

Research Article

Urban noise does not alter spectral characteristics, but increases element delivery rate in the territorial song of the Austral Thrush (*Turdus falcklandii* Quoy & Gaimard, 1824)

Carlos Barrientos^{1,2}, Erik M. Sandvig^{3,4}, Heraldo V. Norambuena^{3,4}

¹ Escuela de Medicina Veterinaria, Facultad de Ciencias de la Vida, Universidad Andres Bello, Concepción, Chile

² Doctorado en Conservación y Gestión de la Biodiversidad, Facultad de Ciencias, Universidad Santo Tomás, Santiago, Chile

³ Centro Bahía Lomas, Facultad de Ciencias, Universidad Santo Tomás, Santiago, Chile

⁴ Red de Observadores de Aves y Vida Silvestre de Chile (ROC), Santiago, Chile

Corresponding author: Carlos Barrientos (carlos.barrientos@unab.cl)



Academic editor: Reinhard Klenke

Received: 20 August 2025

Accepted: 30 June 2026

Published: 16 July 2026

ZooBank: <https://zoobank.org/AAFD147A-430E-45CD-BBEC-DE32989969AD>

Citation: Barrientos C, Sandvig EM, Norambuena HV (2026) Urban noise does not alter spectral characteristics, but increases element delivery rate in the territorial song of the Austral Thrush (*Turdus falcklandii* Quoy & Gaimard, 1824). Nature Conservation 64: 93–109. <https://doi.org/10.3897/natureconservation.64.169272>

Copyright: © Carlos Barrientos et al.
This is an open access article distributed under terms of the Creative Commons Attribution License (Attribution 4.0 International – CC BY 4.0).

Abstract

Vocal communication involves the transfer of information between individuals through acoustic signals. In urban environments, these signals often encounter challenges that can impede effective communication. According to the Acoustic Adaptation Hypothesis (AAH), sound transmission varies across habitats and selection is expected to favour vocalisations that maximise signal propagation in a given environment. To evaluate the relevance of the AAH in the territorial song of the Austral Thrush (*Turdus falcklandii*), a common species in urban areas, we analysed six bioacoustics parameters relevant to communication in urban areas of Concepción, Chile and assessed their association with four disturbance variables related to urban development that could influence vocal communication: ambient noise (dB), vegetation cover (%), built-up area (%) and building height (m). Our results showed no significant relationship between urban disturbance variables and spectral parameters (minimum frequency, maximum frequency, peak frequency) or song duration of Austral Thrush territorial songs. However, ambient noise level significantly affected the temporal delivery rate of song elements: birds in noisier environments sang with faster element rates. Ground cover type also influenced element rate, with birds in bare soil areas singing approximately 0.46 elements/s faster than those in grass-dominated areas. These findings suggest that the Austral Thrush maintains consistent spectral song characteristics across urban disturbance gradients, while modifying the temporal structure of song delivery, representing a previously undocumented behavioural adjustment to urban acoustic conditions in this species.

Key words: Acoustic Adaptation Hypothesis, bioacoustics, urban birds

Introduction

The process of vocal communication involves the transfer of information between individuals through an acoustic signal (Craig 1999; Alvar 2015), which, in the case of birds, is essential, since they are used for the recognition of their partner and conspecifics (Tubaro and Segura 1989; León et al. 2014; Isaksson 2018). Urban environments emerge as new and constantly expanding

ecosystems, exposing wildlife to selective pressures that often differ drastically from those in which they have evolved (Lowry et al. 2013). In this context, within cities, there are gradients of degrees of urbanisation, some characterised by houses with semi-natural private spaces and high vegetation cover (e.g. gardens), while others have areas covered by buildings of various heights and surfaces highly impermeable to water (Marzluff 2001; MacGregor-Fors and Schondube 2011; Isaksson 2018; Bernat-Ponce et al. 2022). Vegetation is one of the main variables influencing bird diversity in urban ecosystems; trees, shrub and herbaceous cover positively influence bird abundance (Leveau and Leveau 2006; Benito et al. 2019), as these cover areas are associated with food availability, nesting sites, shelter and perching sites (Benito et al. 2019; da Silva et al. 2021). Other standard land covers in urban environments, such as pavement and buildings, also influence bird abundance in the city. In general, areas with a high construction density have a low abundance of native birds because habitat quality is considered poor for these species (Amaya-Espinel et al. 2019; Benito et al. 2019; Apfelbeck et al. 2025).

Anthropogenic disturbances vary within cities as green areas (i.e. land surface predominantly covered by vegetation), trees and buildings are not distributed homogeneously (Benito et al. 2019), generating environments that may hinder vocal communication in birds to varying degrees, particularly in species that depend on vocalisation in their intraspecific relationships, which can result in a series of effects on behaviour, distribution and population density (Calderón-Quiroga et al. 2020; Suarez-Romero 2021; Bernat-Ponce et al. 2022). Additionally, urban areas generate acoustic environments characterised by high levels of ambient noise (> 56 dB; Juárez et al. (2020)), which can affect vocal communication and pose a challenge for species that depend on vocalisations in their relationships (Slabbekoorn and Peet 2003; Mendes et al. 2017; Juárez et al. 2020). These high levels of anthropogenic noise can interfere with the detection of relevant biological sounds, such as songs and calls, which could make them more vulnerable to predation, alter their behaviour, in terms of finding breeding territories, defence mechanisms, foraging, communication between pairs and adult-offspring and compromise their chances of reproductive success (Krause 2008; Francis et al. 2011; Halfwerk et al. 2011; Ortega 2012; León et al. 2014; Templeton et al. 2016; Mendes et al. 2017; Suarez 2021; De Kort et al. 2024). Such impacts can ultimately affect population stability and community composition in urban environments (León et al. 2014; Carral-Murrieta et al. 2020; Suarez 2021).

Morton (1975) proposed that habitat structure has influenced the evolution of the acoustic characteristics of songs, a hypothesis known as the Acoustic Adaptation Hypothesis (AAH). This hypothesis holds that, since sound propagation varies according to habitat type, natural selection favours those sounds that maximise sound dispersion from the source. The AAH has been evaluated in urban environments, where multiple species have been reported to have the flexibility to adjust the spectrotemporal characteristics of their vocalisations to avoid being masked by the structure of the urban environment (e.g. vegetation structure, reflective surfaces) or by human-associated factors such as anthropogenic noise (Halfwerk and Slabbekoorn 2009; Dowling et al. 2012; Redondo et al. 2013; Gough et al. 2014; Juárez et al. 2020; Hao et al. 2024; Díaz-Lezama et al. 2025).

In this context, to communicate effectively in urban environments, some birds may: (1) switch to higher-frequency song types (e.g. *Parus major*, Halfwerk and Slabbekoorn (2009)); (2) sing during times of lower anthropogenic disturbance (e.g. *Erithacus rubecula*, Fuller et al. (2007); Isaksson (2018)) or (3) omit low-frequency elements, which may not be well transmitted in noisy environments (e.g. *Haemorhous mexicanus*, Bermúdez-Caumatzin et al. (2009, 2011)). Species described as not only surviving in urban environments, but doing so successfully, occurring in large numbers with high reproductive values, are known as “adapters” or “exploiters” (McKinney 2006; Humphrey et al. 2023).

The Austral Thrush (*Turdus falcklandii*) is a widespread species in Chile (Jaramillo et al. 2005), inhabiting a wide range of habitats and is abundant in urban environments (Medrano et al. 2018). This positions it as a good model species to evaluate the effect of urban disturbances on its vocal communication. In this study, we evaluate the influence of four urban variables relevant to vocal communication on the bioacoustic parameters of the territorial song of *T. falcklandii*. Considering that the AAH postulates that the spectral characteristics and vocal repertoire of its vocalisations are influenced by the environment, we expect to find variation in these parameters associated with greater urbanisation.

