



Noise, resources, and social factors shape space use and movement patterns in a small Amazonian primate

Tainara Venturini Sobroza^{1,2,3} · Marcelo Gordo² · Jacob Charles Dunn^{4,5,6} · Bruna Mendel Naissinger⁷ · Luciano Querido³ · Adrian Ashton Barnett^{8,9,10}

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Abstract

Noisy environments tend to mask sounds and disrupt animal behaviour. One of the most common responses from many animal species to noise is leaving or avoiding the noisiest parts of their ranges. Individuals may alter their movement patterns, either rapidly moving away or changing routes in response to increased noise levels. Here, we tested whether urban-dwelling pied tamarins (*Saguinus bicolor*): (1) preferentially used quieter areas within their home range, (2) increase travel speed, and (3) alter routes to avoid noise levels. To achieve this, we followed nine pied tamarin groups in five forest fragments within the city of Manaus, Brazil, recording their locations and levels of associated ambient noise levels. We also estimated fruit availability at random points within the group's home ranges. We found that pied tamarins use the quieter areas of their ranges more intensively, but only if the fruit availability is high. Furthermore, groups did not increase their travel speed or change turning angles in response to noise alone, but travel speed increase in noisier areas closer to the border of their home ranges. Thus, pied tamarins do seem to use the quieter areas of their home ranges, but do not hurry to reach them unless their location lies closer to their home range borders. This may occur because higher noise levels at home-range borders could diminish intergroup communication effectiveness. In general, we found that pied tamarin's use of space and movement patterns are soundscape-related but mediated by resource availability and social aspects.

Keywords Soundscape · Noise pollution · Use of space · Urban ecology · Amazon · *Saguinus bicolor*

Introduction

Rapid human population growth has driven urbanisation, globalisation, and industrialisation (McDonald et al. 2020), all of which have transformed the acoustic environment in which humans and other animals live (Barber et al. 2010;

Slabbekoom 2018). Human-made noise is now pervasive across terrestrial and marine ecosystems (Barber et al. 2010; Chahouri et al. 2022) and is considered one of the most harmful forms of pollution (World Health Organization 2022). As a result, there is growing concern regarding its negative effects on wildlife ecology, behaviour,

✉ Tainara Venturini Sobroza
tv.sobroza@gmail.com

¹ Universidade Federal do Oeste do Pará (UFOPA), Tv. Carlos Maria Teixeira, Oriximiná, PA, Brazil

² Projeto Sauim-de-Coleira, Universidade Federal do Amazonas (UFAM), Av. General Rodrigo Otávio Jordão Ramos, 6200, Manaus, Brazil

³ Centro de Estudos Integrados da Biodiversidade Amazônica, Instituto Nacional de Pesquisas da Amazônia, Manaus, Brazil

⁴ Primate Evolution and Ecology Research Group, Anglia Ruskin University, Cambridge, UK

⁵ ENES Bioacoustics Research Laboratory, University of Saint-Étienne, Saint-Étienne, France

⁶ Department of Cognitive Biology, University of Vienna, Vienna, Austria

⁷ Programa de Pós Graduação em Recursos Naturais, Universidade Federal de Roraima, Boa Vista, Brazil

⁸ Natural Resources Institute, University of Greenwich, Kent, UK

⁹ Centro de Ciências Biológicas, Departamento de Zoologia, Universidade Federal de Pernambuco, Recife, Pernambuco, Brazil

¹⁰ Departamento de Ciências Biológicas, Universidade Estadual do Maranhão, São Luis, Maranhão, Brazil

reproduction, and health. Noisy environments often mask biologically important sounds related to key behaviours, such as foraging, anti-predator defence, territorial activities, and mate attraction (Brumm et al. 2004; Brumm and Slabbekoorn 2005). To cope with such disruptions, animals may adopt various strategies to avoid or mitigate the impacts of noise pollution, most obviously by avoiding noisy areas (Chen and Koprowski 2015; Johnston and Painter 2024).

