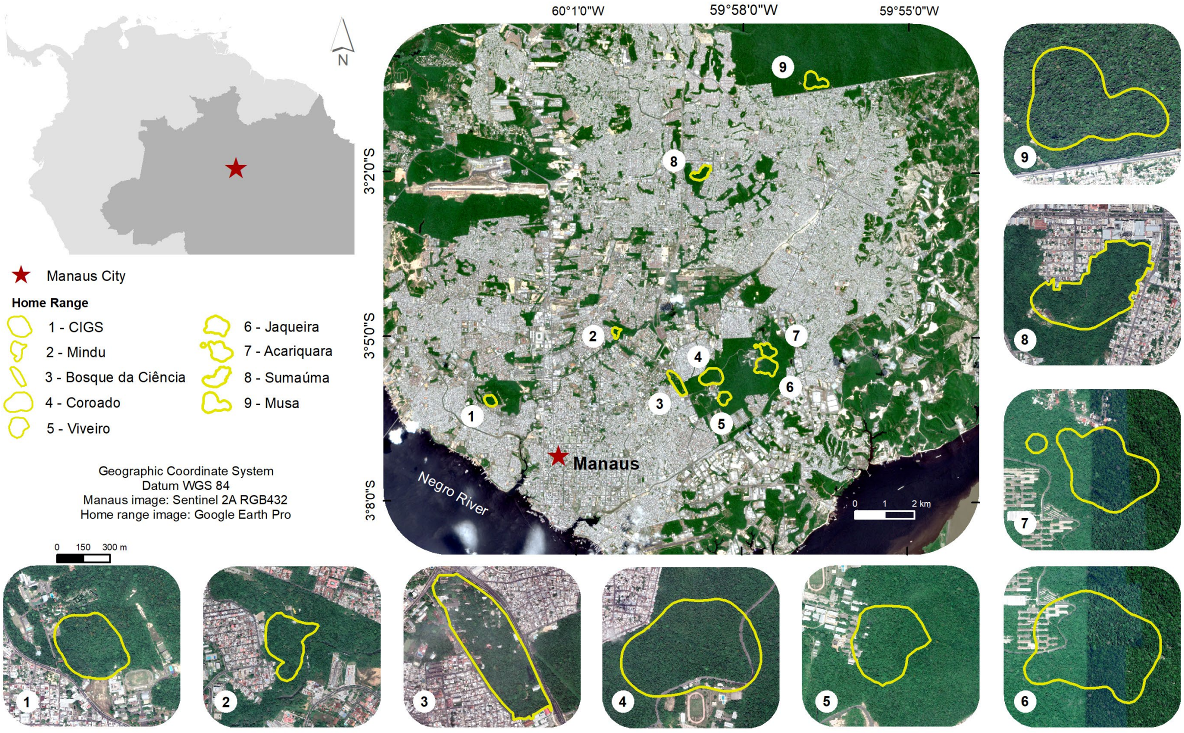

Figure 1. Locations (large maps) and shapes (small maps) of home ranges of pied tamarin (*Saguinus bicolor*) groups (1-9) followed in the urban area of Manaus, Brazil (larger map) from November 2018 to December 2019.

Subject and capture protocols

Data were collected between November 2018 and December 2019. We followed nine pied tamarin groups (Table 1), using radio-telemetry in seven groups to facilitate location and monitoring. The other two groups were well-habituated to humans and so could be followed without radio-telemetry. For those where radio-telemetry was used, we captured whole groups (Lagroteria et al., 2017; Sobroza et al., 2017) and attached a SOM 2380 transmitter (Wildlife Materials, US) to the alpha female of each group, as such individuals are highly philopatric (Gordo, unpublished data). Each attached transmitter emitted a different frequency (across a range from 164.00-164.99 MHz), and these were detected with a two (H) or three (Yagi) element antenna and an ATS® receptor (164-168 MHz). The success of group detection varied when using two or three-element antenna, which relate to different number of behavioral bouts recorded across groups (Table 1). Groups were captured seven days before data collection for research covering three independent projects: two related to pied tamarin health (Chaves et al., 2022) and the current behavioral study.

Data collection

A researcher and a field assistant followed each group for 10 consecutive days from ~ 06:30-17:00, the main period of pied tamarin activity (Egler, 1986). Pied tamarins sleep relatively early, ~15:30-16:00 (Gordo et al. 2017), possibly as an anti-predatory strategy (Caine, 1987). Thus, when around this time ~~if~~ we noticed that the study group selected a tree and remained in the same place for at least 40 minutes, we stopped the data collection for the day. In the field, we collected vocal data during five-minute behavioral bouts followed by five-minute intervals (Martin & Bateson, 1993). During each such bout we registered whether long calls occurred or not (one or zero) and aurally quantified the number of long calls emitted by all group members during the sampling bout. We also recorded the group's location via GPS (GPSMap 78s) and estimated noise levels (Figure 2).

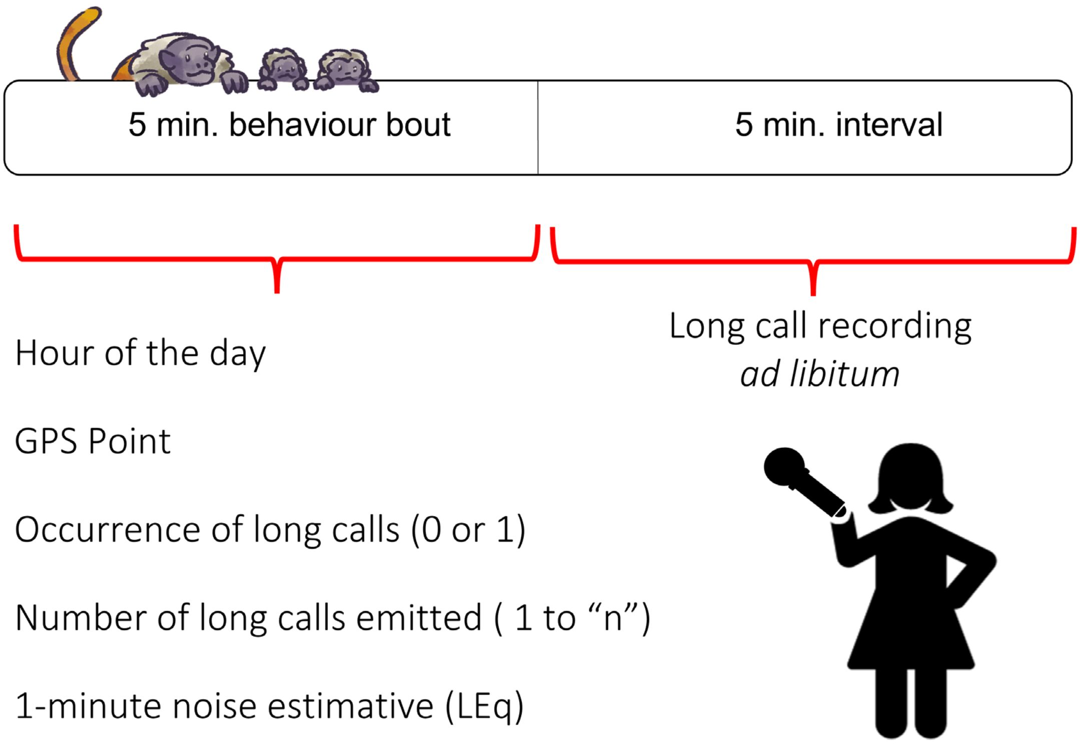

Figure 2 Sampling scheme showing the nature of data collected during 5- minute5-min behavioral bouts and intervals between bouts. Each pied tamarin group was followed for 10 consecutive days from 6:00 a.m. to ~ 5:00 p.m. We recorded a total of 1953 bouts from nine pied tamarin groups (Table 1). Within these, 472 bouts had at least one long call.

During each of these 5-minute sampling bouts, we also took a 1-minute sample of noise amplitude by calculating the equivalent continuous sound levels (LEeq) with a C weighting (dbC) that is appropriate for recording low-frequency sound. The LEq is a time-averaged sound level that, in this survey, was estimated based on sound pressure levels assessed every second during the 1-minute readings of a calibrated CEL-246 sound level meter (Casela Solutions).

After the end of the 10 day group-following period, we estimated the home range (HR) boundaries via the sum of all the GPS points recorded. To do so, we used a kernel density estimator with a reference smooth parameter for all groups (Worton, 1989). We defined HR as the area in which 95% of the points were found (Anderson, 1982). To estimate HR limits, we used the *adehabitatHR* package (Calenge, 2018) in R (R Development Core Team 2020). We estimated the HR limits only to assess the distances from each point to the polygon of HR boundaries (a proxy for the distance to neighbouring groups). To estimate such distances, we used the *Near* function from ArcMap 10.5.