Materials and methods

Study area

The study was conducted in the city of Concepción, Biobío Region, Chile (Fig. 1), across 75 sampling sites. The city has an area of 221.6 km² and a population of 223,574 inhabitants. The climate is Mediterranean, with oceanic influence and a short dry season in summer. The individual recorded at each site was considered independent since the species under study is territorial during the breeding season. Breeding behaviour is concentrated between August and November in areas close to its nest (Marín 2015; Medrano et al. 2018). In areas where more than one pair was identified and were at least 100 metres apart, each vocalising male was recorded.

Methodology

Song recordings

Songs of *T. falcklandii* were recorded from 06:00 h to 08:00 h, corresponding to peak activity for birds (Ralph et al. 1995; Calderón-Quiroga et al. 2020) and at the beginning of the breeding season when individuals are most vocally active (Medrano et al. 2018). Vocalisations were recorded with a ZOOM H4n recorder and a Sennheiser ME66/K6 condenser microphone. All recordings were made in WAV format, at 24 bits, with a sampling frequency of 44.1 kHz (Calderón-Quiroga et al. 2020).

Analysis of vocalisations

The recordings obtained were edited with Audacity (Audacity® software 1999–2019). Before analysis, recordings were standardised to monaural with a sampling rate of 44.1 kHz and 24-bit depth. Subsequently, a bandpass filter was

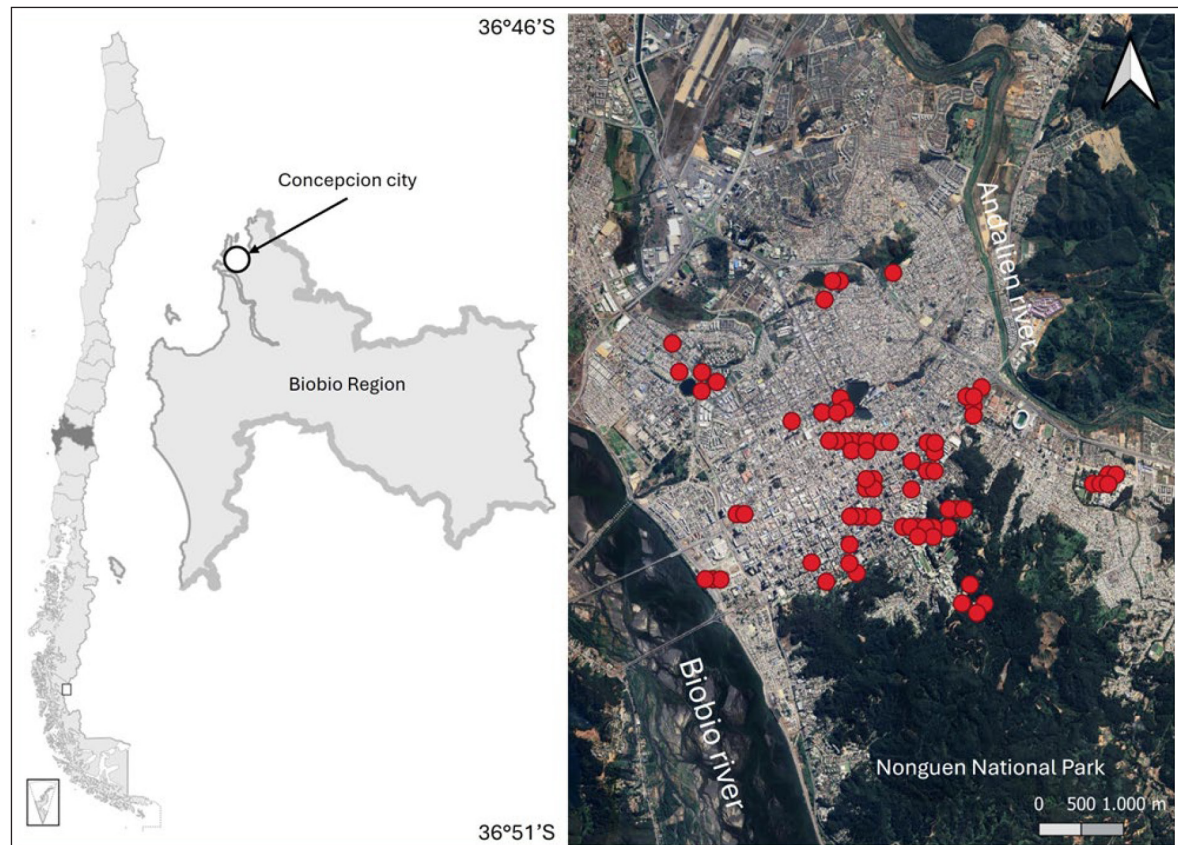


Figure 1. Sampling sites (red dots) for recording *Turdus falcklandii* territorial songs in the City of Concepción, Biobío Region, Chile.

applied to remove noise outside the frequency range of *T. falcklandii* vocalisations, removing noise below 1,000 Hz and above 8,000 Hz. In addition, the recordings were normalised to -3 dB to standardise intensity. Only recordings with a high signal-to-noise ratio were used for analysis. Fine-scale measurements and sonogram analysis were performed with Raven Pro 1.5 (Bioacoustics Research Program 2011), using the default spectrogram parameters (Window-Type: Hann, size: 256 samples = 5.33 ms), 3 dB filter bandwidth: 270 Hz, time grid overlap: 50%, step size: 128 samples = 2.67 ms), grid frequency – DFT: 256 samples, grid spacing: 188 Hz. The variables measured in each sonogram were: (i) total duration of the song (s); (ii) peak frequency (Hz) of the song; (iii) minimum frequency of the song (Hz); (iv) maximum frequency of the song (Hz); (v) number of elements of the song and (vi) number of elements per second of the song. Minimum and maximum frequencies, as well as the peak frequency, were measured using the selection-based measurement tool in Raven Pro 1.5. For each annotated selection, the frequency boundaries of the selection rectangle were manually placed on the spectrogram to enclose approximately 90% of the visible signal energy, excluding the outermost 5% of the spectral energy at both the lower and upper ends of the signal. This criterion guided the placement of selection boundaries and minimises subjectivity in the positioning of frequency limits. Once the selection rectangle was committed, Raven Pro automatically extracted low frequency and high frequency as the lower and upper bounds of the selection (i.e. the y-axis limits of the rectangle) and peak frequency as the frequency bin containing the maximum power spectral density with-

in the selection. This approach reduces the influence of spectrogram display settings on frequency measurements, since boundary placement is guided by the energy content of the signal rather than by visual contrast or brightness thresholds that vary with display gain.

Urban disturbance variables

To understand how differences in the degree of urbanisation affect the songs of *T. falcklandii*, each site was characterised, based on its structural composition. The level of urban disturbance was determined considering the variables: (1) noise (dB); (2) vegetation cover (%); (3) built-up area (%); (4) building height (m) and (5) soil structure (Arévalo et al. 2022). During each focal recording session, ambient noise was measured using a BROAIMX professional sound meter (measurement range 30 to 130 dB). The highest and lowest noise levels were recorded every 10 minutes during each recording session. The average ambient noise value was then calculated following Juaréz et al. (2020). To obtain information on percentage of vegetation cover, percentage of built-up area, building height (m) and soil structure at each sampling point, data were collected on-site (Hao et al. 2015; Rodríguez-Arancibia et al. 2022). A single observer (CB) conducted all field assessments to minimise inter-observer variability. The percentage of vegetation cover and built area were estimated visually within a 25 m radius around the location of each vocalising Austral Thrush (following Hao et al. (2015); Rodríguez-Arancibia et al. (2022)). Within this area, we also defined a ground-cover type variable by determining the predominant composition of the ground as one of four categories: concrete, soil, grass or mixture of grass and soil. This classification describes surface cover rather than pedological soil properties. Within this same area, we visually estimated the height (m) of all buildings and averaged them at each point.

