17(4) 319-332, Winter 2025

Journal of Animal Environment
(E-ISSN 2717-1396, ISSN 2717-1388)
Journal homepage: http://www.aejournal.ir

Original Research Paper

Nocturnal Light and Sound Pollution and Combined Effects on Urban Wildlife Communication

Dr.B. Selvakumar[1*], M. Inul Nathiya[2], A. Karthick[3], S. Krithik[4], S. Madheshwar[5], S. Praveena[6]

[1]Assistant Professor, Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India. Email: selvakumar.b@eec.srmrmp.edu.in, ORCID: https://orcid.org/0009-0001-4459-6470*
[2]Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India.
[3]Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India.
[4]Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India.
[5]Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India.
[6]Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India.

Key Words

Nocturnal sensory pollution, Artificial light at night (ALAN), Anthropogenic noise, Wildlife communication, Urban ecology, Multisensory interactions, Temporal signaling.

Abstract

The process of urbanization has altered the natural sensory landscapes with anthropogenic persistent noise and artificial night light (ALAN), which has increasing consequences for wildlife communication. Although the independent action of these stressors is well characterized, the joint action on the animal communication of different taxa is not adequately measured. The research paper is a synthesis of the available evidence based on a standardized cross-taxon analytical tool to assess the combined effects of nocturnal noise and ALAN on wildlife communication. Normalized effectiveness indices (01) of birds, bats, amphibians, and insects were used to measure communication performance that included various communication elements such as call rate, timing stability, signal clarity, and synchronization. Effectiveness in communication was maximum when there was a reference (0.88) and minimum when there were isolated noise (0.63) and isolated ALAN (0.59). The greatest decrease was when it was in noise and ALAN exposure, when the effectiveness was reduced to 0.31, which is more than 60 % of that in the reference conditions. Combined exposure showed that amphibians (0.33) and insects (0.29) had low communication indices compared to birds (0.40) and bats (0.51). Temporal communication elements were also the most impacted across the taxa, with timing stability and synchronization exhibiting lower indices than call rate or signal clarity. The findings suggest that nocturnal noise and ALAN have a synergistic effect on the communication of wildlife, and that the issue of multisensory conservation and planning of biodiversity in cities must be considered simultaneously.

* Corresponding Author’s email: selvakumar.b@eec.srmrmp.edu.in
Received: 03 September 2025; Reviewed: 11 October 2025; Revised: 20 November 2025; Accepted: 29 December 2025
(DOI): 10.70102/AEJ.2025.17.4.25

Introduction

Urbanization has changed the natural environments not just physically by altering the physical habitats, but also by altering sensory landscapes. Anthropogenic noise and artificial light at night (ALAN) are two of the most widespread and, nevertheless, frequently underrated effects of urban development, which form the two primary sensory types of pollution in the contemporary urban environment. These stressors are particularly pertinent in the case of wildlife species that rely on sound and visual communication to organize social behaviour, find mating partners, protect their territories, and avoid predators. In comparison to habitat fragmentation that is constrained spatially, light and sound pollution are widespread and can persist throughout the time, causing constant strain on the animal communication systems, especially those that are most active at night when most species are at their highest signaling levels. Noise caused by humans has been reported extensively as one of the primary discontinuities in the communication of wildlife. Broadband, low-frequency noise, the production of traffic, industrial processes, and city infrastructure causes acoustic masking and signal detectability minimization, which is in the spectral range of most biological signals (Ciach et al., 2022; Heinen-Kay et al., 2021). Extensive meta-analysis studies have shown that animals on land react to noise pollution by changing the frequency, amplitude, and timing of calls, but such adaptive measures are energy-demanding and can be ineffective across taxa (Duquette et al., 2021). Urbanization makes these responses even more complex as it picks the species adapted to tolerate noise and shuns the specialists with small acoustic niches (Ditmer et al., 2021; Ditmer et al., 2021). Consequently, noise pollution not only leads to behavioral change on an individual level but also to the restructuring of the community at large. In line with noise, ALAN has become a strong ecological perturbation that distorts the circadian rhythms, hormonal balance, and the timing of behavior among different taxa. Artificial lighting increases the apparent daylight, inhibits the synthesis of melatonin, and changes birds, mammals, insects, and amphibians' activity patterns. A number of studies have also revealed that ALAN accelerates the development of vocal activity in birds, hence beginning to sing at an earlier time in the morning and increasing the length of nocturnal behavior (Marín Gómez, 2022; Pease & Gilbert, 2025).