Acoustic analysis

During the five-minute intervals between behavioural bouts we recorded pied tamarin long calls *ad libitum* (Figure 2) for subsequent acoustic analysis. Recordings were not made continuously during these five minutes, as we chose the more appropriate moments to record (i.e. shorter distances between the animals and the recorder and lower background noise). We recorded the calls as .wav files using a Sennheiser-ME67 microphone (microphone frequency response: 1-16.0 kHz), attached to a Zoom H4N recorder (16-bit, sampling rate = 44 kHz). Since we did not estimate noise levels during the intervals that we recorded the calls (see Figure 2), we considered the noise levels estimated from the five-minute bout prior to the long calls recorded in the subsequent five-minute interval. We analyzed the long calls using Raven 1.6 (Bioacoustics, 2019). For each call, we analyzed four acoustic parameters: dominant frequency, lowest frequency, duration and syllable repetition rate (number of syllables divided by call duration). Using Raven, we estimated the parameters from the first (fundamental) harmonic, using the *power spectra* tool to select only high-quality sounds and avoid biased estimates (Zollinger et al., 2012) via a -20 dB cut-off relative to the frequency with maximum energy (Podos, 1997). After such filtering, 520 calls remained for analysis. We distinguished consecutive long calls based on amplitude and general pattern of increasing syllable duration and clearer ∩−shape definition as the call reached its end. Only non-overlapping long calls were used for acoustic analysis. Spectrograms were built with the following configuration: DFT size = 1024 samples, overlap = 80%, window size = 20 ms, window type = *Blackmann*.

Statistical analysis

To test whether the occurrence of tamarin long calls was related to anthropogenic noise and time of day, we used Generalised Linear Mixed Models (GLMM) (Zuur et al., 2009). In the first analysis, each behavioral bout was the sampling unit (Figure 2), and the occurrence of long calls was the response variable (1 = occurred; 0 = did not occur) (N=1953), assuming binomial errors and a logit link. We used 1-minute sound level estimate and time of day as predictors. Because the occurrence of long calls may be related to other social aspects of intra- and inter-group communication (Snowdon 2001), we also included group size and distance from the border of their home ranges (a proxy for proximity to neighbouring groups) as predictors. We included fragment and group identity as random factors to control for non-independence between observations of the same group, differences in sampling sizes (Table 1), and any fragment-level variation (for instance differences in fragment size and resource availability). Initially, we included an interaction factor between sound level and time of day to evaluate whether tamarins altered their vocal activity throughout the day in response to sound level variation. As this interaction term was statistically non-significant ($p>0.1$) we removed it and reran the model (Table S1). The procedure of removing interaction terms from linear models is recommended when the interaction is not significant, since misinterpretation of the effect of other variables might otherwise occur (Engqvist, 2005).

We also used a GLMM with the same predictors to test whether the number of long calls was related to anthropogenic noise, time of the day, and social aspects (e.g. group size and proximity to neighbouring groups). As before, we initially included an interaction factor between sound level and hour of the day to evaluate whether pied tamarins alter their vocal activity during daylight hours. Once again, the interaction term was not statistically significant ($p>0.1$), so we removed it and re-ran the model. For this analysis, we used a subset of behavioral bouts that contained at least one long call ($N=472$) as sampling units. For this model, we used a negative binomial distribution with log link (Zuur et al., 2009) (Table S1).

To test whether pied tamarin long call acoustic features changed in response to anthropogenic noise, we used a GLMM for each of the acoustic parameters. In this case, each long call was used as a sampling unit ($N=520$), and the response variables were dominant frequency, lowest frequency, duration, and syllable repetition rate. For all models, we used the 1-minute sound level as predictor, and fragment and group identity as random factors. We used normal distributions with identity links for all models related to acoustic features, except for “syllable repetition rate”, for which we used the Gamma distribution with log link function. All analyses used the *lme4* and *visreg* packages (Bates et al., 2015; Breheny & Burchett, 2017) in R version 3.5 (R Core Team, 2018). Residuals were checked using *DHARMAa* package (Hartig, 2020), multicollinearity and conditional R^2 was tested and estimated with the *performance* package (Lüdecke et al., 2021). A column showing overall sample sizes and sampling effort for each followed group appears in Table 1. For the different response variables, we had different sampling units, as follows: 1) long call occurrence: sampling unit = behavioral bout; 2) number of long calls: sampling unit = behavioral bout with at least one long call; 3) long call acoustic features (i.e. frequency, duration, syllable repetition rate): sampling unit = recorded long call of sufficient quality to allow analysis.

Ethical approval

The research was approved by the Ethical Committee of the Instituto Nacional de Pesquisas da Amazônia (SEI.01280.00900\2018-58). SISBIO/MMA (Ministry of Environment) granted us the necessary licenses to capture, anesthetize, manipulate, mark, and release the study animals (N. 60347-1). Appropriate permissions were also obtained to access the parks and military areas surveyed. The study was in accordance with ethical standards from the American Society of Primatologists Code of Best Practices for Field Primatology.

Results

The average noise in all sampled areas was 59.19 dB (SD = 5.9) with a standard deviation of 5.54 dB throughout the day (Figure 3), ranging from a minimum of 40.2 dB to a maximum of 84.8 dB. The most common anthropogenic noise source in all areas was road traffic. However, there was also air traffic, park visitors, the talking, screaming, and singing of children and university students, and gunshots from military training activities. Further acoustic sources included biotic sounds such as bird, frogs, and insects. There was some difference in noise distribution across studied groups, although variation across the day was not extensive (Figure 3).

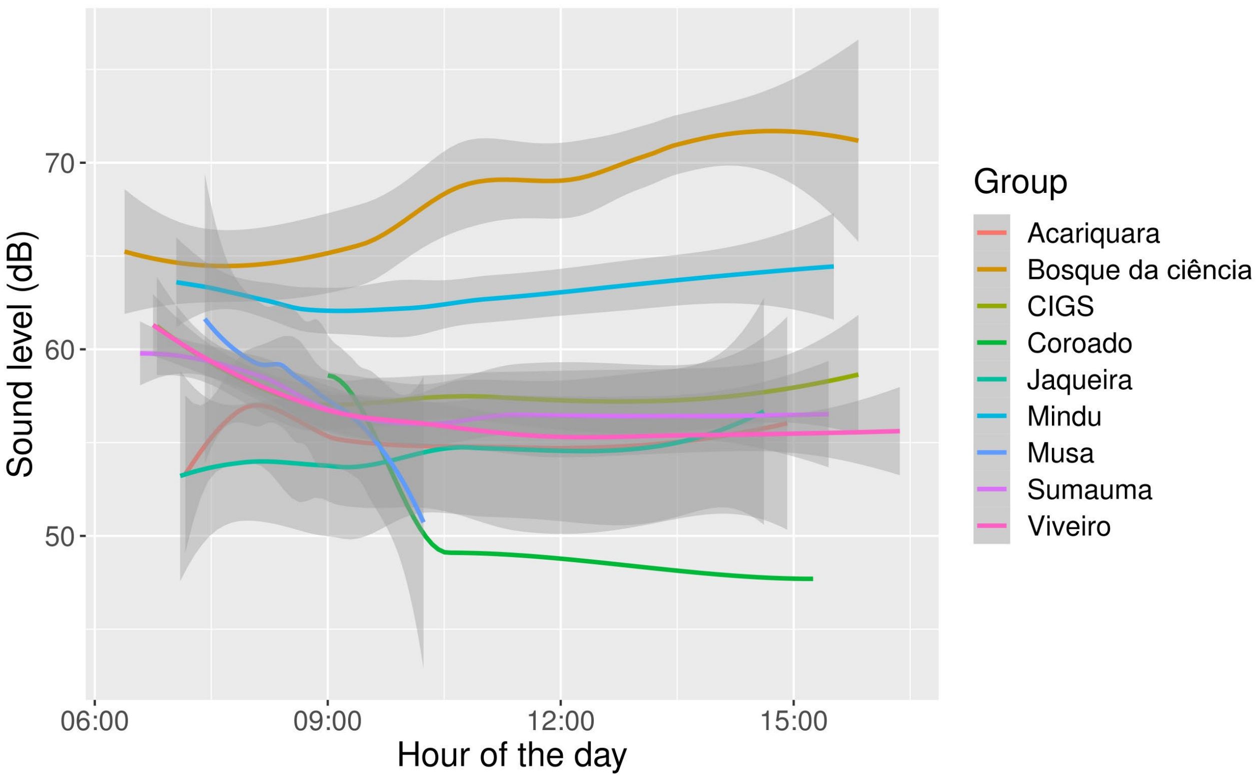

Figure 3 Variation in noise levels throughout the day in areas occupied by different pied tamarin (*Saguinus bicolor*) groups. Estimates based on 1953 noise estimates of 1 -min duration.

Long-call occurrence (binary data)

We analyzed the probability of animals calling or not. We found that the occurrence of long calls was positively related to anthropogenic noise and group size, and negatively related to the time of day (Figure. 4), while the distance from the border of the group home ranges had no detectable effect on long call occurrence probability (Table 2). The occurrence of long calls was also related to group size and time of day, but not the interaction between time of the day and anthropogenic noise (Table 2; Table S1) (Figure .4) (Table S1).