Data analysis

To determine the effect of the different urban disturbance variables on the bioacoustic parameters of the songs (spectral characteristics and vocal repertoires), we used Generalised Linear Mixed Models (GLMMs) implemented in R 4.3.1 (R Core Team 2026). Individual identity was included as a random effect to account for the non-independence of multiple songs recorded from the same bird (mean = 2.96 songs per individual). For continuous response variables (song duration, peak frequency, minimum frequency, maximum frequency, elements per second), we fitted linear mixed models using the lme4 package (Bates et al. 2015). For count response variables (number of elements), we fitted Poisson GLMMs using glmmTMB (Brooks et al. 2017) and tested for overdispersion using the DHARMA package (Hartig 2022); no overdispersion was detected (dispersion = 0.87, $P = 0.46$).

We first, assessed the distribution of all bioacoustics (Suppl. material 1: fig. S1) and disturbance variables (Suppl. material 1: fig. S2) and examined correlations amongst predictors (Suppl. material 1: fig. S3). Vegetation cover and built-up area were nearly perfectly correlated ($r = -0.998$), indicating that the urban gradient in our study area was essentially unidimensional. To examine

the variance structure of urban disturbance variables, we conducted a principal component analysis (PCA) on the four standardised continuous predictors. PC1 explained 55.2% of variance and represented a general urbanisation gradient, with strong positive loading on built-up area (0.65) and negative loading on vegetation cover (-0.65). PC2 (22.7%) captured variation in building height (0.76) and noise (0.52), while PC3 (22.1%) reflected noise variation independent of building height. Vegetation cover and built-up area loaded almost exclusively on opposite ends of PC1, with PC4 explaining only 0.04% of variance, confirming their near-perfect collinearity ($r = -0.998$). We therefore excluded the built-up area from subsequent analyses to avoid multicollinearity while retaining vegetation cover, noise and building height as independent predictors representing distinct aspects of urban structure. We also assessed correlations amongst bioacoustic response variables; song duration and number of elements were highly correlated ($r = 0.87$), but both were retained as they capture different aspects of song structure.

All continuous predictors (noise, vegetation cover, building height) were standardised (z-transformed) prior to analysis to facilitate comparison of effect sizes across variables measured on different scales (Zuur et al. 2010). Ground-cover type was included as a categorical predictor with four levels (grass, concrete, bare soil, mixture). For model comparison, we used Maximum Likelihood (ML) estimation rather than Restricted Maximum Likelihood (REML), as REML is not appropriate for comparing models with different fixed effects structures (Zuur et al. 2010). For each bioacoustic response variable, we performed model selection using the dredge function from the MuMIn package (Bartoń 2022) on a global model including all urban disturbance variables. We calculated model-averaged coefficients across all models within $\Delta AIC_c < 4$ to account for model uncertainty and report 95% confidence intervals for all effect estimates. We also tested for a potential interaction between noise and vegetation cover on minimum frequency.

Power analysis indicated that, with our effective sample size of approximately 141 (accounting for clustering within individuals assuming ICC = 0.3), we had > 80% power to detect effect sizes of $f^2 \geq 0.088$, corresponding to R^2 approximately equal to 0.08. This suggests adequate power to detect even small-to-medium effects.

Results

We analysed 222 songs from 75 individual male Austral Thrushes (mean = 2.96 songs per individual, range: 2-3). Ambient noise levels across the 75 sampling sites ranged from 40.4 to 79.9 dBA (mean $\pm$ SE: 56.3 $\pm$ 1.2 dBA), encompassing both relatively quiet residential areas and busier urban zones.

The number of elements in the territorial song varied between individuals with a range of 3 to 21 elements (mean = 7.95, SD = 3.51; Fig. 2). The mean duration of the song was 4.35 s (SD = 2.12), with a maximum frequency of 10,821 Hz (SD = 4,230), minimum frequency of 1,613 Hz (SD = 241) and peak frequency of 3,158 Hz (SD = 299). Element delivery rate averaged 1.95 elements per second (SD = 0.45, range: 1.15–3.45). Song duration and number of elements were highly correlated ($r = 0.87$), while other bioacoustic variables showed weaker intercorrelations ($|r| < 0.45$; Suppl. material 1: fig. S3).

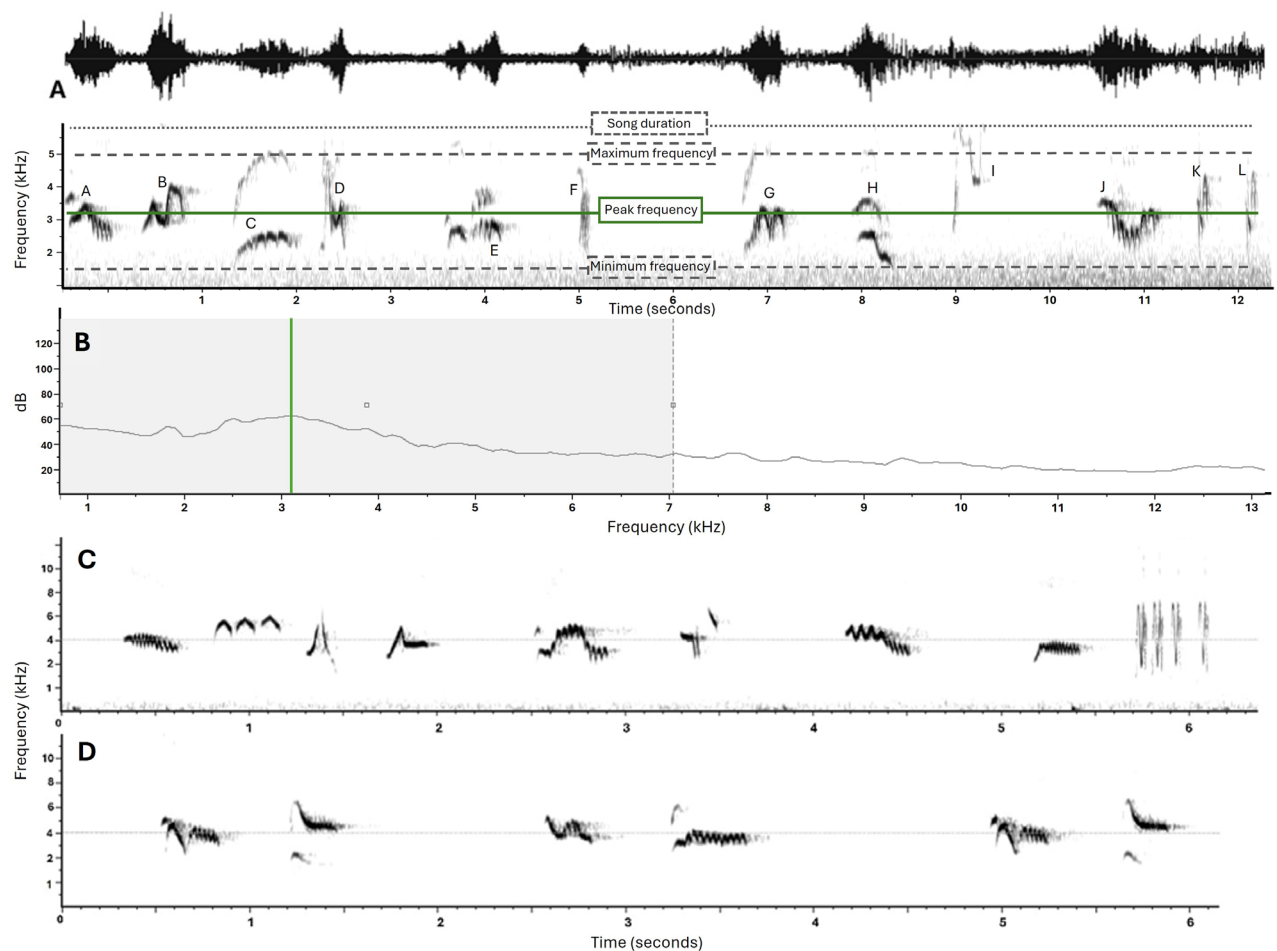


Figure 2. **A.** Waveform (top) and sonogram of the territorial song of *Turdus falcklandii*, illustrating the acoustic variables measured: song duration (horizontal line spanning the full bout), peak frequency (green line at ~ 3.1 kHz), maximum frequency (upper dashed line at ~ 5 kHz) and minimum frequency (lower dashed line at ~ 1.5 kHz). Twelve distinct element types (A–L) are labelled across the time axis, reflecting the structural diversity within a single song bout; **B.** Power spectrum (amplitude in dB vs. frequency in kHz) of the recorded song, showing the dominant energy band between ~ 1–7 kHz (shaded region); the green vertical line marks the peak frequency (~ 3.1 kHz) and the dashed vertical line marks the upper frequency limit (~ 7 kHz); **C, D.** Sonograms of songs from two additional individual birds, illustrating inter-individual variation in element structure, frequency modulation and temporal patterning. Dashed horizontal lines in C and D at 4 kHz serve as visual references for frequency comparison across individuals.