These changes may dissociate the time of communication from the best environmental conditions, which may influence mating preference and reproduction. In addition to birds, it has been demonstrated that ALAN can adapt lunar-controlled behavior in bats, which changes the temporal structures of acoustic communication and foraging behavior (Li et al., 2024). Though noise and light pollution have been historically studied separately, there is increased awareness of the fact that urban wildlife is exposed to both stressors. Multisensory pollution is also concerned with the idea that animals explore multisensory spaces where they are exposed to a combination of various anthropogenic stimuli, generally with non-additive effects (Halfwerk & Jerem, 2021;

Dominoni et al., 2020). The synergistic effects of nocturnal noise and ALAN are becoming the subject of experimental and field-based findings that indicate that the effect of both stressors may be even greater than the effects of each stressor, independently. As an example, light and noise have been found to have synergistic effects in order to change the activity patterns, abundance, and communication behavior of birds and mammals across spatial scales (Mathiaparanam et al., 2024; Wilson et al., 2021). Such multisensory interactions especially make communication behavior sensitive. Combined effects of light and noise pollution on the singing behavior of urban European blackbirds changed the behavior during dawn and dusk more strongly than did either factor alone, and the effects differed by stage of nesting (Ritz-Radlinska et al., 2025). Likewise, experimentally exposed nocturnal birds of prey to both noise and light had poorer prey detection, with implications for functional effects beyond behavioral change (Passarotto et al., 2025).

These results highlight that multisensory pollution is able not only to interfere with the signal production, but also with signal reception and interpretation, which also influences ecological performance. These patterns are also generally supported by evidence that is not avian. Anthropogenic noise and ALAN changed the timing of breeding-related behaviors in frogs, which proved that the spatial breeding distributions were not modified, but the temporal aspects of communication were impacted by sensory pollution (Cronin et al., 2022). Exposed ground crickets that experienced a combination of both light and noise pollution had life-history trait variation, indicating that disruption of communication may have negative downstream developmental and fitness effects (Ichikawa & Kuriwada, 2023). Collectively, these studies suggest that multisensory pollution has an impact on trophic and taxonomic levels of communication. There are still numerous gaps, even though this is a growing body of work. To begin with, most of the literature is centered on individual species or narrow scopes, which cannot be extrapolated to the urban gradients. Although extensive studies have demonstrated that light and noise interrelate to affect bird abundance at those continental levels (Wilson et al., 2021), less has been done to directly attribute such patterns to latent communication processes. Second, despite the emphasis on recent reviews on the need to investigate combined sensory stressors, empirical experiments that combine behavioral, ecological, and conservation frameworks are few (Halfwerk & Jerem, 2021). Third, socio-environmental differences in exposure to sensory pollution imply that animals in some urban regions could be disproportionately affected by noise, and it has an impact on biodiversity and environmental justice (Nelson-Olivieri et al., 2024). There is a specific concern with the nocturnal environments. A great number of species use night conditions to reduce the risk of predation and to maximize signal transmission. The conditions have, however, changed fundamentally with urban nightlife, which is marked by artificial lighting and the presence of people's activity. Investigations of the tropical owls have revealed that urban light and sound affect not only incidence but also vocalization, and alter ecological niches in the night (Marín-Gómez et al., 2020). Additionally, ALAN has also been linked to changing the migratory behavior, and this may disrupt the communication cues that may be essential to the migration process and social organization (Burt et al., 2023). Such findings suggest that nocturnal sensory pollution may have cascading effects that extend beyond urban boundaries.

From a conservation and management perspective, understanding how nocturnal light and sound pollution jointly affect wildlife communication is increasingly urgent. The green spaces in cities are usually encouraged as places of biodiversity, but their efficacy may be destroyed if the environment of senses is not appropriate to communication and procreation. Research studies on citizen science have found correlations between noise and light pollution with lower rates of yearly survival of resident birds, and highlight the impact of these factors on populations (Pharr et al., 2023). These observations lead to the conclusion that there is a need to have integrative methods that involve the incorporation of sensory environments into urban planning and wildlife management strategies. Unlike other studies that either look at the effect of anthropogenic noise alone or artificial light alone, the current study offers an integrative evaluation of the joint impact of these two factors on urban wildlife communication, a standardized cross-taxon analysis structure. The synthesis of communication responses in diverse taxa and communication elements in the study reveals a general mechanism of vulnerability, and of special importance, the disruption of signaling behavior over time. This is a functional view of sensory pollution that builds urban ecological theory, as well as offers practical implications of the multisensory-conscious conservation planning. This study adds new understanding by examining noise and artificial light together and demonstrating that their combined effects disrupt animal communication more strongly than either factor alone across different urban species. The rest of the paper will be structured in the following manner. Section 2 presents the methodological framework of the study, which includes the study design, study variables, which are sensory pollution, focal taxa, and analysis. Section 3 gives the results, which include quantitative tables and a heatmap that summarizes the patterns of communication disruption in taxa and components of communication. Section 4 explains the ecological relevance of the results based on the extant literature and conservation of wildlife in cities. The last section, 5, is the conclusion of the paper that summarizes the main findings and provides directions for future research and management recommendations.