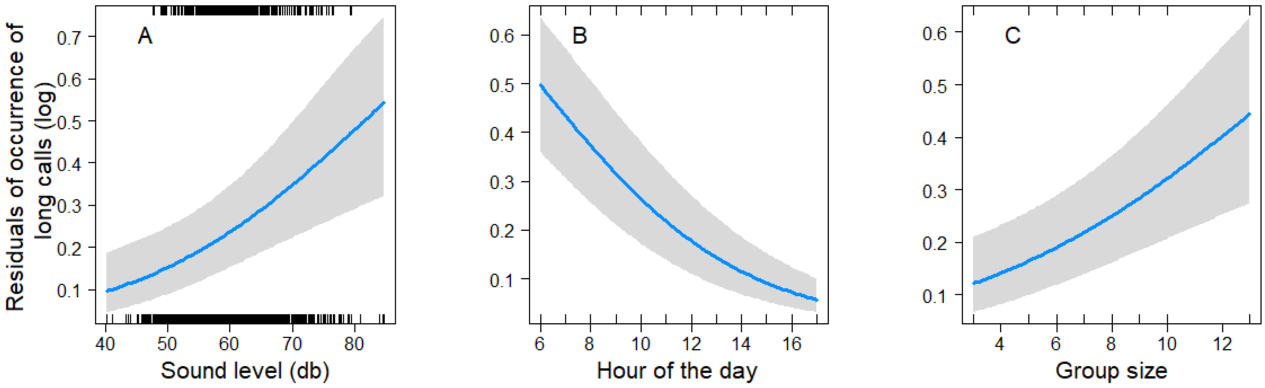

Figure 4 Relation between occurrence of pied tamarin (*Saguinus bicolor*) long calls (1 = *long call occurred*; 0 = *long call did not occur*) and (a) sound levels (dB), (b) hour of the day, and (c) group size (N = 1953). Lines represent predicted means for each group of observations from the models presented in Table 2. Plots use partial residuals of the response variable and show the effect of a given relation while controlling for the effects of remaining predictors.

Number of long calls (count data)

The number of long calls per behavioral bout varied from 1 to 66. Such variation was not related to anthropogenic noise (Table 2). In contrast, distance from the border of group home ranges influenced the number of long calls — pied tamarins called more when distances to neighboring groups were shorter (Figure 5). The number of long calls was also related to the time of day, with pied tamarins calling more in the early morning, though this was independent of anthropogenic noise levels or group size (Table 2; Table S1) (Figure 5).

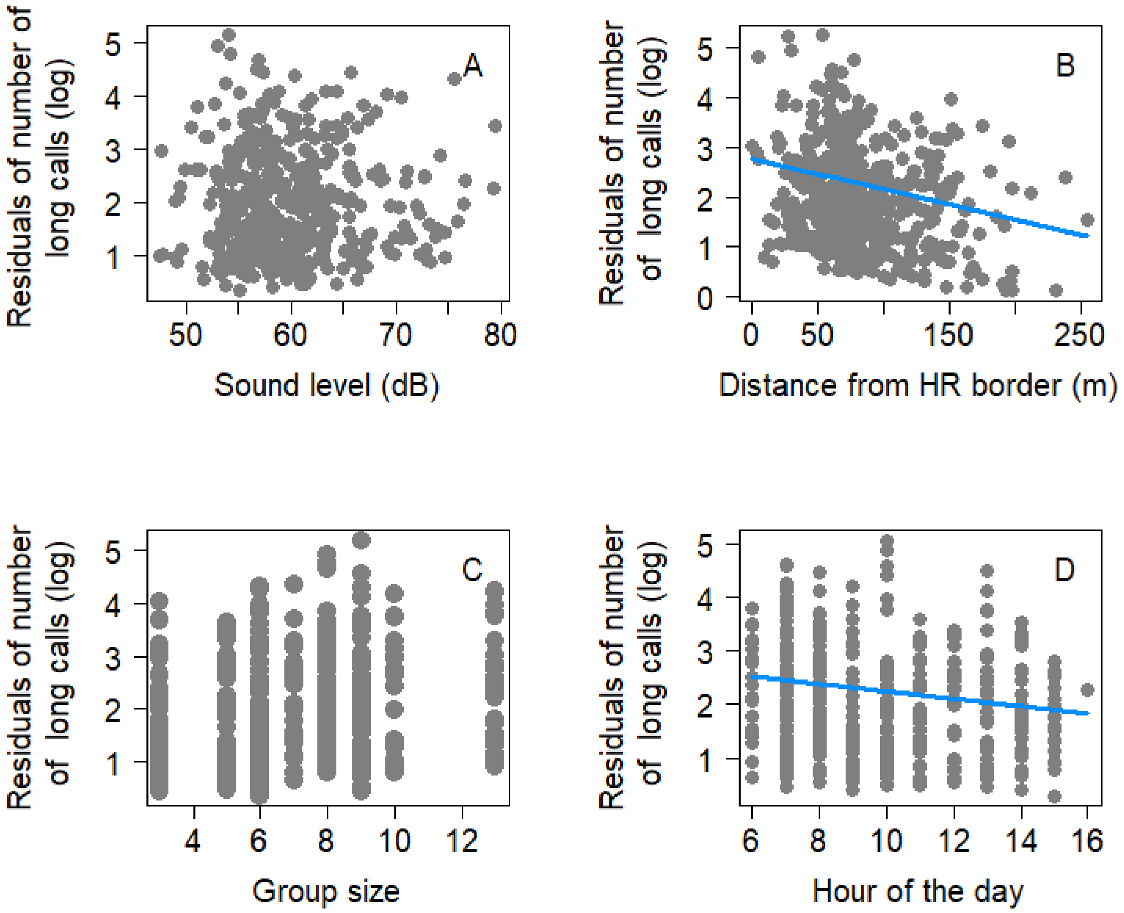

Figure 5 Relationships between the number of pied tamarin (Saguinus bicolor) long calls and: (a) sound level; (b) distance from home range border; (c) group size, and (d) hour of the day. Each point represents a behavioral bout with at least one long call (N = 472). Lines represent predicted means for each group of observations from the models presented at Table 2. Plots use partial residuals of the response variable and show the effect of a given relationship while controlling for the effects of the remaining predictors. The tendency line is shown only for significative relationships.

Long call acoustic features

The lowest and dominant frequency of pied tamarin long calls did not change in response to anthropogenic noise levels. Similarly, long call duration did not alter in response to anthropogenic sound levels. Syllable repetition rate, on the other hand, decreased as anthropogenic noise increased (Table 3) (Figure 6).