Random effects for individual identity accounted for substantial variance in most response variables, with intraclass correlations (ICC) ranging from 0.39 (peak frequency) to 0.76 (maximum frequency), confirming the importance of accounting for repeated measures within individuals (Table 1).

From the GLMMs, we found that noise level had a significant positive effect on the rate of element delivery (elements per second): birds in noisier environments sang with faster element rates (model-averaged beta = 0.134 elements/s per SD increase in noise, 95% CI: 0.034–0.234, $P = 0.009$; standardised effect size = 0.25; Fig. 3, Table 1). Ground cover type also significantly influenced element rate, with birds in bare soil areas (ground-cover type 3) singing approximately 0.46 elements/s faster than those in grass-dominated areas ($P = 0.003$).

In contrast, noise, vegetation cover, building height and ground-cover type had no significant effects on song duration, peak frequency, minimum frequency, maximum frequency or the total number of elements per song (all $P > 0.05$;

Table 1. Results of Generalised Linear Mixed Models (GLMMs) assessing the effects of urban disturbance variables on bioacoustic parameters of Austral Thrush (*Turdus falcklandii*) territorial songs (n = 222 songs from 75 individuals). All models included individual identity as a random effect and used Maximum Likelihood (ML) estimation for model comparison. Model-averaged coefficients (β) with 95% confidence intervals are shown for all predictors. Continuous predictors (noise, vegetation cover, building height) were z-standardised prior to analysis; coefficients represent the change in response per 1 SD change in predictor. Ground-cover type was included as a categorical predictor with grass as reference level. ICC = intraclass correlation coefficient for individual identity. Significant effects ($P < 0.05$) are shown in bold.

Response variable	Predictor	β (95% CI)	SE	P	Std. β	ICC	Family
Duration (s)	Noise	-0.05 (-0.35, 0.25)	0.15	0.75	-0.02	0.69	Gauss
	Veg. cover	0.05 (-0.28, 0.38)	0.17	0.76	0.02		
	Bldg. height	-0.02 (-0.28, 0.23)	0.13	0.85	-0.01		
	Ground cover	(see notes)	—	0.65	—		
Peak freq. (Hz)	Noise	30.5 (-42.9, 103.9)	37.5	0.42	0.10	0.39	Gauss
	Veg. cover	-2.3 (-40.0, 35.3)	19.2	0.90	-0.01		
	Bldg. height	-23.5 (-90.5, 43.4)	34.2	0.49	-0.08		
	Ground cover	(see notes)	—	0.82	—		
Min. freq. (Hz)	Noise	47.6 (-17.8, 113.0)	33.4	0.15	0.19	0.49	Gauss
	Veg. cover	-9.0 (-49.7, 31.8)	20.8	0.67	-0.04		
	Bldg. height	-8.1 (-46.4, 30.2)	19.5	0.68	-0.03		
	Ground cover	(see notes)	—	0.87	—		
Max. freq. (Hz)	Noise	-15.5 (-462, 431)	228	0.95	-0.01	0.76	Gauss
	Veg. cover	65.5 (-488, 619)	282	0.82	0.02		
	Bldg. height	9.4 (-435, 453)	227	0.97	0.00		
	Ground cover	(see notes)	—	0.67	—		
No. elements	Noise	0.003 (-0.04, 0.05)	0.02	0.91	0.01	0.26	Poiss
	Veg. cover	0.003 (-0.06, 0.07)	0.03	0.93	0.01		
	Bldg. height	-0.007 (-0.06, 0.05)	0.03	0.80	-0.02		
	Ground cover	(see notes)	—	0.53	—		
Elements/s	Noise	0.134 (0.034, 0.234)	0.051	0.009	0.25	0.46	Gauss
	Veg. cover	-0.013 (-0.10, 0.08)	0.05	0.78	-0.03		
	Bldg. height	-0.012 (-0.08, 0.05)	0.03	0.72	-0.02		
	Ground cover	Bare soil: +0.46	0.15	0.003	—		

Notes: Gauss = Gaussian (identity link); Poiss = Poisson (log link). Std. β = standardised coefficient. Ground-cover type is a categorical variable with four levels: grass (reference), concrete (Type 2), bare soil (Type 3) and mixture (Type 4). Overall P-values for ground-cover type represent likelihood ratio tests; individual contrasts vs. grass reference are not shown, except for the significant effect of Type 3 (bare soil) on elements/s. The interaction between noise and vegetation cover was tested for minimum frequency, but was not significant ($\chi^2 = 0.12$, $P = 0.73$).

Table 1). The relationship between noise and minimum song frequency showed a non-significant positive trend (model-averaged beta = 47.6 Hz per SD increase in noise, 95% CI: -17.8 to 113.0, $P = 0.15$; standardised effect = 0.19). The interaction between noise and vegetation cover was not significant for minimum frequency (chi-square = 0.12, $P = 0.73$).

Model-averaged effect estimates with 95% confidence intervals for all response variables are presented in Table 1. For spectral parameters, all confidence intervals for urban disturbance variables included zero and standardised effect sizes were uniformly small ($|d| < 0.20$).

Discussion

Our results reveal a nuanced response of Austral Thrush territorial songs to urban conditions: while spectral parameters remained unaffected by urbanisation variables, the temporal structure of song delivery was significantly influ-

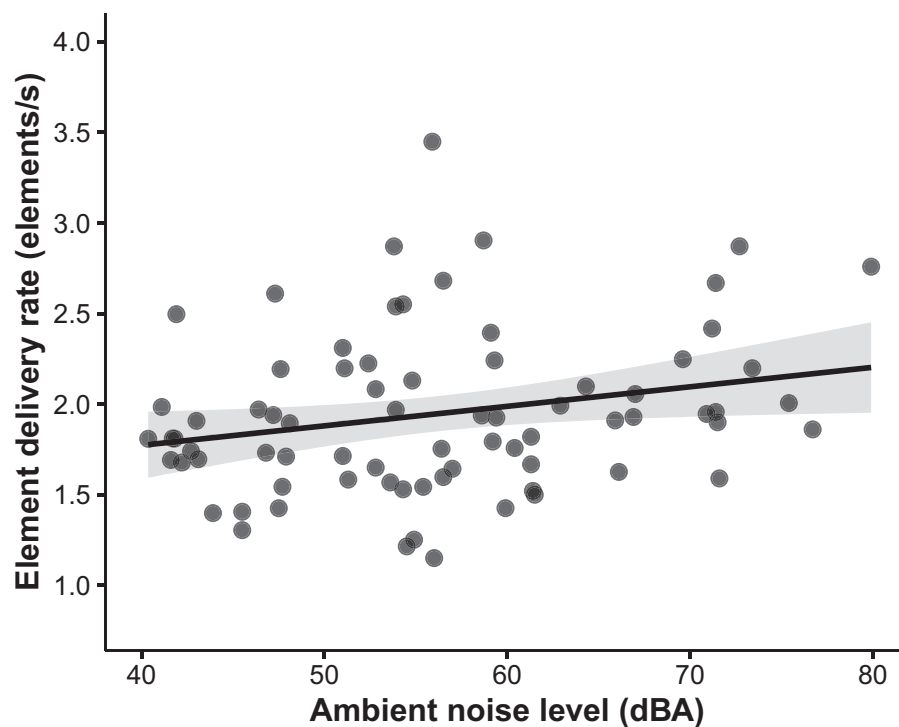


Figure 3. Relationship between ambient noise (dBA) and element delivery rate (elements/s) in Austral Thrush territorial songs. Fitted line: GLMM prediction ($\beta = 0.134$, $P = 0.009$); shading: 95% CI.

enced by ambient noise levels. Birds in noisier environments sang with faster element delivery rates, representing a behavioural adjustment to urban acoustic conditions that has not been previously documented in this species.