In response to noise, animals have been shown to alter their use of space at both regional and local scales. For example, at the regional scale, entire bird communities may shift their distribution patterns (Ware et al. 2015). At finer scales, individual animals may avoid noisier areas by adjusting their home range use and establishing core areas in quieter places (Chen and Koprowski 2015; Duarte et al. 2011). Black-tufted marmosets (*Callithrix penicillata*), for instance, use the quieter areas of their range more, even if they contain less food (Duarte et al. 2011). In other cases, species may not change the overall use of space but demonstrate more subtle changes in movement patterns within an area (van der Knaap et al. 2022). One common response when animals are stressed by acute anthropogenic noise is to flee, rapidly moving away from the sound source (Rylander 2004), as blue whales (*Balaenoptera musculus*) that increase their swimming speed to move away from simulated noise from military sonar (Goldbogen et al. 2013). On the other hand, other taxa, such as frogs, reduce their mobility or remain motionless with increased noise levels (Zaffaroni-Caorsi et al. 2022). Such varied responses may be related to the influence of other factors that also drive how animals use and move through their habitats, such as the availability of food (Reyna-Hurtado et al. 2018), and refugia (Sullivan et al. 2016), the presence of inter- or intra-specific competitors (Crofoot 2013), and predation risk (Hammond et al. 2007). These aspects are often also related to how direct animal movements are (De Knecht et al. 2007; Turchin 1998). Straight-line travel indicates spatial memory and the ability to compare the distance and direction from one site to many others and so choose the best route (Garber 1989). Deviation from straight-line trajectories may be related to landscape structure, such as the presence of areas of transition to less-optimal habitat (i.e. barrier effect) (Fahrig 2007), but also social constraints, and variations in predation risk (Noser and Byrne 2007). Thus, while many animals do change their routes to avoid noisy areas (Goldbogen et al. 2013; Velasquez Jimenez et al. 2020), it is likely that they face a trade-off between remaining in or avoiding a given area in response to noise, while also accounting for other drivers of such behaviour.

Primates are among the most threatened taxa in the world (Estrada et al. 2017). Even so, studies evaluating the impact

of anthropogenic noise on the behaviour of wild primates, especially in the neotropics, remain limited (Duarte et al. 2011, 2018; Gómez-Espinosa et al. 2022; Lineros et al. 2020; Santos et al. 2017). A good model for understanding the effect of the acoustic environment on a species' use of space and movement is the pied tamarin, *Saguinus bicolor* Spix 1823, a small and critically endangered primate from the central Brazilian Amazon (Gordo et al. 2013). Much of this species' range is now occupied by the city of Manaus, where urbanisation has restricted individual groups to isolated forest fragments with consequent loss of individuals to roadkill, electrocution, and attacks by domestic animals (Gordo et al. 2013; Farias et al. 2015). In addition to playing an important ecological role as a seed disperser (Fernandes et al. 2024), the species is a flagship species for the city of Manaus and has been the focus of numerous conservation initiatives. A key action to secure viable urban populations of pied tamarins has been to create ecological corridors connecting different urban forest fragments and reserves in and around the city of Manaus (Albernaz et al. 2025; Barr 2016; Coelho et al. 2018). With the intention of creating an ecological corridor for the species, Manaus City Council created an Environmental Protected Area (APA Sauim-de-Manaus) to link multiple urban forest fragments (Coelho et al. 2018). Ecological corridors are designed to help animals traverse low-quality habitats to reach higher-quality areas (Beier and Noss 1998). However, their effectiveness depends on habitat permeability, including both physical and acoustic properties, which can influence species' movement and spatial use (Allen and Singh 2016; Gregory et al. 2021).

To evaluate how urban noise may affect pied tamarin spatial and movement patterns, we tested whether the species uses the quieter areas inside their home ranges to avoid noise. As food availability is one of the main factors affecting the density and behaviour of wildlife (Ciach and Fröhlich 2017), we expected an interaction between noise levels and resource availability. Accordingly, we predicted that pied tamarins would use the quieter areas of their ranges more often, as long as abundant food resources were also present. We also aimed to test whether pied tamarins flee from noise. Because pied tamarins are often very sensitive to environmental conditions (Price et al. 2019), we expected group travel speed to increase in noisier areas. We also expected pied tamarins to increase group travel speed when closer to the border of home ranges, due to competition and potential encounters with other groups (Crofoot 2013). We also predicted that in noisier areas travel routes would be less direct, suggesting less oriented movement (Benhamou 2004) due to impact of noise on group coordination capacity.