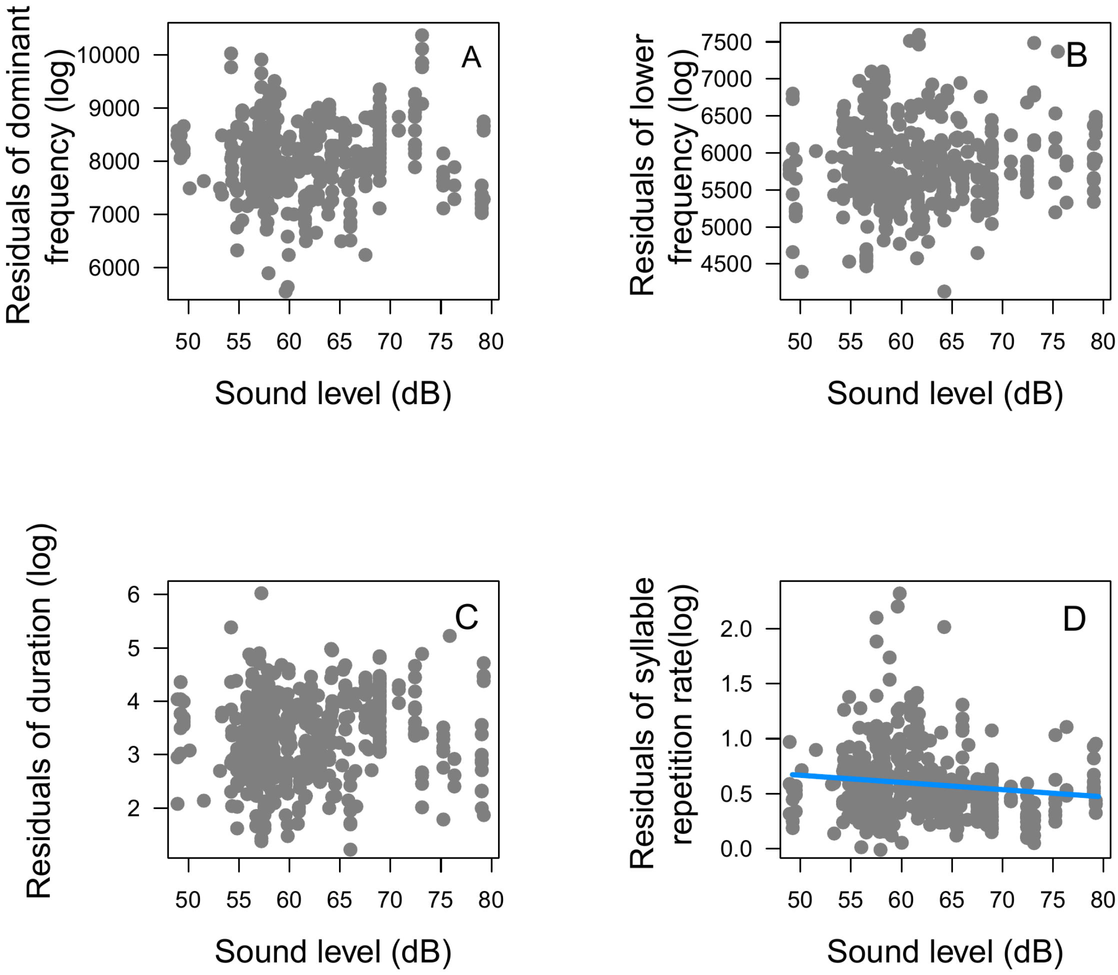

Figure 6 Relationship between frequency (a,b) and temporal (c,d) acoustic features of pied tamarin (*Saguinus bicolor*) long calls and sound level (dB). Each point represents a long call recording (N = 520). Lines represent predicted means for each group of observations from the models presented in Table 3. Plots use partial residuals of the response variable and show the effect of a given relationship while controlling for the effects of the remaining predictors. The tendency line is shown only for the significative relationship.

Discussion

We found that the occurrence and number of long calls emitted by pied tamarins in urban areas are affected by anthropogenic noise levels, time of day, and distance from neighboring groups. However, pied tamarins did not alter their diel vocal activity across the day in response to anthropogenic noise (Table S1). Patterns of daily vocal activity were independent of sound levels, with individuals calling most often early in the morning. Even if pied tamarins did not change the temporal pattern of daily calling activity in response to anthropogenic noise, fine-scale timing of signalling was influenced by sound level, with pied tamarins calling with a slower syllable repetition rate in noisier areas. Other pied tamarin acoustic features, such as dominant frequency, lowest frequency and long call duration did not change in response to anthropogenic noise.

In the current study, we found an average noise of ~59 dB in areas occupied by pied tamarins. For humans, 50-60 dB causes from moderate to serious annoyance (Guski et al., 2017). Unfortunately, we do not have estimates of parameters such as “annoyance” for non-human primates. What is considered “noise” may also depend on a species’ hearing capacities (Clark & Dunn, 2022) and pied tamarin audiograms are currently unavailable. Even though we lack such clearcut values to establish what constitutes noise for pied tamarins, we found that when sound levels were relatively higher, the probability of pied tamarins emitting a long call increased. Since long calls are used for group cohesion and may also help in navigation (Fischer & Zinner, 2011; Snowdon, 2017), it may be that when sound levels surpass a threshold, pied tamarins move to quieter areas. Many studies have shown that loud noises can induce escape responses that influence patterns of both short- and long-range movements, such as the use of space, dispersion, and migration (Duarte et al., 2011; Neo et al., 2014; Tennessen et al., 2014; Velasquez Jimenez et al., 2020; Ware et al., 2015). However, this hypothesis remains to be tested for pied tamarins.

Contrary to our predictions, we found no association between the number of pied tamarin long calls and anthropogenic noise levels (Williams et al., 2014). When facing intense noise, pied tamarins do not necessarily call more, likely because this could lead to additional energy expenditure and increase predation risk. Other strategies, such as changes in syllable repetition rate (see below), and complimenting their communication with other communication channels, including olfaction (Sobroza et al. 2023), could be sufficient to circumvent the deleterious effects of increased noise (Bejder et al., 2009). In noisier places, the pied tamarins’ long calls had reduced syllable repetition rates, meaning that they emitted slower long calls, with either time between syllables being longer or the syllables themselves being more prolonged. A longer inter-syllable duration could allow pied tamarins to call during short periods when noise levels were reduced, a feature also observed with captive cotton-top tamarins (*Saguinus oedipus*) and common marmosets (*Callithrix jacchus*) that called between bursts of loud noises (Egnor et al., 2007; Roy et al., 2011). If in pied tamarins, the syllables function as a unit of information, as in cotton-top tamarins (Miller et al., 2003), and the lower syllable repetition rate implies that the syllables are longer, this could also be advantageous as longer signals would have more chance to reach the receiver.

As predicted, we did not find a difference in frequency features of long calls in response to sound levels, possibly because pied tamarins sounds are already high-pitched (Sobroza et al., 2017). This is different from the situation described for other callitrichids which modulate frequency features rapidly (Zhao et al., 2019). Analysis of the frequency contours of each syllable in relation to the spectral composition of background noise could be instructive in this context. Also, many species increase the amplitude of their calls (Lombard effect) to boost the signal-to-noise ratio and enhance signal transmission capacity (Brumm & Zollinger, 2011). We did not analyze amplitude because it requires different field techniques (Zollinger et al., 2012). However, this is a strategy widely used by wildlife in response to noise (Brumm & Zollinger, 2011) and pied tamarins could well be using this too.

Our data also did not corroborate the hypothesis that pied tamarins alter their daily vocal activity in response to anthropogenic noise. However, individuals of this species vocalize more during the morning, which is also a widespread pattern among birds and primate species (Schneider et al., 2008; Van Belle et al., 2013), supposedly because temperature, humidity and wind conditions are generally more favorable to sound propagation at this time (Waser & Brown, 1984). However, these propagation capacities are usually tested in pristine areas, and the distinct microclimate and the ubiquity of planar surfaces in urban areas could cause subtle changes to acoustic propagation (Slabbekoorn et al., 2007). An alternative hypothesis for the peaking of vocal activity during the morning relies on pied tamarin diel behavior: individuals usually enter their sleeping sites relatively early in the afternoon (~15:30 -16:00) and begin their daily activities around 05:30 (Egler, 1986; Gordo et al., 2017). After more than 12 hours of resting, individuals must be hungry, and long calls could be important to coordinate the group when searching for fruits.

We also found that social aspects are important predictors for the occurrence and number of long calls. As expected, we found that the occurrence of long calls was related to group size, and there was no evidence of a correlation between group size and the number of long calls. Such a finding is in accordance with a previous pied tamarin playback study which showed that, unlike other group-living animals (Kitchen, 2004; Van Belle & Scarry, 2015), larger groups of pied tamarins do not emit more long calls when exposed to conspecific long calls (Sobroza, Gordo, Barnett, et al., 2021). We recognize that our sampling size is relatively small as each group had a different number of individuals (Table 1). However, in our study, we included group identity as a random factor in the model to account for the non-independence of observations. We also found a negative relationship between the number of long calls and the distance from home range boundaries. This result matches findings from other territorial species that patrol their territories regularly; signalling occurs more at territorial boundaries (Da Cunha & Jalles-Filho, 2007; Mitani & Watts, 2005). The models we proposed to evaluate effect of different predictors on the occurrence and number of long calls lacked explanatory power, accounting for only 18% to 21% of the data (Table 2). It is possible that other variables not included in the current study, such as distance between group members and resource availability, may have an important role and should be considered in future studies.

It is important to note that in our study, we characterized noise in terms of amplitude. However, noise is complex and variable in terms of spectral and temporal signatures (Clark & Dunn, 2022; Gill et al., 2015; Neo et al., 2014). Howler monkeys, for instance, respond more to aerial traffic than other human-produced noises (Gómez-Espinosa et al., 2022). This trend is possibly related to the nature of their low-pitched calls that coincide with the frequencies in which aerial traffic has the most energy. Perhaps, as high-pitched callers, pied tamarins would present a different pattern of response towards different noise categories with varying frequency profiles (Gómez-Espinosa et al., 2022). We did not directly evaluate the composition of the soundscape, thus our "noise" estimates include not only anthropophonies (i.e. sounds of anthropogenic origin), but also biophonies (i.e. sounds of biological origins, such as other animals calling or moving). For instance, cicadas are an important component in tropical soundscapes as their sounds can achieve very loud amplitudes, often occupy a large frequency band, and they can produce sounds for several minutes and even hours, affecting the overall use of the acoustic space (Aide et al., 2017). Future studies should consider the composition of noise, to disentangle the different impacts of amplitude vs. spectral and temporal features.