The significant effect of noise on element delivery suggests that Austral Thrushes modify the temporal pacing of their songs in response to urban noise, even while maintaining consistent spectral characteristics. This temporal compression of song structure may represent an alternative strategy to the frequency shifts commonly reported in other species. Similar adjustments in temporal pacing have been reported in other taxa; for example, some species increase song rate or reduce inter-song intervals in noisy conditions (Brumm and Slabbekoorn 2005). However, findings on element delivery rate are mixed. Slabbekoorn and den Boer-Visser (2006) found that urban great tits (*Parus major*) sang songs with fewer notes than forest birds, potentially an adaptation to reduce reverberation effects. In contrast, Ríos-Chelén et al. (2015) found no significant relationship between noise levels and trill rate in red-winged blackbirds (*Agelaius phoeniceus*), suggesting that temporal adjustments may be species-specific. Our finding that Austral Thrushes increase element delivery rate in noisier environments adds to this growing body of evidence that birds may employ diverse temporal strategies in response to urban noise.

The concurrent effect of ground-cover type on element rate suggests that multiple environmental factors may interact to shape temporal aspects of song delivery in urban Austral Thrushes. Birds singing in areas with bare soil delivered elements approximately 0.46 elements/s faster than those in grass-dominated areas. Notably, this effect was independent of ambient noise levels: bare soil areas were quieter on average (51.5 dBA) than grass-dominated areas (58.7 dBA),

indicating that the ground-cover effect is not simply a proxy for noise exposure. Concrete and mixed ground cover showed non-significant positive trends in the same direction and the difference between bare soil and concrete effects was not statistically significant. The consistent positive direction across all non-vegetated substrates suggests that open or hard ground surfaces may generally favour faster element delivery, though only the bare soil effect was statistically detectable with our sample sizes ($n = 30$ songs for bare soil vs. $n = 65$ for concrete).

The Acoustic Adaptation Hypothesis predicts that animals in open habitats should produce signals with higher repetition rates compared to those in densely vegetated closed habitats, where reverberation and sound degradation are more severe (Morton 1975; Wiley and Richards 1982; Boncoraglio and Saino 2007). Ground surface composition can influence sound propagation through differential reflection and absorption: vegetated surfaces absorb acoustic energy while hard surfaces, such as bare soil or concrete, produce stronger reflections (Aylor 1972; Richards and Wiley 1980). However, flat reflective surfaces like concrete also generate reverberation that can blur rapidly delivered temporal elements (Bradbury and Vehrencamp 1998; Naguib 2003), potentially counteracting any tendency towards faster delivery rates. This may explain why concrete areas did not show a significant effect despite their expected acoustic reflectivity. Job et al. (2016) found that urban structure influenced spectral, but not temporal features of Chipping Sparrow (*Spizella passerina*) songs, noting that temporal features of trill songs are highly vulnerable to degradation through reverberation. In contrast, bare soil – which is reflective, but with irregular surface texture – may create acoustic conditions that favour faster element delivery without the reverberant blurring associated with flat concrete surfaces.

Alternatively, the ground-cover effect may reflect ecological or behavioural correlates rather than purely acoustic mechanisms. Bare soil areas in urban Concepción likely represent open, exposed microhabitats, such as garden patches, park edges or disturbed areas where birds may experience heightened vigilance or territorial pressure, prompting faster song delivery as a behavioural response. Further experimental work manipulating ground cover, while controlling for other habitat variables, would be needed to distinguish between acoustic and ecological explanations for this pattern.

In contrast to element delivery rate, spectral parameters of Austral Thrush songs showed no significant association with urban disturbance variables. This lack of spectral adjustment contrasts with patterns reported for other thrushes, such as the pale-breasted thrush (*Turdus leucomelas*) and Eurasian blackbird (*Turdus merula*), where individuals in urban environments have been found to sing at higher minimum frequencies (Mendes et al. 2011; Mendes et al. 2017). Similarly, in great tit (*Parus major*), urban populations produce shorter songs compared to rural counterparts (Slabbekoorn and den Boer-Visser 2006). Such vocal adjustments are thought to enhance signal transmission under the specific constraints of urban environments (Brown and Handford 2000; Brumm and Slabbekoorn 2005; Mendes et al. 2017). Shorter songs may reduce overlap with reverberant echoes from buildings and other hard surfaces, thereby improving signal clarity in acoustically complex urban habitats (Slabbekoorn 2013). When sound reflects off buildings and pavement, longer vocalisations are more susceptible to temporal smearing, where echoes from earlier portions of the signal

interfere with later portions (Naguib 2003). By producing shorter songs, birds may minimise this self-masking effect and maintain signal integrity.

However, not all species respond to noise in the same way. For example, Peris and Pescador (2004) found that, in more than half of the passerine populations they studied near roads with varying noise levels, breeding densities did not differ significantly between areas with different noise levels. Interestingly, because noise propagates more effectively in open habitats (Reijnen et al. 1996), one might expect species in these environments to be more exposed to anthropogenic noise. However, species naturally adapted to open habitats typically produce vocalisations with acoustic features – such as higher frequencies, simpler structures and faster temporal patterns – that are already optimised for transmission in low-reverberation environments (Morton 1975; Boncoraglio and Saino 2007). These pre-existing adaptations may confer resilience to urban noise masking, as their signals are less dependent on the acoustic refugia provided by vegetation. This could explain the higher abundance of open-habitat passerines near noisier roads (Peris and Pescador 2004) - species with vocal repertoires pre-adapted to open environments may tolerate or even thrive in noisy roadside habitats where forest-adapted species with lower-frequency, more reverberant songs are acoustically disadvantaged.

These findings suggest that habitat preferences and ecological adaptations may mediate the degree to which noise impacts vocal communication – potentially helping to explain why *T. falcklandii*, a generalist species often found in open and semi-open habitats, does not exhibit spectral modifications in response to urban noise in our study. The Austral Thrush may already possess song characteristics that are robust to urban acoustic challenges or spectral shifts may not be an effective strategy for this species given its vocal structure.

Urban landscapes are often composed of dense exotic vegetation (Borgmann and Rodewald 2005), trees and buildings (Warren et al. 2006), all of which can hinder acoustic transmission (Dowling et al. 2012; Hao et al. 2024; Díaz-Lezama et al. 2025). However, in some species, these structural elements appear to have little impact on vocal behaviour (Dowling et al. 2012). For example, *Melospiza melodia* and *Cardinalis cardinalis* showed no significant variation in song attributes across differing urban habitat structures and noise (Dowling et al. 2012; Desirée and Rodewald 2015). Similarly, in our study, the territorial song of *T. falcklandii* was unaffected by variation in vegetation cover, built-up area, building height or soil structure – suggesting a comparable insensitivity to urban structural features. These urbanisation characteristics could have parallels with natural systems, such as streams, canyons and windy environments – where birds have long adapted their vocal strategies (Warren et al. 2006). However, concrete and glass canyons are more likely to reverberate sounds further (Warren et al. 2006), enhancing the propagation of urban background noise, while also possibly benefitting the transmission of acoustic signals, as the communication distance may be greater in open urban areas with impermeable surfaces that act as sound channels, thereby enhancing signal propagation (Gall et al. 2012). This dual effect raises the possibility that certain urban structures may inadvertently facilitate vocal communication under specific conditions.