Methods

Study area

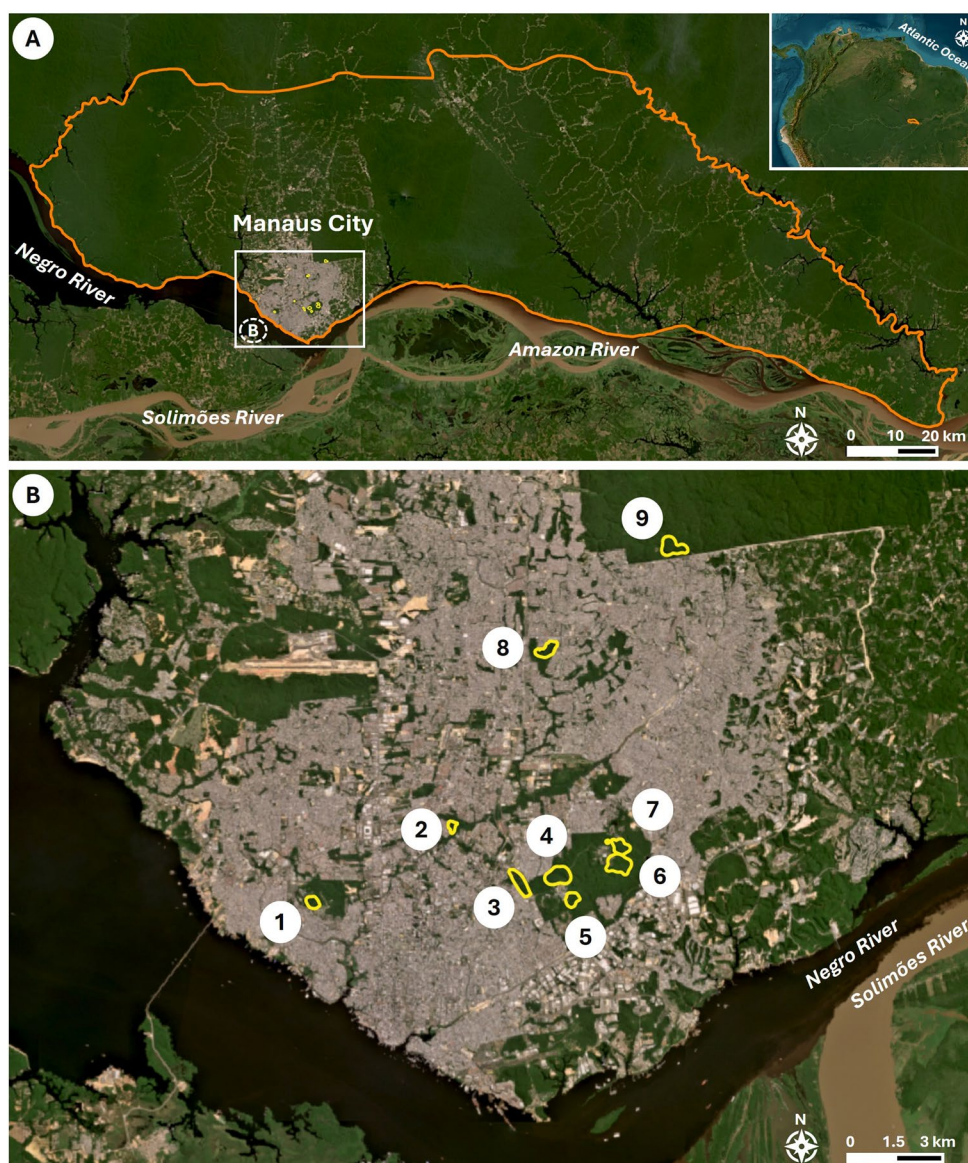
The study took place in Manaus, Central Brazilian Amazon ($3^{\circ}04'25''$ S, $60^{\circ}00'20''$ W). The topography of the area is predominantly flat, but there are also slopes and stream-side forest areas (*baixios*) (Oliveira et al. 2008). Within the urbanised study area, the natural vegetation cover is dominated by fragments of tropical humid *terra firme* forest surrounded by an urban matrix. Pied tamarins were monitored in five forest fragments (24 to ~ 700 ha) and one continuous forested area within the legal limits of the city of Manaus (Fig. 1). According to the nearest recording station of the Brazilian Institute for Meteorology (INMET- station A101), the mean temperature was 27.7°C ($\text{sd}=2.6$) and humidity $\sim 73.3\%$ ($\text{sd}=13.9$) during the sampling period. Noise

amplitude varied from 40.2 dB to 84.8 dB with an average of 59.19 dB ($\text{sd}=5.9$) (Sobroza et al. 2024). The most common anthropogenic source of noise in all areas was road traffic (Sobroza et al. 2024).

Subjects and capture proceedings

Data collection took place between November 2018 and December 2019. We followed nine pied tamarin groups, seven of them using radio-telemetry (Supplementary Material, Table S1). To capture the groups, we used Tomahawk TH105 ($10 \times 10 \times 40$ cm) live traps baited with bananas and placed ~ 1.60 m above the ground. Once the animals were captured, we sedated them with 0.1 ml of Ketamine anaesthetic and attached a radio-collar to the alpha female of each group, where possible. The attached transmitter emits specific frequencies (164.00–164.99.00.99 MHz) that were

Fig. 1 Pied tamarin geographic distributions (A) and locations and shapes of home ranges of the nine groups followed in the urban area of Manaus, Brazil (B)



detected with two (H) or three (Yagi) element antennas and an AT5[®] receptor (164–168 MHz). This protocol has been widely used by the long-term Pied Tamarin Project (Projeto Sauim-de-Coleira, UFAM) (Lagroteria et al. 2017; Sobroza et al. 2024). All capture and handling procedures were approved by the Ethical Committee of the Instituto Nacional de Pesquisas da Amazônia (SEI.01280.009002018–58). SISBIO/MMA (Ministry of Environment) granted us the necessary licenses to capture, anaesthetise, manipulate, and mark the subjects (N. 60347–1).