In summary, pied tamarins do not increase the long call rate in response to noise, but the occurrence of long calls is influenced by sound levels. As long calls are important for group cohesion during movement, it is possible that the tamarins emit a single call with a changed acoustic structure (i.e. lower syllable repetition rate and probably higher amplitude). Neither occurrence nor the number of long calls were altered to occur in quieter periods of the day, although, independent of sound levels, the emission of long calls is more likely to occur early in the morning. Further, the number of long calls was negatively related to the distance to home range boundaries. Overall, pied tamarins are likely to adjust their vocal behavior and call features in a way that could possibly allow for effective communication in urban settings. Which, from a long-term perspective, could enable this Critically Endangered species to continue surviving in the largest city in the Brazilian Amazon.

Author contributions

T.V. Sobroza, A.A. Barnett, M. Gordo and J.C. Dunn originally formulated the research topic. T.V. Sobroza raised funds, collected data, and wrote the original draft. B.M. Naissinger and T.V. Sobroza performed exploratory and current spatial analysis, P. Pequeno and T.V. Sobroza performed statistical analyses, A.A. Barnett, M. Gordo, and J.C. Dunn supervised. A.A. Barnett and J.C. Dunn checked the English. All authors contributed to the writing and reviewing.

Acknowledgements

We thank Caio Fábio Pereira, and colleagues from the Projeto Sauim-de-Coleira and Amazonian Mammals Research Group (AMRG) for logistical and field assistance. We also thank Dr. William Magnusson for reviewing early versions of the manuscript. During the study TVS received a scholarship from Fundação de Amparo à Pesquisa do Estado do

Amazonas (FAPEAM) (062.01758/2018). This study was supported by Casella Solutions, International Primatological Society, Idea Wild, National Geographic (EC-419R-18), Rufford Foundation (24762-1), and Margot Marsh Biodiversity (Foundation Primate Action Fund SMA-CCO-G0000000111).

Data availability statement

The data that support the findings of this study are available from the corresponding author upon request.

Conflict of interest

The authors declare no conflict of interest.

References

Aaden, A., Chan, Y.-H., & Blumstein, D. T. (2011). Attention, noise, and implications for wildlife conservation and management. *Applied Animal Behaviour Science*, *131*, 1–7. https://doi.org/10.1016/j.applanim.2011.01.007

Aide, T. M., Hernández-Serna, A., Campos-Cerqueira, M., Acevedo-Charry, O., & Deichmann, J. L. (2017). Species richness (of insects) drives the use of acoustic space in the tropics. *Remote Sensing*, *9*(11), 1–12. https://doi.org/10.3390/rs9111096

Allen, L. C., Barber, J. R., Hristov, N. I., Rubin, J. J., & Lightsey, J. T. (2021). *Noise distracts foraging bats*. https://doi.org/10.1098/rspb.2020.2689

Alquezar, R. D., & Macedo, R. H. (2019). Airport noise and wildlife conservation: What are we missing? In *Perspectives in Ecology and Conservation* (Vol. 17, Issue 4). https://doi.org/10.1016/j.pecon.2019.08.003

Anderson, D. J. (1982). The home range: a new nonparametric estimation technique. *Ecology*, *63*(1), 103–112. https://doi.org/10.2307/1937036

Barbosa, K. V. de C., Rodewald, A. D., Ribeiro, M. C., & Jahn, A. E. (2020). Noise level and water distance drive resident and migratory bird species richness within a Neotropical megacity. *Landscape and Urban Planning*, *197*(January), 103769. https://doi.org/10.1016/j.landurbplan.2020.103769

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Bejder, L., Samuels, A., Whitehead, H., Finn, H., & Allen, S. (2009). Impact assessment research: Use and misuse of habituation, sensitisation and tolerance in describing wildlife responses to anthropogenic stimuli. *Marine Ecology Progress Series*, *395*. https://doi.org/10.3354/meps07979

Benítez, M. E., Pappano, D. J., Beehner, J. C., & Bergman, T. J. (2017). Evidence for mutual assessment in a wild primate. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-02903-w

Breheny, P., & Burchett, W. (2017). Visualization of regression models using visreg. *R Journal*, *9*(2), 56–71. https://doi.org/10.32614/rj-2017-046

Brumm, H., & Bee, M. (2016). A meta-analytic castle built on sand? A comment on Roca et al. In *Behavioral Ecology* (Vol. 27, Issue 5). https://doi.org/10.1093/beheco/arw118

Brumm, H., & Slabbekoorn, H. (2005). Acoustic communication in noise. *Advances in the Study of Behavior*, *35*(05), 151–209. https://doi.org/10.1016/S0065-3454(05)35004-2

Brumm, H., & Slater, P. J. B. (2006). Ambient noise, motor fatigue, and serial redundancy in chaffinch song. *Behavioral Ecology and Sociobiology*, *60*(4), 475–481. https://doi.org/10.1007/s00265-006-0188-y

Brumm, H., Voss, K., Köllmer, I., & Todt, D. (2004). Acoustic communication in noise: Regulation of call characteristics in a New World monkey. *Journal of Experimental Biology*, *207*(3), 443–448. https://doi.org/10.1242/jeb.00768

Brumm, H., & Zollinger, A. (2011). The evolution of the Lombard effect: 100 years of psychoacoustic research. *Behaviour*, *148*(11–13), 1173–1198. https://doi.org/10.1163/000579511X605759

Buxton, R. T., McKenna, M. F., Brown, E., Ohms, R., Hammesfahr, A., Angeloni, L. M., Crooks, K. R., & Wittemyer, G. (2020). Varying behavioral responses of wildlife to motorcycle traffic. *Global Ecology and Conservation*, *21*. https://doi.org/10.1016/j.gecco.2019.e00844

Caine, N. G., Addington, R. L., & Windfelder, T. L. (1995). Factors affecting the rates of food calls given by red-bellied tamarins. *Animal Behaviour*, *50*(1). https://doi.org/10.1006/anbe.1995.0220

Caine, N. G. (1987). Vigilance, vocalizations, and cryptic behavior at retirement in captive groups of red-bellied tamarins (*Saguinus labiatus*). *American Journal of Primatology*, *12*(3), 241-250.

Calenge, C. (2018). *Package “adehabitat” Title Analysis of Habitat Selection by Animals*.

Caorsi, V., Guerra, V., Furtado, R., Llusia, D., Miron, L. R., Borges-Martins, M., Both, C., Narins, P. M., Meenderink, S. W. F., & Márquez, R. (2019). Anthropogenic substrateborne vibrations impact anuran calling. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-55639-0

Caselli, C. B., Ayres, P. H. B., Castro, S. C. N., Souto, A., Schiel, N., & Miller, C. T. (2018). The role of extragroup encounters in a Neotropical, cooperative breeding primate, the common marmoset: a field playback experiment. *Animal Behaviour*, *136*, 137–146. https://doi.org/10.1016/j.anbehav.2017.12.009

Chaves, B. A., de Alvarenga, D. A. M., Pereira, M. de O. C., Gordo, M., Da Silva, E. L., Costa, E. R., Medeiros, A. S. de M., Pedrosa, I. J. M., Brito, D., Lima, M. T., Mourão, M. P., Monteiro, W. M., Vasilakis, N., de Brito, C. F. A., Melo, G. C., & Lacerda, M. V. G. (2022). Is zoonotic Plasmodium vivax malaria an obstacle for disease elimination? *Malaria Journal*, *21*(1). https://doi.org/10.1186/s12936-022-04349-6

Clark, F. E., & Dunn, J. C. (2022). *From Soundwave to Soundscape : A Guide to Acoustic Research in Captive Animal Environments*. *9*(June), 1–19. https://doi.org/10.3389/fvets.2022.889117

Coelho, L., Barr, S., Silva dos Santos, L., Rohe, F., Monteiro-Neto, B. D., Raseira, M., Lagroteria, D., & Gordo, M. (2018). Conservação de Saguinus bicolor (Callitrichidae) em paisagens fragmentadas na Amazônia Central, Brasil. In B. Urbani, M. M. Kowalewski, R. G. T. Da Cunha, S. De La Torre, & L. Cortés-Ortiz (Eds.), *La Primatología en Latinoamérica 2* (pp. 187–197). Instituto Venezolano de Investigaciones Científicas.