The habitat structure and spatial arrangement of urban green spaces is a crucial factor influencing bird-song behaviour, jointly shaping their acoustic niche in

urban environments. Vegetation can absorb, reflect and scatter sound, thereby dampening anthropogenic noise and creating acoustic refuges (Watts et al. 1999; Bormpoudakis et al. 2013; Darras et al. 2016; Job et al. 2016; Priyadarshani et al. 2018). Abundant vegetation not only provides suitable habitats and feeding grounds, but can also buffer anthropogenic noise, creating acoustic refugia where birds experience reduced masking of their vocalisations (Watts et al. 1999; Bormpoudakis et al. 2013). By attenuating traffic and industrial noise, vegetated areas may allow birds to communicate effectively at lower amplitudes or maintain larger active spaces for their signals (Hao et al. 2024). However, dense vegetation can also degrade signal transmission through absorption and scattering (Richards and Wiley 1980), suggesting a trade-off where intermediate vegetation density may optimise the balance between noise reduction and signal propagation.

Another potential strategy for coping with urban disturbances is behavioural adjustment in the timing of vocalisations. Some species, such as *E. rubecula*, shift their singing activity to night-time hours to reduce overlap with periods of high noise (Fuller et al. 2007), while *T. merula* begins its dawn chorus earlier to avoid traffic noise and artificial light (Nordt and Klenke 2013). Arroyo-Solís et al. (2013) also found that, in areas with greater noise exposure, *Sturnus unicolor* and *Passer domesticus*, advanced the onset of their vocal activity. Our finding that Austral Thrushes increase element delivery rate in noisy areas represents another form of temporal adjustment, operating at the within-song level rather than the daily activity level.

Conclusions

Our findings indicate that urban noise significantly influences the temporal structure of *T. falcklandii*'s territorial songs, with birds in noisier environments singing at faster element delivery rates. In contrast, spectral parameters, including minimum frequency, maximum frequency and peak frequency, showed no significant association with urban disturbance variables. This pattern suggests that the *T. falcklandii* adjusts the temporal pacing of its songs rather than their spectral characteristics in response to urban acoustic conditions. The discovery of this temporal adjustment, combined with the null findings for spectral parameters, underscores the importance of examining multiple acoustic dimensions when evaluating avian responses to urbanisation. Future research should explore whether faster element delivery enhances signal detection in noisy environments and whether this behavioural adjustment has fitness consequences for urban-dwelling *T. falcklandii*.

Acknowledgements

EMS was funded by a Subvención a la Inserción a la Academia (SIA8522018) grant from the Agencia Nacional de Investigación y Desarrollo (ANID) of Chile.

References

- Alvar RSM (2015) Plasticidad fenotípica del canto en el chincol, *Zonotrichia capensis*: Variación intraindividual por efecto de la actividad antrópica y ruido ambiente. Tesis para optar al Grado de Licenciado en Ciencias Biológicas. Escuela de Cs., Facultad de Cs., Univ. Austral de Chile, Valdivia, Chile.

- Amaya-Espinel JD, Hostetler M, Henríquez C, Bonacic C (2019) The influence of building abundance on Neotropical bird communities found in small urban parks. *Landscape and Urban Planning* 190: 103578. <https://doi.org/10.1016/j.landurbplan.2019.05.009>
- Apfelbeck BA, Navalpotro Buscail M, Sommer A, Petermann JS (2025) Bird community responses to urbanization and vegetation parameters across the city of Salzburg, Austria. *Urban Ecosystems* 28: 131. <https://doi.org/10.1007/s11252-025-01738-y>
- Arévalo C, Amaya-Espinel JD, Henríquez C, Ibarra JT, Bonacic C (2022) Urban noise and surrounding city morphology influence green space occupancy by native birds in a Mediterranean-type South American metropolis. *Scientific Reports* 12: 4471. <https://doi.org/10.1038/s41598-022-08654-7>
- Arroyo-Solís A, Castillo-Segura JM, Figueroa-Clemente ME, López- Sánchez JL, Slab-bekoorn H (2013) Experimental evidence for an impact of anthropogenic noise on dawn chorus timing in urban birds. *Journal of Avian Biology* 44: 288–296 <https://doi.org/10.1111/j.1600-048X.2012.05796.x>
- Aylor D (1972) Noise Reduction by Vegetation and Ground. *The Journal of the Acoustical Society of America* 51: 197–205. <https://doi.org/10.1121/1.1912830>
- Bartoń K (2022) MuMIn: Multi-Model Inference. R package version 1.47.1. <https://doi.org/10.32614/cran.package.mumin>
- Bates D, Mächler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. *Journal of Statistical Software* 67: 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Benito JF, Escobar MAH, Villaseñor NR (2019) Conservación en la ciudad: ¿Cómo influye la estructura del hábitat sobre la abundancia de especies de aves en una metrópoli latinoamericana?. *Gayana (Concepción)* 83(2): 114–125. <https://doi.org/10.4067/S0717-65382019000200114>
- Bermúdez-Cuamatzin E, Ríos-Chelén AA, Gil D, Garcia CM (2009) Strategies of song adaptation to urban noise in the house finch: syllable pitch plasticity or differential syllable use? *Behaviour* 146: 1269–1286. <https://doi.org/10.1163/156853909x423104>
- Bermúdez-Cuamatzin E, Ríos-Chelén AA, Gil D, Garcia CM (2011) Experimental evidence for real-time song frequency shift in response to urban noise in a passerine bird. *Biology Letters* 7(1): 36–38. <https://doi.org/10.1098/rsbl.2010.0437>
- Bernat-Ponce E, Gil-Delgado JA, López-Iborra GM (2022) Efectos de las características de las ciudades occidentales contemporáneas sobre la avifauna urbana. *Ecosistemas* 31(1): 2158. <https://doi.org/10.7818/ECOS.2158>
- Boncoraglio G, Saino N (2007) Habitat structure and the evolution of bird song: a meta-analysis of the evidence for the acoustic adaptation hypothesis. *Functional Ecology* 21: 134–142. <https://doi.org/10.1111/j.1365-2435.2006.01207.x>
- Borgmann KL, Rodewald AD (2005) Forest restoration in urbanizing landscapes: interactions between land uses and exotic shrubs. *Restoration Ecology* 13: 334–340. <https://doi.org/10.1111/j.1526-100X.2005.00042.x>
- Bormpoudakis D, Sueur J, Pantis JD (2013) Spatial heterogeneity of ambient sound at the habitat type level: ecological implications and applications. *Landscape Ecology* 28: 495–506. <https://doi.org/10.1007/s10980-013-9849-1>
- Bradbury JW, Vehrencamp SL (1998) *Principles of Animal Communication*. Vol. 132. Sinauer Associates.
- Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Mächler M, Bolker BM (2017) glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *The R Journal* 9(2): 378–400. <https://doi.org/10.32614/RJ-2017-066>