Behavioural and noise data collection

We followed each group for 10 days from 06:30–17:00, the main period of pied tamarin activity (Egler 1986). We collected behavioural data during five-minute bouts followed by a five-minute interval (Sobroza et al. 2024). At the start of the five-minute behavioural bouts, we recorded the location with a GPS (GPSMap 78s) of approximately 5 m precision. During behavioural bouts we also made a 1-minute reading of equivalent continuous sound levels (LEq). The LEq is a time-averaged sound level that, in this survey, was estimated based on sound pressures assessed every second while readings were being made with a calibrated sound level meter CEL-246 (Casela SolutionsTM). We chose 1-minute measurements because pied tamarins change position constantly, so staying longer in a single spot to estimate sound intensity would not have been representative. The sound level meter was equipped with a foam windshield and collected C-weighted data (Kinsler et al. 2000) with a range of 30–100 dB. In our study, we characterised noise in terms of amplitude but not sound frequency composition. Therefore, our noise estimate may include sounds of both anthropogenic and biotic origins (Supplementary Material, Table S2).

Home range, use of space and selection of sampling points

We estimated group home ranges (HR) and intensities of use of space using all recorded GPS points. To do this, we calculated the probability density functions (Utilization Distribution - UD) based on kernel density analysis using the *adehabitatHR* package (Calenge 2007) in R (R Core Team 2024). We used a reference smooth parameter for all groups (Worton 1989) and defined home range (HR) as the area where 95% of the points were found (Calenge 2007; Gregory 2016). After estimating HR borders, we built a 50 × 50 m virtual grid using QGIS 3.16, and each edge had a unique geographic point with associated coordinates (Supplementary Material, Figure S1). We randomly selected points from these coordinates to collect information on fruit availability.

For each group, we selected a different number of points depending on HR size. For each 10 ha of estimated HR, we selected seven points where we would install plots. This value was chosen so we could install 10 m X 10 m plots and estimate the fruit availability in a period of two days maximum, so it would more closely reflect the phenology of the trees when we collected the behavioural data. The total area of the plots corresponded to ~1% of groups' HR. Whilst we are aware that home range size may vary seasonally (Passamani and Rylands 2000; Veracini 2009), our main goal was not to estimate home range size per se, but to understand why, within it, tamarins used some areas more than others. Though, relative home range size was important to establish the number of plots to estimate fruit availability and infer potential HR borders.

Resource availability

Within the 24 h following behavioural observations, we installed 10 m X 10 m plots (100 m²) at randomly selected points within their HR. Within these, we counted all fleshy fruits that had fallen on the floor (Butynski 1990). This metric was chosen because of the likelihood that it corresponded to the overall abundance of fruit in that area during the period of behavioural data collection (Furuichi et al. 2001). We did not identify fruit types to species level but quantified those possessing characteristics of fruits most often eaten by pied tamarins (Egler 1992; Xavier de Oliveira et al. 2020; Fernandes et al. 2024). In these plots, we made additional noise estimative (LEq) for 15 min, directing the equipment to the nearest source of anthropogenic noise as perceived by human hearing. The time of the day that each plot had its noise amplitude estimated was randomised (from 6.00 to 17.00). As we expected human activities and, therefore, associated noise levels, to vary between periods, we also randomised which of the plots would have their noise estimates made during weekdays or weekends. Half of the plots had their noise estimates made during weekdays and half during weekends.

Use of space and movement analysis

To test whether pied tamarins used the quieter areas of their ranges more frequently than noisier areas, we estimated and extracted the intensity of space use from each point where noise estimates had been collected. To do this, we calculated the probability density functions (Utilization Distribution - UD) based on kernel estimates using a reference smooth pattern in the *adehabitatHR* package (Calenge 2007) in R (R Core Team 2024). We estimated per-group travel speed (m/s) and route change using the *speed* and *turnAngleGc* functions from the *Move* package

in R (Kranstauber 2021). We defined group travel speed (m/s) as the distance (m) between two consecutive points divided by time (s). We estimated route changes as the turning angle, defined as the angular difference between two consecutive points. Angles can vary from -180° to $+180^\circ$, with positive values related to forward progression and negative values indicating backtracking. When we lost sight of animals for more than 20 min, speed and turning angles were not calculated to avoid errors in the estimates of distances and, therefore, speed and angles. Defining a trajectory as the path between two GPS points recorded when tamarins moved sequentially (Fig. 2), we had between 114 and 406 trajectories per group, with trajectory distances varying from 0 to 245 m.