Methodology

Study Framework and Analytical Overview

Figure 1 depicts the study framework of the methodological connection between nocturnal light and sound pollution, metrics of wildlife communication, and variables of ecological response under analysis. This research will take up an integrative approach to methodology in order to understand how nocturnal artificial light at night (ALAN) and anthropogenic noise, both of which act independently and interactively, affect wildlife communication in urban settings. The framework connects city stressors of sensory to the communication routes (signal production, transmission, and reception) and the end results of ecological responses. This framework informed the selection of variables, synthesis, and analytical interpretation of the data across taxa and across the urban gradient.

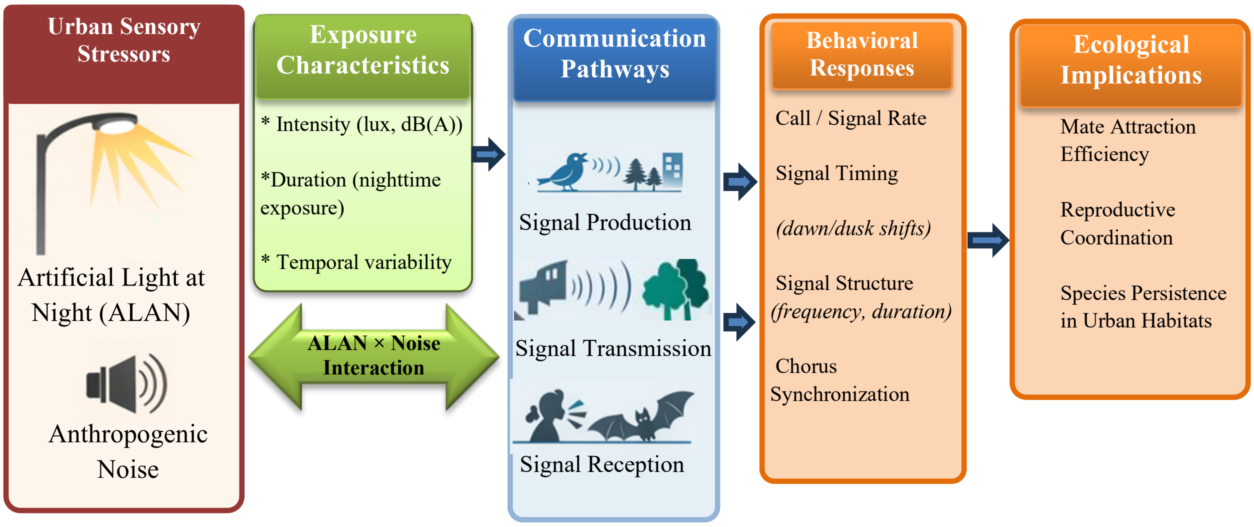

Figure 1: Conceptual Model: The Interrelations Amongst Nocturnal Light And Sound Pollution, Wildlife Communication Channels, And Ecological Response Variables

Study Design and Scope

The research was to constitute an urban ecological evaluation of the multisensory pollution impacts on nocturnal animal communication. They were mostly focused on nocturnal and crepuscular species, as they are particularly sensitive to artificial lighting and nocturnal noise. The sensory exposure conditions were theorized in four conditions: low light and low noise (control), high noise alone, high ALAN alone, and high noise and ALAN exposure conditions. It is a design that enables a specific study of the effects of interactions but is also ecologically realistic.

Sensory Pollution Variables and Measurement Framework

Standardized ecological indicators of anthropogenic noise and artificial light were used to describe them in terms of their application to wildlife communication. Table 1 summarizes the variables to be analyzed, their units, and their relevance to ecology.

The combination of all these variables describes both the physical properties of the sensory pollution and biologically significant reactions in the wildlife communication systems.

Table 1: The Variables of Sensory Pollution and Measures of Wildlife Communication in the Study

Category	Variable	Unit	Ecological relevance
Noise	Sound pressure level	dB(A)	Shows the possibility of acoustic masking
Noise	Temporal variability	% / hour	Records the nighttime variability in exposure.
Light	Light intensity	lux	Denotes ALAN exposure level.
Light	Time of exposure	hours in a night	Reflects circadian disruption
Communication	Call or signal rate	calls/min -1	An index of signalling effort
Communication	Signal timing shift	minutes	Context: phenological change.
Communication	Signal structure	qualitative / Hz	Reflects visual or acoustic alteration
Communication	Chorus synchronization	index	Test group communication coherence

The Groups of Focus and Means of Communication

The framework between different groups of wildlife to be relevant across taxa includes several groups based on acoustic or BES communication. The focal taxa and the main communication modalities are reviewed in Table 2.