Da Cunha, R. G. T., & Jalles-Filho, E. (2007). The roaring of southern brown howler monkeys (Alouatta guariba clamitans) as a mechanism of active defence of borders. *Folia Primatologica*, *78*(4), 259–271. https://doi.org/10.1159/000105545

Deoniziak, K., & Osiejuk, T. S. (2016). Disentangling relations among repertoire size, song rate, signal redundancy and ambient noise level in European Songbird. *Ethology*, *122*(9), 734–744. https://doi.org/10.1111/eth.12520

Do Nascimento, L. A., Pérez-Granados, C., & Beard, K. H. (2021). Passive acoustic monitoring and automatic detection of diel patterns and acoustic structure of howler monkey roars. *Diversity*, *13*(11). https://doi.org/10.3390/d13110566

Dolotovskaya, S., & Heymann, E. W. (2022). Coordinated Singing in Coppery Titi Monkeys (Plecturocebus cupreus): Resource or Mate Defense? *Frontiers in Ecology and Evolution*, *10*(May), 1–13. https://doi.org/10.3389/fevo.2022.898509

Duarte, M., Caliari, E. P., Scarpelli, M. D. A., Lobregat, G. O., Young, R. J., & Sousa-Lima, R. S. (2019). Effects of mining truck traffic on cricket calling activity. *The Journal of the Acoustical Society of America*, *146*(1), 656–664. https://doi.org/10.1121/1.5119125

Duarte, M., Kaizer, M. C., Young, R. J., Rodrigues, M., & Sousa-Lima, R. S. (2018). Mining noise affects loud call structures and emission patterns of wild black-fronted titi monkeys. *Primates*, *59*(1), 89–97. https://doi.org/10.1007/s10329-017-0629-4

Duarte, M., Vecci, M. a., Hirsch, A., & Young, R. J. (2011). Noisy human neighbours affect where urban monkeys live. *Biology Letters*, *7*(6), 840–842. https://doi.org/10.1098/rsbl.2011.0529

Egler, S. G. (1986). *Estudos bionônicos de Saguinus bicolor (Spix, 1823) (Callitrichidae: Primates), em mata tropical alterada, Manaus, AM*.

Egnor, S. E. R., Wickelgren, J. G., & Hauser, M. D. (2007). Tracking silence: adjusting vocal production to avoid acoustic interference. *Journal of Comparative Physiology. A, Neuroethology, Sensory, Neural, and Behavioral Physiology*, *193*(4), 477–483. https://doi.org/10.1007/s00359-006-0205-7

Engqvist, L. (2005). The mistreatment of covariate interaction terms in linear model analyses of behavioural and evolutionary ecology studies. In *Animal Behaviour* (Vol. 70, Issue 4). https://doi.org/10.1016/j.anbehav.2005.01.016

Fischer, J., & Zinner, D. (2011). Communication and cognition in primate group movement. *International Journal of Primatology*, *32*(6), 1279–1295. https://doi.org/10.1007/s10764-011-9542-7

Fuller, R. A., Warren, P. H., & Gaston, K. J. (2007). Daytime noise predicts nocturnal singing in urban robins. *Biology Letters*, *3*(4), 368–370. https://doi.org/10.1098/rsbl.2007.0134

Fuzessy, L., Cornelissen, T. G., Janson, C., & Silveira, F. A. O. (2016). How do primates affect seed germination? A meta-analysis of gut passage effects on neotropical plants. *Oikos*, *125*(8), 1069–1080. https://doi.org/10.1111/oik.02986

Fuzessy, L., Silveira, F. A. O., Culot, L., Jordano, P., & Verdú, M. (2021). Phylogenetic congruence between Neotropical primates and plants is driven by frugivory. *Ecology Letters*. https://doi.org/10.1111/ele.13918

Gil, D., Honarmand, M., Pascual, J., Pérez-Mena, E., & Macías Garcia, C. (2015). Birds living near airports advance their dawn chorus and reduce overlap with aircraft noise. *Behavioral Ecology*, *26*(2), 435–443. https://doi.org/10.1093/BEHECO/ARU207

Gill, S. A., Job, J. R., Myers, K., Naghshineh, K., & Vonhof, M. J. (2015). Toward a broader characterization of anthropogenic noise and its effects on wildlife. *Behavioral Ecology*, *26*(2), 328–333. https://doi.org/10.1093/beheco/aru219

Gómez-Espinosa, E., Dias, P. A. D., & Rangel-Negrín, A. (2022). The influence of anthropogenic noise on the behavior of male mantled howler monkeys. *American Journal of Primatology*. https://doi.org/10.1002/AJP.23377

Gontijo, J. C. F. (2008). Uso e características dos fragmentos florestais urbanos da cidade de Manaus/AM. Master's dissertation, Manaus.

Gordo, M., Calleia, F. O., Vasconcelos, S. A., Leite, J. J. F., & Ferrari, S. F. (2013). The challenges of survival in a concrete jungle: Conservation of the pied tamarin (Saguinus bicolor) in the urban landscape of manaus, Brazil. In L. Marsh & C. A. Chapman (Eds.), *Primates in Fragments: Complexity and Resilience* (pp. 357–370). Springer. https://doi.org/10.1007/978-1-4614-8839-2_23

Gordo, M., Jerusalinsky, L., Mittermeier, R. A., Rohe, F., Boubli, J. P., Subirá, R. J., & Vidal, M. D. (2019). Saguinus bicolor. *The IUCN Red List of Threatened Species*. https://doi.org/https://dx.doi.org/10.2305/IUCN.UK.2019-3.RLTS.T40644A17931870.en

Gordo, M., Subirá, R. J., Vidal, M. D., Röhe, F., Spironello, W. R., Valente, L. M., Oliveira, J. B., Pissinatti, A., & Wormell, D. (2017). Contextualização do Sauim-de-coleira. In L. Jerusalinsky, R. Azevedo, & M. Gordo (Eds.), *Plano de ação nacional para a conservação do sauim-de-coleira* (pp. 25–44). Instituto Chico Mendes de Conservação da Biodiversidade.

Grabarczyk, E. E., & Gill, S. A. (2019). Anthropogenic noise affects male house wren response to but not detection of territorial intruders. *PLOS ONE*, *14*(7), e0220576. https://doi.org/10.1371/journal.pone.0220576

Guski, R., Schreckenberg, D., & Schuemer, R. (2017). WHO environmental noise guidelines for the European region: A systematic review on environmental noise and annoyance. In *International Journal of Environmental Research and Public Health* (Vol. 14, Issue 12). https://doi.org/10.3390/ijerph14121539

Heymann, E. W. (1990). Interspecific relations in a mixed-species troop of moustached tamarins, Saguinus mystax, and saddle-back tamarins, *Saguinus fuscicollis* (Platyrrhini:Callitrichidae), at the Río Blanco, Peruvian Amazonia. *American Journal of Primatology*, *21*(2). https://doi.org/10.1002/ajp.1350210205

Heymann, E. W., Culot, L., Knogge, C., Smith, A. C., Tirado Herrera, E. R., Müller, B., Stojan-Dolar, M., Lledo Ferrer, Y., Kubisch, P., Kupsch, D., Slana, D., Koopmann, M. L., Ziegenhagen, B., Bialozyt, R., Mengel, C., Hambuckers, J., & Heer, K. (2019). Small Neotropical primates promote the natural regeneration of anthropogenically disturbed areas. *Scientific Reports*, *9*(1), 10356. https://doi.org/10.1038/s41598-019-46683-x

Hopkins, M. E. (2013). Relative dominance and resource availability mediate mantled howler (Alouatta palliata) spatial responses to neighbors' loud calls. *International Journal of Primatology*, *34*(5), 1032–1054. https://doi.org/10.1007/s10764-013-9713-9

Hubert, J., Campbell, J., van der Beek, J. G., den Haan, M. F., Verhave, R., Verkade, L. S., & Slabbekoorn, H. (2018). Effects of broadband sound exposure on the interaction between foraging crab and shrimp – A field study. *Environmental Pollution*, *243*, 1923–1929. https://doi.org/10.1016/j.envpol.2018.09.076

Huet des Aunay, G., Grenna, M., Slabbekoorn, H., Nicolas, P., Nagle, L., Leboucher, G., Malacarne, G., & Draganoiu, T. I. (2017). Negative impact of urban noise on sexual receptivity and clutch size in female domestic canaries. *Ethology*, *123*(11), 843–853. https://doi.org/10.1111/eth.12659

Janik, V. M., & Slater, P. J. B. (1997). Vocal learning in mammals. In *Advances in the Study of Behavior* (Vol. 26, Issue C, pp. 59–99). https://doi.org/10.1016/S0065-3454(08)60377-0

Kaiser, K., Scofield, D. G., Alloush, M., Jones, R. M., Marczak, S., Martineau, K., Oliva, M. A., & Narins, P. M. (2011). When sounds collide: The effect of anthropogenic noise on a breeding assemblage of frogs in Belize, Central America. *Behaviour*, *148*(2), 215–232. https://doi.org/10.1163/000579510X551660

Kirchhof, J., & Hammerschmidt, K. (2006). Functionally referential alarm calls in tamarins (Saguinus fuscicollis and Saguinus mystax) - Evidence from playback experiments. *Ethology*, *112*(4), 346–354. https://doi.org/10.1111/j.1439-0310.2006.01165.x

Kitchen, D. M. (2004). Alpha male black howler monkey responses to loud calls: Effect of numeric odds, male companion behaviour and reproductive investment. *Animal Behaviour*, *67*(1), 125–139. https://doi.org/10.1016/j.anbehav.2003.03.007

Kondo, N., & Watanabe, S. (2009). Contact calls: Information and social function. In *Japanese Psychological Research* (Vol. 51, Issue 3). https://doi.org/10.1111/j.1468-5884.2009.00399.x

Lagroteria, D., Pissinatti, A., Solorio, M., Wormell, D., & Gordo, M. (2017). Protocolos de cativeiro. In L. Jerusalinsky, R. B. De Azevedo, & M. Gordo (Eds.), *Plano de ação nacional para a conservação do sauim-de-coleira* (pp. 78–129). ICMBio.