We also tested whether the distances to HR borders and to fragment borders were related to group speed of travel and change of routes. These distances were calculated between all the location points for each group, using the algorithm *shortest line between features* from QGIS (QGIS Development Team 2024). To represent the fragment border, we created line polygons from the raster image representing the Forest Formation class from the land use classification of the MapBiomas Project (MapBiomas Project 2024), using the *polygonise* and *polygon to line* algorithms in QGIS.

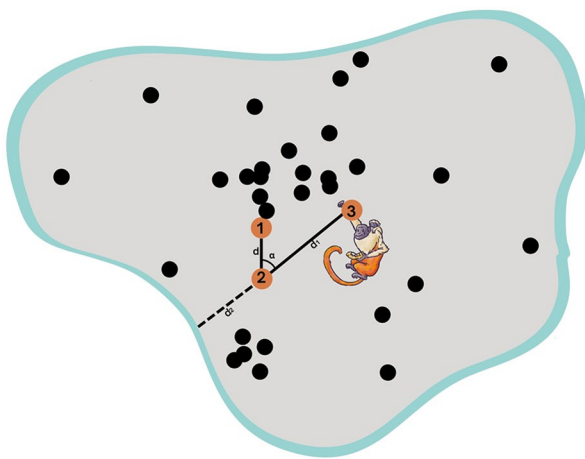


Fig. 2 Schematic diagram showing different spatial variables estimated for the use of space and movement patterns in a hypothetical group of wild pied tamarins (*Saguinus bicolor*) from Manaus, Brazil. Each point corresponds to a spatial coordinate recorded every 10 min while following the pied tamarin groups. Based on the density of points, we estimated the home ranges (grey area), and their home range borders (blue line). For movement analysis, we estimated the distance (e.g. d and $d1$) between consecutive points (e.g., orange dots) which constitute a trajectory (black line). The turning angle (α) is a measurement of route change and was calculated as the angular difference between two consecutive points. Each point is also located at a certain distance ($d2$) from the border of the home range (dotted line) and from the border of the forest fragment (not shown in this diagram)

Statistical analysis

To test if pied tamarins used the quieter areas within their home ranges more intensively, and whether this relationship was affected by the availability of resources, we used a Generalised Linear Mixed Model (GLMM). In this analysis, each plot was treated as the sampling unit ($N=130$). The kernel utilization distribution (UD) value, representing the intensity of use in each plot, was used as the response variable. As a predictor, we used the interaction between the 15-minute sound level estimate and the number of fruits estimated within the same plot. We included both the fragment and group identity as random factors to control for non-independence owing to landscape-induced variation or multiple observations of the same group. Since the values of intensity of use of space are rates, we used a Gamma distribution model, which is appropriate for data that accounts for non-integer numbers (Zuur et al. 2009). We conducted the analysis using the *lme4* package and *visreg* packages (Bates et al. 2015; Breheny and Burchett 2017) in R version 4.1.

To test if pied tamarins increased their travel speed (m/s) and changed their routes (i.e., turning angles) in response to noise, we also used two GLMMs, using each trajectory as the sampling unit ($N=1078$). The noise difference between a given point and the preceding point was used as a predictor. We also included as predictors the distances to the home range border, distance to the fragment border, time of day, and the interaction between noise difference and distance from the home range border, since noise levels could mediate intergroup interactions. Again, fragment and group identities were used as random factors. Since speed (m/s) had a skewed distribution that also contained zeros, we used a Tweedie distribution in the model, while for the turning angle model, we used a normal distribution (Zuur et al. 2009). Both analyses were implemented using *glmmTMB* and *visreg* packages. For all tests, we used the *performance* package to assay for multicollinearity between predictors (Lüdtke et al. 2021). All terms had a VIF lower than five, indicating low collinearity. Visual inspections of the residuals were performed to identify any violations of the model assumptions and, to do that, we used the *DHARMA* package (Hartig 2020). In the turning angle model, the Kolmogorov-Smirnov test on the simulated residuals indicated a slight deviation from the expected uniformity (KS test, $p=0.042$). However, visual inspection of the residual plots did not reveal any substantial systematic patterns, indicating that the model can be considered appropriate for the data analysed. We also tested for autocorrelation in the speed (m/s) and turning angle models residuals using the *acf* function but found no significant relationship. Consequently, we did not need to control spatial or temporal autocorrelation in our models.