- Brown TJY, Handford P (2000) Sound design for vocalizations: quality in the woods, consistency in the fields. *Condor* 102: 81–92. <https://doi.org/10.1093/condor/102.1.81>
- Brumm H, Slabbekoorn H (2005) Acoustic communication in noise. *Advances in the Study Behaviour* 35: 151–209. [https://doi.org/10.1016/S0065-3454\(05\)35004-2](https://doi.org/10.1016/S0065-3454(05)35004-2)
- Calderón-Quiroga S, Riquero M, Marchant M, Norambuena HV (2020) Variación del canto del chincol (*Zonotrichia capensis*) en un gradiente urbano-natural del Concepción metropolitano, Chile. *Revista Chilena de Ornitología* 26(1): 13–18.
- Carral-Murrieta CO, García-Arroyo M, Marín-Gómez OH, Sosa-López JR, MacGregor-Fors I (2020) Noisy environments: untangling the role of anthropogenic noise on bird species richness in a Neotropical city. *Avian Research* 11(1): 1–7. <https://doi.org/10.1186/s40657-020-00218-5>
- Craig RT (1999) Communication theory as a field. *Communication Theory* 9: 199–161. <https://doi.org/10.1111/j.1468-2885.1999.tb00355.x>
- Da Silva BF, Pena JC, Viana-Junior AB, Vergne M, Pizo MA (2021) Noise and tree species richness modulate the bird community inhabiting small public urban green spaces of a neotropical city. *Urban Ecosystems* 24(1): 71–81. <https://doi.org/10.1007/s11252-020-01021-2>
- Darras K, Pütz P, Fahrurrozi, Rembold K, Rembold K, Tschardt T (2016) Measuring sound detection spaces for acoustic animal sampling and monitoring. *Biological Conservation* 201: 29–37. <https://doi.org/10.1016/j.biocon.2016.06.021>
- De Kort SR, Porcedda G, Slabbekoorn H, Mossman HL, Sierro J, Hartley IR (2024) Noise impairs the perception of song performance in blue tits and increases territorial response. *Animal Behaviour* 215: 131–141. <https://doi.org/10.1016/j.anbehav.2024.07.011>
- Desirée LN, Rodewald AD (2015) Urban-associated drivers of song variation along a rural–urban gradient. *Behavioral Ecology* 27(02): 608–616. <https://doi.org/10.1093/beheco/arv197>
- Díaz-Lezama X, Ríos-Chelén AA, Castellanos-Albores J, Enríquez PL (2025) Are urbanization, biotic and social factors associated with the song frequency and song entropy attributes of three urban syntopic passerines? *Avian Research* 16(1): 100219. <https://doi.org/10.1016/j.avrs.2024.100219>
- Dowling JL, Luther DA, Marra PP (2012) Comparative effects of urban development and anthropogenic noise on bird songs. *Behavioral Ecology* 23(1): 201–209. <https://doi.org/10.1093/beheco/arr176>
- Francis CD, Ortega CP, Cruz A (2011) Noise pollution filters bird communities based on vocal frequency. *PLoS ONE* 6: e27052. <https://doi.org/10.1371/journal.pone.0027052>
- Fuller RA, Warren PH, Gaston KJ (2007) Daytime noise predicts nocturnal singing in urban robins. *Biology Letters* 3(4): 368–370. <https://doi.org/10.1098/rsbl.2007.0134>
- Gall MD, Ronald KL, Bestrom ES, Lucas JR (2012) Effects of habitat and urbanization on the active space of brown-headed cowbird song. *The Journal of the Acoustical Society of America* 132: 4053–4062. <https://doi.org/10.1121/1.4764512>
- Gough DC, Mennill DJ, Nol E (2014) Singing seaside: Pacific Wrens (*Troglodytes pacificus*) change their songs in the presence of natural and anthropogenic noise. *The Wilson Journal of Ornithology* 126: 269–278. <https://doi.org/10.1676/13-088.1>
- Halfwerk W, Slabbekoorn H (2009) A behavioural mechanism explaining noise-dependent frequency use in urban birdsong. *Animal Behaviour* 78: 1301–1307. <https://doi.org/10.1016/j.anbehav.2009.09.015>
- Halfwerk W, Botb S, Buikx J, van der Velde M, Komdeur J, ten Cate C, Slabbekoorn H (2011) Low-frequency songs lose their potency in noisy urban conditions.

- Proceedings of the National Academy of Sciences of the United States of America 108: 14549–14554. <https://doi.org/10.1073/pnas.1109091108>
- Hao Y, Kang J, Krijnders JD (2015) Integrated effects of urban morphology on birdsong loudness and visibility of green areas. *Landscape and Urban Planning* 137: 149–162. <https://doi.org/10.1016/j.landurbplan.2015.01.006>
- Hao Z, Chengyun Z, Le L, Bingtao G, Ruichen W, Nancai P, Yang L (2024) Anthropogenic noise and habitat structure shaping dominant frequency of bird sounds along urban gradients. *iScience* 27(2): 109056. <https://doi.org/10.1016/j.isci.2024.109056>
- Hartig F (2022) DHARMa: residual diagnostics for hierarchical (multi-level/mixed) regression models. R package version 0.4. 6. <https://doi.org/10.32614/cran.package.dharma>
- Humphrey JE, Haslem A, Bennett AF (2023) Avoid, adapt or exploit: Re-visiting bird responses to urbanisation using a novel landscape approach. *Global Ecology and Conservation* 48: e02735. <https://doi.org/10.1016/j.gecco.2023.e02735>
- Isaksson C (2018) Impact of urbanization on birds. In: Tietze DT (Ed.) *Bird species. How they arise, modify and vanish*, Springer open, Cham, Suiza, 235–257.
- Jaramillo A, Burke P, Beadle D (2005) *Aves de Chile*. Lynx edicions, Barcelona, España.
- Job JR, Kohler SL, Gill SA (2016) Song adjustments by an open habitat bird to anthropogenic noise, urban structure, and vegetation. *Behavioural Ecology* 27: 1734–1744. <https://doi.org/10.1093/beheco/arw105>
- Juaréz R, Araya-Ajoy YG, Barrantes G, Sandoval L (2020) House Wrens *Troglodytes aedon* reduce repertoire size and change song element frequencies in response to anthropogenic noise. *Ibis* 163: 52–64. <https://doi.org/10.1111/ibi.12844>
- Krause B (2008) Anatomy of the soundscape: evolving perspectives. *Journal of Audio Engineering Society* 56: 1–2.
- León E, Beltzer A, Quiroga M (2014) El jilguero dorado (*Sicalis flaveola*) modifica la estructura de sus vocalizaciones para adaptarse a hábitats urbanos. *Revista Mexicana de Biodiversidad* 85: 546–552. <https://doi.org/10.7550/rmb.32123>
- Leveau CM, Leveau LM (2006) Ensamblajes de aves en calles arboladas de tres ciudades costeras del sudeste de la provincia de Buenos Aires, Argentina. *El hornero* 21(1): 25–30. <https://doi.org/10.56178/eh.v21i1.795>
- Lowry H, Lill A, Wong BBM (2013) Behavioural responses of wildlife to urban environments. *Biological Reviews* 88: 537–549. <https://doi.org/10.1111/brv.12012>
- MacGregor-Fors I, Schondube JE (2011) Gray vs. green urbanization: Relative importance of urban features for urban bird communities. *Basic and Applied Ecology* 12: 372–381. <https://doi.org/10.1016/j.baae.2011.04.003>
- Marín M (2015) Biología reproductiva e historia natural del zorzal (*Turdus falcklandii*) en Chile central. *Boletín del Museo Nacional de Historia Natural, Chile* 62: 121–132. <https://doi.org/10.54830/bmnhn.v64.2015.114>
- Marzluff JM (2001) Worldwide increase in urbanization and its effects on birds. In: Marzluff JM, Bowman R, Donnelly R (Eds) *Avian ecology and conservation in an urbanizing world*. Kluwer Academic, Norwell, MA, 19–47. https://doi.org/10.1007/978-1-4615-1531-9_2
- McKinney ML (2006) Urbanisation as a major cause of biotic homogenization. *Biological Conservation* 127(3): 247–260. <https://doi.org/10.1016/j.biocon.2005.09.005>
- Medrano FM, Barros R, Norambuena HV, Matus R, Schmitt F (2018) *Atlas de las aves nidificantes de Chile*. Red de Observadores de Aves y Vida Silvestre de Chile. Santiago, Chile.
- Mendes S, Colino-Rabanal VJ, Peris SJ (2011) Bird song variations along an urban gradient: the case of the European Blackbird (*Turdus merula*). *Landscape and Urban Planning* 99: 51–57. <https://doi.org/10.1016/j.landurbplan.2010.08.013>