Lineros, L. M. H., Chimènes, A., Maille, A., Dingess, K., Rumiz, D. I., & Adret, P. (2020). Response of Bolivian gray titi monkeys (Plecturocebus donacophilus) to an anthropogenic noise gradient : behavioral and hormonal correlates. *PeerJ*, 1–33. https://doi.org/10.7717/peerj.10417

Lüdecke, D., Ben-Shachar, M., Patil, I., Waggoner, P., & Makowski, D. (2021). performance: An R Package for Assessment, Comparison and Testing of Statistical Models. *Journal of Open Source Software*, *6*(60). https://doi.org/10.21105/joss.03139

Martin, P., & Bateson, P. (1993). Measuring behaviour: an introductory guide. In *Measuring behaviour An introductory guide* (3rd ed.). Cambridge University Press.

Miller, C. T., Flusberg, S., & Hauser, M. D. (2003). Interruptibility of long call production in tamarins: Implications for vocal control. *Journal of Experimental Biology*, *206*(15), 2629–2639. https://doi.org/10.1242/jeb.00458

Mitani, J. C., & Watts, D. P. (2005). Correlates of territorial boundary patrol behaviour in wild chimpanzees. *Animal Behaviour*, *70*(5), 1079–1086. https://doi.org/10.1016/j.anbehav.2005.02.012

Neo, Y. Y., Seitz, J., Kastelein, R. A., Winter, H. V., ten Cate, C., & Slabbekoorn, H. (2014). Temporal structure of sound affects behavioural recovery from noise impact in European seabass. *Biological Conservation*, *178*(April 2019), 65–73. https://doi.org/10.1016/j.biocon.2014.07.012

Norconk, M. A. (1990). Mechanisms promoting stability in mixed Saguinus mystax and S. fuscicollis troops. *American Journal of Primatology*, *21*(2), 159–170. https://doi.org/10.1002/ajp.1350210208

Peres, C. A., Emilio, T., Schietti, J., Desmoulière, S. J. M., & Levi, T. (2016). Dispersal limitation induces long-term biomass collapse in overhunted Amazonian forests. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(4), 892–897. https://doi.org/10.1073/PNAS.1516525113

Pérez-Granados, C., & Schuchmann, K. L. (2021). Passive acoustic monitoring of the diel and annual vocal behavior of the Black and Gold Howler Monkey. *American Journal of Primatology*, *83*(3), e23241. https://doi.org/10.1002/ajp.23241

Picciulin, M., Sebastianutto, L., Codarin, A., Calcagno, G., & Ferrero, E. A. (2012). Brown meagre vocalization rate increases during repetitive boat noise exposures: A possible case of vocal compensation. *The Journal of the Acoustical Society of America*, *132*(5). https://doi.org/10.1121/1.4756928

Podos, J. (1997). A performance constraint on the evolution of trilled vocalizations in a songbird family (Passeriformes: Emberizidae). *Evolution*, *51*(2), 537–551. https://doi.org/10.1111/J.1558-5646.1997.TB02441.X

R Core Team. (2018). A Language and Environment for Statistical Computing. In *R Foundation for Statistical Computing*.

Ravaglia, D., Ferrario, V., De Gregorio, C., Carugati, F., Raimondi, T., Cristiano, W., Torti, V., Hardenberg, A. Von, Ratsimbazafy, J., Valente, D., Giacoma, C., & Gamba, M. (2023). There You Are! Automated Detection of Indris' Songs on Features Extracted from Passive Acoustic Recordings. *Animals*, *13*(2). https://doi.org/10.3390/ani13020241

Roca, I. T., Desrochers, L., Giacomazzo, M., Bertolo, A., Bolduc, P., Deschesnes, R., Martin, C. A., Rainville, V., Rheault, G., & Proulx, R. (2016). Shifting song frequencies in response to anthropogenic noise: A meta-analysis on birds and anurans. *Behavioral Ecology*, *27*(5), 1269–1274. https://doi.org/10.1093/beheco/arw060

Roy, S., Miller, C. T., Gottsch, D., & Wang, X. (2011). Vocal control by the common marmoset in the presence of interfering noise. *Journal of Experimental Biology*, *214*(21), 3619–3629. https://doi.org/10.1242/jeb.056101

Santos, S. G., Duarte, M. H. L., Sousa-Lima, R. S., & Young, R. J. (2017). Comparing contact calling between black tufted-ear marmosets (Callithrix penicillata) in a noisy urban environment and in a quiet forest. *International Journal of Primatology*, *38*(6), 1130–1137. https://doi.org/10.1007/s10764-017-0002-x

Schneider, C., Hodges, K., Fischer, J., & Hammerschmidt, K. (2008). Acoustic niches of Siberut primates. *International Journal of Primatology*, *29*(3), 601–613. https://doi.org/10.1007/s10764-007-9181-1

Schuster, S., Zollinger, S. A., Lesku, J. A., & Brumm, H. (2012). On the evolution of noise-dependent vocal plasticity in birds. *Biology Letters*, *8*(6), 913–916. https://doi.org/10.1098/rsbl.2012.0676

Sierro, J., Schloesing, E., Pavón, I., & Gil, D. (2017). European blackbirds exposed to aircraft noise advance their chorus, modify their song and spend more time singing. *Frontiers in Ecology and Evolution*, *5*(JUN), 68. https://doi.org/10.3389/FEVO.2017.00068/BIBTEX

Sih, A., Ferrari, M. C. O., & Harris, D. J. (2011). Evolution and behavioural responses to human-induced rapid environmental change. *Evolutionary Applications*, *4*(2), 367–387. https://doi.org/10.1111/j.1752-4571.2010.00166.x

Slabbekoorn, H., Bouton, N., van Opzeeland, I., Coers, A., ten Cate, C., & Popper, A. N. (2010). A noisy spring: The impact of globally rising underwater sound levels on fish. *Trends in Ecology and Evolution*, *25*(7), 419–427. https://doi.org/10.1016/j.tree.2010.04.005

Slabbekoorn, H., & Halfwerk, W. (2009). Behavioural ecology: noise annoys at community level. *Current Biology*, *19*(16), R693–R695. https://doi.org/10.1016/j.cub.2009.07.002

Slabbekoorn, H., & Peet, M. (2003). Birds sing at a higher pitch in urban noise. *Nature*, *424*(6946), 267–267. https://doi.org/10.1038/424267a

Slabbekoorn, H., Yeh, P., & Hunt, K. (2007). Sound transmission and song divergence: A comparison of urban and forest acoustics. *Condor*, *109*(1), 67–78. https://doi.org/10.1650/0010-5422(2007)109[67:STASDA]2.0.CO;2

Snowdon, C. T. (2001). Social processes in communication and cognition in callitrichid monkeys: A review. *Animal Cognition*, *4*(3–4), 247–257. https://doi.org/10.1007/s100710100094

Snowdon, C. T. (2017). Vocal communication in family-living and pair-bonded primates. In R. M. Quam, M. A. Ramsier, R. R. Fay, & A. N. Popper (Eds.), *Primate Hearing and*

Communication (pp. 141–174). Springer. https://doi.org/https://doi.org/10.1007/978-3-319-59478-1_6

Sobroza, T. V., Cerqueda, L. S., Simões, P. I., & Gordo, M. (2017). Vocal repertoire and its behavioral contexts in the pied tamarin, Saguinus bicolor. *International Journal of Primatology*, *38*(4), 642–655. https://doi.org/10.1007/s10764-017-9971-z

Sobroza, T. V., Gordo, M., Barnett, A. P. A., Boubli, J. P., & Spironello, W. R. (2021). Parapatric pied and red-handed tamarin responses to congeneric and conspecific calls. *Acta Oecologica*, *110*, 103688. https://doi.org/10.1016/j.actao.2020.103688

Sobroza, T. V., Gordo, M., Pequeno, P. A. C. L., Dunn, J. C., Spironello, W. R., Rabelo, R. M., & Barnett, A. P. A. (2021a). Convergent character displacement in sympatric tamarin calls (Saguinus spp.). *Behavioral Ecology and Sociobiology*, *75*(5). https://doi.org/10.1007/s00265-021-03028-x

Sobroza, T. V., Dunn, J. C., Gordo, M., & Barnett, A. A. (2023). Do pied tamarins increase scent-marking in response to urban noise?. *Ethology Ecology & Evolution*, 1-14.