Table 1 Summary of generalised linear mixed model for different descriptors of use of space and movement patterns (speed and turning angle) of nine pied Tamarin (*Saguinus bicolor*) groups in forest fragments of the urban areas of Manaus, Amazonas, Brazil

Response variable	<i>N</i>	Predictor	Estimate	SE	<i>t</i>	<i>p</i>
Intensity of use of space (kernel values UD)	130	Intercept	-11.83	0.005	-2227	<0.001
		Sound level (dB)	-0.006	-0.002	-2.257	0.024
		Number of fruits	1.745	<0.001	11.596	<0.001
		Sound level (dB) × Number of fruits	-0.0002	<0.001	-11.53	<0.001
Group travel speed (m/s)	1078	Intercept	-2.678	0.138	-19.36	<0.01
		Difference in sound level (dB)	0.02	0.01	1.692	0.09
		Hour of the day	-0.03	0.008	-4.08	<0.001
		Distance to forest fragment border	-0.000	0.000	-1.44	0.149
		Distance to HR border	<0.001	<0.001	1.579	0.114
		Distance to HR border × Difference in sound level (dB)	-0.000	0.000	-2.033	0.042
		Turning angle	1078	Intercept	-6.323	11.451
Difference in sound level (dB)	0.074	0.700		0.107	0.915	
Hour of the day	0.248	0.886		0.280	0.779	
Distance to forest fragment border	0.034	0.062		0.553	0.580	

HR home range, × interacting factor

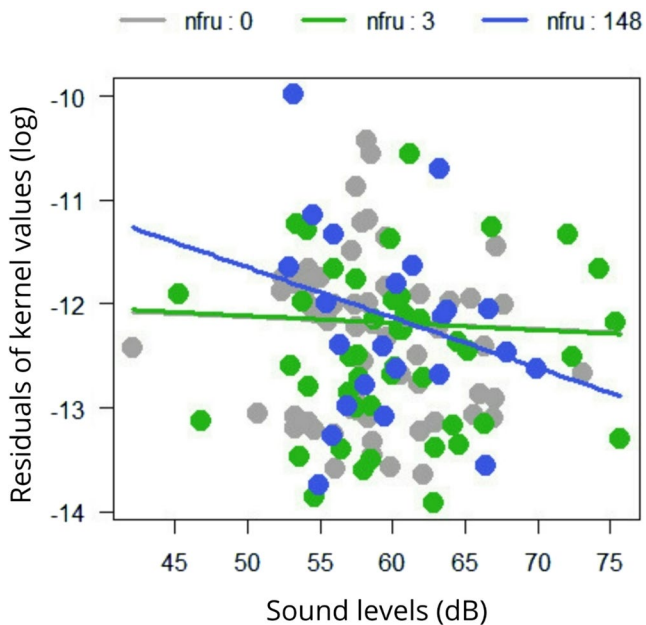


Fig. 3 Relationships between the intensity of use of space (kernel values UD), sound level (LEq), and resource availability (number of fruits). Nfru=Number of fallen fruits recorded on the forest floor in 10 × 10 m plots. Grey=zero fruits recorded, Green=one to three fruits recorded, Blue=four to 148 fruits recorded

Results

Use of space by pied tamarins was not uniform within home ranges, some areas were visited more frequently than others. As expected, pied tamarins used the quieter areas of their ranges more intensively, but this only occurred in locations where fruit availability was high (Table 1; Fig. 3). Overall, groups had a mean daily path of 3.11 km/day (sd=344 m)

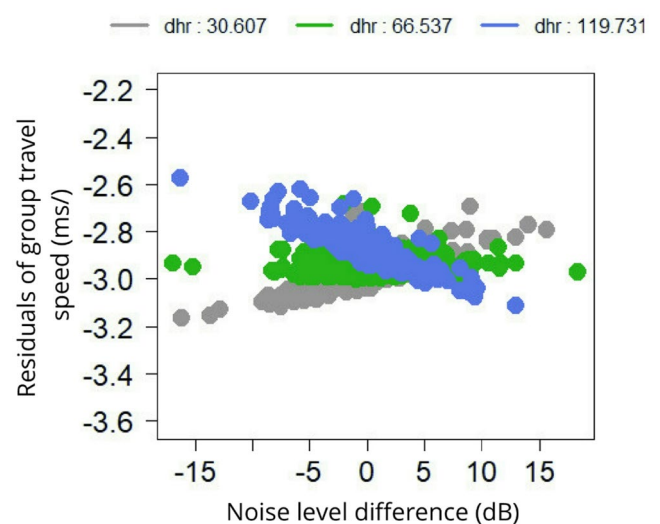


Fig. 4 Relation between pied tamarin group travel speed (m/s) and difference in noise level (dB) interacting with distance from home range boundaries. Dhr=Distance from home range boundaries. Grey=zero to 30.60 m, Green=30.61 m to 63.53 m, Blue=63.54 to 119.73 m. Each point represents a trajectory from a group of pied tamarins (*Saguinus bicolor*) from forest fragments of the urban area of Manaus, Amazonas, Brazil

and moved at a mean speed of 0.055 m/s (sd=0.04 m/s). Pied tamarins remained still in only 8.6% (speed=zero m/s) of the analysed trajectories. Group travel speed in response to noise depends on the distance to the home range border (Table 1; Fig. 4; Supplementary Material, Figure S2). When closer to the home range border, groups travelled faster when the noise difference was greater. In contrast, when far from the home range border, they travelled more slowly. Independent of the other variables, pied tamarin travel speed decreased during the course of the day (Table 1; Fig.