- Mendes S, Solino-Rabanal VJ, Peris SJ (2017) Adaptación acústica del canto de *Turdus leucomelas* (Passeriformes: Turdidae) a diferentes niveles de ruido antrópico, en el área metropolitana de Belém, Pará, Brasil. *Revista de Biología Tropical* 65(2): 633–642. <https://doi.org/10.15517/rbt.v65i2.25721>
- Morton ES (1975) Ecological sources of selection on avian sounds. *American Naturalist* 109: 17–34. <https://doi.org/10.1086/282971>
- Naguib M (2003) Reverberation of rapid and slow trills: implications for signal adaptations to long range communication. *The Journal of the Acoustical Society of America* 133: 1749–1756. <https://doi.org/10.1121/1.1539050>
- Nordt A, Klenke R (2013) Sleepless in town: drivers of the temporal shift in dawn song in urban European blackbirds. *PLoS ONE*. 8: e71476. <https://doi.org/10.1371/journal.pone.0071476>
- Ortega CP (2012) Effects of noise pollution on birds: A brief review of our knowledge. *Ornithological Monographs* 74: 6–22. <https://doi.org/10.1525/om.2012.74.1.6>
- Peris SJ, Pescador M (2004) Effects of traffic noise on passerine population in mediterranean wooden pastures. *Applied Acoustic* 65: 357–366. <https://doi.org/10.1016/j.apacoust.2003.10.005>
- Priyadarshani N, Castro I, Marsland S (2018) The impact of environmental factors in birdsong acquisition using automated recorders. *Ecology and Evolution* 8: 5016–5033. <https://doi.org/10.1002/ece3.3889>
- Ralph CJ, Sauer JR, Droege S (1995) Monitoring bird populations by point counts. U.S. Department of Agriculture, Albany, NY, EE.UU, 171 pp. <https://doi.org/10.2737/psw-gtr-149>
- R Core Team (2026) R: A Language and Environment for Statistical Computing (Version 4.5.3). R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>
- Redondo P, Barrantes G, Sandoval L (2013) Urban noise influences vocalization structure in the House Wren *Troglodytes aedon*. *Ibis* 155: 621–625. <https://doi.org/10.1111/ibi.12053>
- Reijnen R, Foppen R, Meeuwsen H (1996) The effects of traffic on the density of breeding birds in Dutch agricultural grasslands. *Biological Conservation* 75: 255–260. [https://doi.org/10.1016/0006-3207\(95\)00074-7](https://doi.org/10.1016/0006-3207(95)00074-7)
- Richards DG, Wiley RH (1980) Reverberations and amplitude fluctuations in the propagation of sound in a forest: implications for animal communication. *The American Naturalist* 115: 381–399. <https://doi.org/10.1086/283568>
- Ríos-Chelén AA, Lee GC, Patricelli GL (2015) Anthropogenic noise is associated with changes in acoustic but not visual signals in red-winged blackbirds. *Behavioral Ecology and Sociobiology* 69: 1139–1151. <https://doi.org/10.1007/s00265-015-1928-7>
- Rodríguez-Arancibia J, Escobar MH, Villaseñor NR (2022) Efecto del ruido, cobertura arbórea y hora del día sobre la detectabilidad de aves en ecosistemas urbanos. *El Hornero* 37: 2. <https://doi.org/10.56178/eh.v37i2.406>
- Slabbekoorn H (2013) Songs of the city: noise-dependent spectral plasticity in the acoustic phenotype of urban birds. *Animal Behaviour* 85: 1089–1099. <https://doi.org/10.1016/j.anbehav.2013.01.021>
- Slabbekoorn H, den Boer-Visser A (2006) Cities change the songs of birds. *Current Biology* 16: 2326–2331. <https://doi.org/10.1016/j.cub.2006.10.008>
- Slabbekoorn H, Peet M (2003) Birds sing at higher pitch in urban noise. *Nature* 426: 267–267. <https://doi.org/10.1038/424267a>
- Suarez-Romero JD (2021) Comparación del horario de canto del copetón *Zonotrichia capensis* en dos zonas con diferente intervención antrópica en el municipio de Puente Nacional Santander Colombia. <https://ciencia.lasalle.edu.co/biologia/113>

- Templeton CN, Zollinger SA, Brumm H (2016) Traffic noise drowns out great tit alarm calls. *Current Biology* 26: R1167–R1176. <https://doi.org/10.1016/j.cub.2016.09.058>
- Tubaro PL, Segura E (1989) Aprendizaje vocal y dialectos de canto en las aves. Bogotá, Colombia. *Revista Latinoamericana de Psicología* 21: 195–217.
- Warren PS, Katti M, Ermann M, Brazel A (2006) Urban bioacoustics: it's not just noise. *Animal Behaviour* 71: 491–502. <https://doi.org/10.1016/j.anbehav.2005.07.014>
- Watts G, Chinn L, Godfrey N (1999) The effects of vegetation on the perception of traffic noise. *Applied Acoustics* 56: 39–56. [https://doi.org/10.1016/s0003-682x\(98\)00019-x](https://doi.org/10.1016/s0003-682x(98)00019-x)
- Wiley RH, Richards DG (1982) Adaptations for acoustic communication in birds: sound transmission and signal detection. In: Kroodsma DE, Miller EH, Ouellet H (Eds) *Acoustic communication in birds*. Academic Press, New York, 131–181. <https://doi.org/10.1016/b978-0-08-092416-8.50014-0>
- Zuur AF, Ieno EN, Elphick CS (2010) A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution* 1: 3–14 <https://doi.org/10.1111/j.2041-210X.2009.00001.x>

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

The authors indicate that all the ethical principles governing the publication of a research article in a journal have been followed.

Artificial Intelligence (AI) use

The authors accept full responsibility for the content of the manuscript, including the disclosure of any use of AI.

No AI tools were used in the preparation of this manuscript.

Funding

No funding was reported.

Author contributions

CB and HVN designed the study. CB performed the literature review and data collection. EMS and HVN produced the figures and/or tables. CB wrote the first draft of the manuscript. EMS and HVN wrote sections of the manuscript. All authors reviewed and/or analysed the literature, contributed to manuscript revision and approved the submitted version.

Author ORCIDs

Carlos Barrientos  <https://orcid.org/0009-0007-7276-7402>

Erik M. Sandvig  <https://orcid.org/0000-0002-4180-000X>

Heraldo V. Norambuena  <https://orcid.org/0000-0003-0523-3682>

Data availability

The data that support the findings of this study are available as follows: (1) audio recordings are deposited in Xeno-Canto (www.xeno-canto.org; catalogue numbers XC954070–XC954583, see Suppl. material 1: table S1); (2) Data and code for reproducing the analysis can be found at <https://github.com/Chilesummits/Austral-Thrush-urban-noise-bioacoustics>. No permits were required for this non-invasive observational study.

Supplementary material 1

Supplementary information

Authors: Carlos Barrientos, Erik M. Sandvig, Herardo V. Norambuena

Data type: zip

Explanation note: Recordings for all vocalisations included in the analysis can be found on the online bioacoustic repository Xeno-Canto (table S1). Distributions and correlations between variables can be found in figs S1–S3.

Copyright notice: This dataset is made available under the Open Database License (<http://opendatacommons.org/licenses/odbl/1.0/>). The Open Database License (ODbL) is a license agreement intended to allow users to freely share, modify, and use this Dataset while maintaining this same freedom for others, provided that the original source and author(s) are credited.

Link: <https://doi.org/10.3897/natureconservation.64.169272.suppl1>