Soudijn, F. H., van Kooten, T., Slabbekoorn, H., & de Roos, A. M. (2020). Population-level effects of acoustic disturbance in Atlantic cod: a size-structured analysis based on energy budgets. *Proceedings of the Royal Society B: Biological Sciences*, *287*(1929), 20200490. https://doi.org/10.1098/rspb.2020.0490

Steinbrecher, F., Dunn, J. C., Price, E. C., Buck, L. H., Wascher, C. A., & Clark, F. E. (2023). The effect of anthropogenic noise on foraging and vigilance in zoo-housed pied-tamarins. *Applied Animal Behaviour Science*, 105989.

Swaddle, J. P., Francis, C. D., Barber, J. R., Cooper, C. B., Kyba, C. C. M., Dominoni, D. M., Shannon, G., Aschehoug, E., Goodwin, S. E., Kawahara, A. Y., Luther, D., Spoelstra, K., Voss, M., & Longcore, T. (2015). A framework to assess evolutionary responses to anthropogenic light and sound. *Trends in Ecology and Evolution*, *30*(9), 550–560. https://doi.org/10.1016/j.tree.2015.06.009

Tennessen, J. B., Parks, S. E., & Langkilde, T. (2014). Traffic noise causes physiological stress and impairs breeding migration behaviour in frogs. *Conservation Physiology*, *2*(1). https://doi.org/10.1093/conphys/cou032

Thatcher, H. R., Downs, C. T., & Koyama, N. F. (2023). *Primates in the Urban Mosaic: Terminology, Flexibility, and Management*. https://doi.org/10.1007/978-3-031-11736-7_8

Van Belle, S., Estrada, A., & Garber, P. A. (2013). Spatial and diurnal distribution of loud calling in black howlers (Alouatta pigra). *International Journal of Primatology*, *34*(6), 1209–1224. https://doi.org/10.1007/s10764-013-9734-4

Van Belle, S., & Scarry, C. J. (2015). Individual participation in intergroup contests is mediated by numerical assessment strategies in black howler and tufted capuchin monkeys. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *370*(1683). https://doi.org/10.1098/rstb.2015.0007

Vargas-Salinas, F., & Amézquita, A. (2014). Abiotic noise, call frequency and stream-breeding anuran assemblages. *Evolutionary Ecology*, *28*(2). https://doi.org/10.1007/s10682-013-9675-6

Velasquez Jimenez, L., Fakan, E. P., & McCormick, M. I. (2020). Vessel noise affects routine swimming and escape response of a coral reef fish. *PLOS ONE*, *15*(7), e0235742. https://doi.org/10.1371/journal.pone.0235742

Ware, H. E., McClure, C. J. W., Carlisle, J. D., Barber, J. R., & Daily, G. C. (2015). A phantom road experiment reveals traffic noise is an invisible source of habitat degradation. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(39). https://doi.org/10.1073/pnas.1504710112

Waser, P. M., & Brown, C. H. (1984). Is there a “sound window” for primate communication? *Behavioral Ecology and Sociobiology*, *15*(1), 73–76. https://doi.org/10.1007/BF00310219

WHO. (2022). *Environmental noise*.

Wich, S. A., & Nunn, C. L. (2002). Do male “long-distance calls” function in mate defense? A comparative study of long-distance calls in primates. *Behavioral Ecology and Sociobiology*, *52*(6), 474–484. https://doi.org/10.1007/s00265-002-0541-8

Williams, R., Erbe, C., Ashe, E., Beerman, A., & Smith, J. (2014). Severity of killer whale behavioral responses to ship noise: A dose-response study. *Marine Pollution Bulletin*, *79*(1–2), 254–260. https://doi.org/10.1016/j.marpolbul.2013.12.004

Wolfenden, A. D., Slabbekoorn, H., Kluk, K., & de Kort, S. R. (2019). Aircraft sound exposure leads to song frequency decline and elevated aggression in wild chiffchaffs. *Journal of Animal Ecology*, *88*(11), 1720–1731. https://doi.org/10.1111/1365-2656.13059

Worton, B. J. (1989). Kernel methods for estimating the utilization distribution in home-range studies. *Ecology*, *70*(1), 164–168. https://doi.org/10.2307/1938423

Zhao, L., Roy, S., & Wang, X. (2019). *Rapid modulations of the vocal structure in marmoset monkeys*. https://doi.org/10.1016/j.heares.2019.107811

Zollinger, S. A., Podos, J., Nemeth, E., Goller, F., & Brumm, H. (2012). On the relationship between, and measurement of, amplitude and frequency in birdsong. *Animal Behaviour*, *84*(4), e1–e9. https://doi.org/10.1016/j.anbehav.2012.04.026

Zuur, A. F., Ieno, E. N., Walker, N., Saveliev, A. A., & Smith, G. M. (2009). *Mixed effects models and extensions in ecology with R*. Springer New York.

Table 1. Characteristics of sampling locations, sampling sizes and pied tamarin (*Saguinus bicolor)* groups followed in urban areas of Manaus, Amazonas State, Brazil.

Group	**Approximate Fragment size (ha)***	**Group Size**	**Group composition**	**Number of behavioral bouts recorded**	**Number of long call recordings**
Viveiro	700	8	1F + 2M + 3JF + I + 1UN	403	20
Jaqueira	700	13	3F + 5M + 2JF + 1JM + 1I + 1UN	60	30
Coroado	700	7	3M + 1JM + 1I + 2UN	54	0
Acariquara	700	7	2F + 1 JF + 1 MF + 3UN	43	47
CIGS	100	5	1F + 2M + 1FJ + 1 UN	440	58
Mindu	50	6	2F + 1M + 1MJ + 2 UN	215	61
Sumaúma	50	9	3F + 3M + 1FJ + 2MJ	418	106
Bosque da Ciência	24	3	2F + 1M	275	117
Musa	continuous	10	UN	45	5

* Fragment size estimate is not precise as some of the fragments are more or less connected with other forested areas by gardens or riverside vegetation. Group composition: M= adult male; F= adult female; JF= juvenile female; JM= juvenile male; I=infant; UN=adults of unknown sex.

Table 2. Summary of Generalized Mixed Effects Models for different descriptors of emissions of long calls by nine pied tamarin (*Saguinus bicolor)* groups in urban areas of Manaus, Brazil.

Response variable	**Predictor**	**Estimate**	**SE**	**Z**	***p***
Occurrence of long calls	Intercept	-2.997	1.088	-2.755	<0.001
(binary data)	Sound level (dB)	0.054	0.014	3.623	<0.001
	Hour of the day	-0.253	0.021	-11.57	<0.001
	Group size	0.175	0.0452	3.879	<0.001
	Distance from HR border	0.001	0.001	1.068	0.285
	Marginal R^2 / Conditional R^2	0.167/ 0.182			
Number of long calls	Intercept	3.036	0.916	3.313	<0.001
(count data)	Sound level (dB)	-0.003	0.012	-0.289	0.772
	Hour of the day	-0.069	0.018	-3.843	<0.001
	Group size	0.070	0.042	1.683	0.092
	Distance from HR border	-0.006	0.001	-4.202	<0.001
	Marginal R^2 / Conditional R^2	0.12/ 0.21			

HR= home range.

Table S1. Summary of Generalized Mixed Effects Models including interaction factors for different descriptors of emissions of long calls by nine groups of pied tamarin (*Saguinus bicolor)* in urban areas of Manaus, Brazil.

Response variable	**Predictor**	**Estimate**	**SE**	**Z**	***p***
Occurrence of long calls	Intercept	-0.655	2.893	-0.22	0.820
(binary data)	Sound level (dB)	0.015	0.047	0.32	0.748
	Hour of the day	-0.466	0.244	-1.92	0.055
	Group size	0.172	0.045	3.79	<0.001
	Distance from HR border	0.0018	0.001	1.11	0.262
	Sound level (dB) × Hour of the day	0.003	0.004	0.878	0.380
Number of long calls rate	Intercept	4.336	2.131	2.03	0.041
(count data)	Sound level (dB)	-0.022	0.035	-0.64	0.516
	Hour of the day	-0.176	.0184	-0.96	0.337
	Group size	0.04	0.033	1.22	0.22
	Distance from HR border	-0.004	0.001	-3.29	<0.001
	Sound level (dB) × Hour of the day	0.001	0.003	0.52	0.59

HR = home range; × Interaction term

Table 3. Summary of Generalized Mixed Effects Models for different descriptors of emissions of long calls by nine pied tamarin (*Saguinus bicolor)* groups in urban areas of Manaus, Brazil.

Response variable	**Predictor**	**Estimate**	**SE**	**Z**	***p***
Dominant frequency	Intercept	7548.51	561.38	13.44	<0.01
	Sound level (dB)	7.789	8.32	0.93	0.35
Lowest frequency	Intercept	5713.75	421.32	13.56	<0.01
	Sound level (dB)	3.15 6	6.434	0.49	0.624
Duration	Intercept	2.389	0.557	4.283	<0.01
	Sound level (dB)	0.111	0.099	1.239	0.215
Syllable repetition rate	Intercept	0.925	0.133	6.955	<0.001
	Sound level (dB)	-0.006	0.002	-3.227	<0.01*