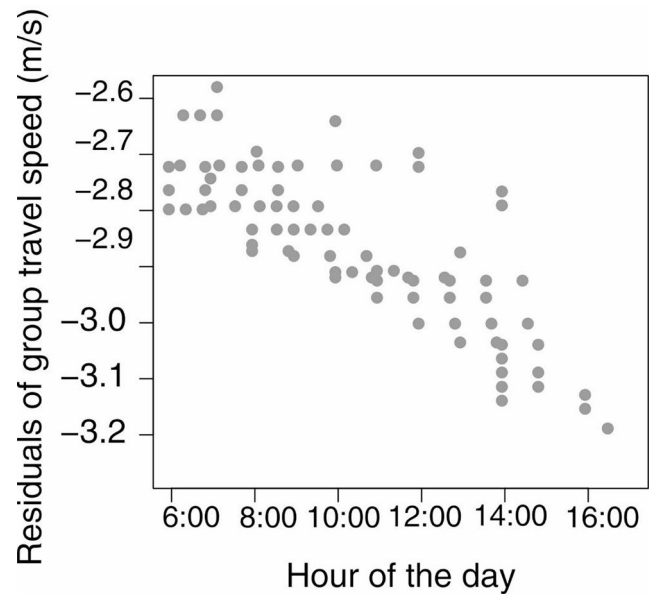
5), and they seemingly did not change routes in response to noise, as we found no difference in turning angles (Table 1).

Discussion

In this study, we tested whether pied tamarin groups changed their spatial use and movement patterns in response to noise levels. As expected, pied tamarins used the quieter areas of their ranges more intensively, but this change only occurred where fruit availability was high. We have reported previously that the occurrence of long calls was directly related to environmental sound level (Sobroza et al. 2024) and raised the hypothesis that when faced with intense noise levels, pied tamarins emitted a single long call, a call related to territoriality and group cohesion and moved to quieter areas. Here, we found evidence to partially support such a hypothesis. Additionally, we found that the pied tamarins increased their travel speed in response to noise, but only when the distance to their home range borders, a proxy for neighbour proximity, was short. Furthermore, groups reduce their travel speed gradually throughout the day, an expected pattern for callitrichids, as these small primates lower their metabolism prior to sleeping (Thompson et al. 1994).

Tamarins appear to avoid noisier areas when food is abundant, but under food scarcity they may be unable to forego these disturbed habitats without risking nutritional stress. This is different from results reported for another callitrichid, the black tufted marmoset (*Callithrix penicillata*), which was found to use the quieter areas of an urban park more than noisier areas, even if quieter areas had less food (Duarte et al. 2011). Similarly, hylid frogs (*Boana* spp.) move away from high noise areas (Caorsi et al. 2017), while red squirrels (*Tamiasciurus hudsonicus*) also change their occupancy under noisy conditions, which is a measure of spatial use at a populational level (Chen and Koprowski 2015). Despite finding trends of avoidance at the group level, we are not confident that a similar pattern occurs at the population level. However, an understanding of the pied tamarin spatial use at a broader scale is likely to be important for implementing conservation actions, such as ecological corridors (Beier and Noss 1998) which are a key element for the planned conservation of urban *S. bicolor* populations.

In addition to horizontal habitat use, it is possible that pied tamarins adjust their habitat use vertically to avoid having their calls masked by noise. For example, brilliant-thighed poison frogs (*Allobates femoralis*), adjust the height of their calling perch according to background noise, to optimise the propagation of their calls (Rodríguez et al. 2020). Similarly, golden lion tamarins (*Leontopithecus rosalia*), also change their use of forest strata when calling to improve call



defend their territories with vocal displays to neighbouring groups, and call masking could be potentially detrimental during such encounters. Previous studies have found that pied tamarin groups increase the number of long calls when closer to their home range borders (Sobroza et al. 2024). In combination, the increase in group travel speed and in the number of long calls may result in high energy expenditure when defending territories with noisy contexts. In contrast to our results, Bolivian titi monkeys (*Plecturocebus donacophilus*) in noisier areas do not change their travel speed and spend less time moving in noisy situations (Líneros et al. 2020). In howler monkeys, fleeing represented only 2% of the recorded responses to anthropogenic noise (Gómez-Espinosa et al. 2022). Our findings suggest that in territorial primate species, intergroup social relationships may play an important role in decision-making regarding the pace and direction of movements in noisy contexts. Such movement patterns related to social contexts have also been reported for other territorial primate species, such as capuchin monkeys (Crofoot 2013).

In general, we found a relatively slow travel speed for pied tamarin groups (~ 0.05 m/s); this differs from those reported for captive cotton-top tamarins, which move at a mean speed of 0.55 m/s (Caperos et al. 2012). However, any group velocity is an average of the behaviour of several individuals and the possibility that individual patterns of movement, recorded with GPS trackers or accelerometers (Sha et al. 2017; Sánchez-Giraldo and Daza 2019) would likely provide different values from those we found here. In addition, both the use of space and animal movement are often driven by the spatial distribution and availability of key resources (Johnson et al. 2015; Bufalo et al. 2024). We found a positive relationship between the intensity of use of space and fruit abundance but were unable to test its possible effects on movement patterns such as speed and turning angles. Future studies that consider such aspects to evaluate pied tamarin movement in urban landscapes may well be instructive.

We expected that tamarins would change their routes to avoid noise, however, we found no relationship between turning angles and noise levels. Straightness in animal movement is often associated with minimising energetic costs (Robira et al. 2024), and animal navigation is often associated with some form of spatial learning (Benhamou 2010). If tamarins become relatively well habituated to highly repetitive sounds, such as traffic noise, and it becomes a “*soundmark*” (an analogy to the term *landmark*, used in animal movement ecology), groups can still maximise the straightness of their routes while avoiding or ignoring noisy areas. In urban areas, it is common to see pied tamarins near roads, so it is likely that they are habituated to such noise sources. This is certainly known in other

primates: in chacma baboons (*Papio ursinus*), for example, individuals that used the urban areas more frequently had more direct travel paths in such places (Bracken et al. 2024). Thus, habituation may play an important role in the energetics of primate movement in urban landscapes.

One limitation of our study was that we estimated noise using amplitude (dB) metrics, not frequency or sound composition, which could differentially mask pied tamarin calls. Future work incorporating spectral analyses would refine our understanding of acoustic constraints on pied tamarins’ use of space and movement. In addition, we monitored the groups for a relatively short period of time (10 days) in different months of the year, and such trends may vary seasonally, both regarding noise levels (Munir et al. 2021), but also fruit availability (Aleixo et al. 2023), and therefore in animal movement and use of space. Our results show a general trend that would be worth investigating on other time scales. Additionally, our conclusions are based on the observation of only nine groups, which reduces our generalization power. Thus, sampling more groups would be desirable.

An ecological corridor network is being developed in the city of Manaus to link forest fragments to increase pied tamarin habitat connectivity and facilitate movements between forest-patches (Coelho et al. 2018). The forest fragments studied here are either part of or near the area designated for the corridor. Our discovery that the species prefer quieter areas only when they contain abundant food has several important applied implications, especially for conservation planning. For example, enriching depleted forest fragments with tree species fed on by tamarins for their fruits could benefit groups by allowing them to choose a quieter area with food resources. Also, the currently narrow areas of the ecological corridor still in need of reforestation might benefit from the planting of fruit-producing trees so tamarins can choose whether or not to avoid the noise. Planting fruit-producing trees may be especially important in the case of narrow and long corridors; the main function of such corridors is to facilitate the dispersal of individuals, which is important for gene flow and forest fragment recolonisations. Since these corridors will be areas of transition for dispersal individuals, it is important to have food to temporarily sustain individuals during such movements.

Conclusion

In summary, pied tamarins use the quieter areas of their range more if there is good food availability. When faced with intense sound levels, group travel speed increases, but only in areas closer to the border of their home ranges. Possibly because higher noise levels at home-range borders could affect intergroup communication. In addition, we

found that pied tamarins do not alter routes abruptly due to noise levels. Overall, pied tamarin use of space and movement patterns are partially related to noise levels but also driven by social aspects and resource availability. From a conservation perspective, this is an interesting result as it shows that increased noise levels appear not to cause pied tamarins to expend more energy than necessary in avoidance-related movements, such as fleeing or changing routes. In addition, the study supports the proposal of using fruiting trees to selectively enrich forest fragments, thus enabling these endangered primates to choose areas with high-quality soundscapes as well as food resource availability. Our findings highlight the need to integrate acoustic environments into conservation planning, particularly in urban landscapes where critically endangered primates, such as the pied tamarin, persist.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Tainara V. Sobroza. Spatial analysis was performed by Tainara V. Sobroza, Bruna N. Mendel and Luciano C.A. Querido. Adrian P.A. Barnett, Marcelo Gordo and Jacob C. Dunn supervised. The first draft of the manuscript was written by Tainara Venturini Sobroza, and all authors commented and edited the previous and current versions of the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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