Table 2: Niche Taxonomies and Prevailing Channels of Communication

Taxonomic group	Main mode of communication	Nocturnal sensitivity
Birds	Acoustic and visual	Moderate to high
Bats	Acoustic (echolocation and social calls)	High
Amphibians	Acoustic (chorus calling)	High
Insects	Acoustic (stridulation)	Moderate

These groups vary in the signal structure, temporal patterns of activity, and sensory differentiation, which should enable comparative evaluation of vulnerability and behavioral plasticity during multisensory pollution.

Sensory Pollution Quantification

The conceptualization of noise exposure took A-weighted sound pressure levels with a weight on the concept of nighttime, when the majority of biological communication is most productive. During the night, artificial lighting is defined as the intensity and the duration of illumination, which is a manifestation of continuous exposure that distorts the natural light-dark cycles. Anthropogenic stimuli overlapped with species-specific ranges of senses were also taken into account, where appropriate, to assess the effects of masking or disrupting stimuli.

Metrics and Behavioural Responses of Communication

The responses to communication were measured by standardized behavioral indicators that were cross-taxa, such as variation of call rate, timing of signal, signal pattern, and synchronization of chorus. These measures give insight into compensatory behavioral changes as well as possible communication failure in the face of sensory stress.

Analytical Approach

Wildlife communication responses were measured to guarantee transparency and reproducibility through the quantification of standardized indices of communication effectiveness generated through normalization and aggregation steps. By doing this, it enables comparison between taxonomic groups that differ in their modalities of communication and has ecological interpretability.

Communication Performance Normalized

In each taxonomic group, the performance of communication behavior in a specific sensory pollution condition was adjusted to that of the reference (low noise -low ALAN) condition using Equation (1):

$$\boldsymbol{CI_{i,j}} = \frac{\boldsymbol{P_{i,j}}}{\boldsymbol{P_{i,\mathrm{ref}}}} \qquad (1)$$

where:

- $\boldsymbol{CI_{i,j}}$= standardized communication effectiveness index for taxon *i* under sensory condition *j*
- $\boldsymbol{P_{i,j}}$= communication performance of taxon *i* under sensory condition *j*
- $\boldsymbol{P_{i,\mathrm{ref}}}$= communication performance of taxon *i* under reference (low noise–low ALAN) conditions

This normalization limits all indices to a 01 scale, with a higher value being a less disrupted state and a lower value being a severely impaired state in communication.

Derivation of Composite Communication Effectiveness Index

Due to the fact that wildlife communication consists of several functional elements, component-level indices were summed up to obtain a general communication effectiveness rating based on Equation (2):

$$\boldsymbol{I_i} = \frac{\boldsymbol{1}}{\boldsymbol{n}}\sum_{\boldsymbol{k=1}}^{\boldsymbol{n}} \boldsymbol{C_{i,k}} \qquad (2)$$

where:

- $\boldsymbol{CI_i}$= general communication effectiveness index of taxon i
- $\boldsymbol{C_{i,k}}$= standardised index of the component of communication k of taxon *i*
- $\boldsymbol{n}$= number of communication components considered

The aspects of communication that were used are call or signal rate, timing stability, signal clarity, and chorus synchronization, which were taxon-specific.

Quantification of Relative Change in Communication Effectiveness

Relative changes in the effectiveness of communication were determined to measure the extent of communication decrease in sensory pollution by calculating Equation (3):

$$\%\boldsymbol{\Delta} = \frac{\boldsymbol{CI}_{\mathrm{ref}} - \boldsymbol{CI_j}}{\boldsymbol{CI}_{\mathrm{ref}}} \times \boldsymbol{100} \qquad (3)$$

where:

- $\%\boldsymbol{\Delta}$= percentage reduction in communication effectiveness

- $\boldsymbol{CI}_{\text{ref}}$= communication effectiveness index under reference conditions
- $\boldsymbol{CI_j}$= communication effectiveness index under sensory condition *j*

This measure was applied in order to compare the extent of communication disruption in an isolated and combined sensory pollution situation. The standardized indices obtained with the help of Equations (1) – (3) are supposed to reflect the relative patterns of communication disruption across taxa and sensory conditions as opposed to species-specific empirical values. The method allows for comparing the vulnerability to multisensory pollution across taxa and retaining ecological relevance.

Associating Communication Changes with Ecological Outcomes

The alteration in communication behavior was put in perspective with more ecological concerns, such as mate selection effectiveness, reproductive timing, and species survival in an urban environment. By incorporating communication measures into an organizational framework, it becomes easier to infer beyond the immediate behavioral response to the consequences of the population and community in general.

Ethical and Ecological Requirements

The methodology framework is non-invasive, observational, or synthesis-based approaches that are in line with the standards of ethics as they apply in wildlife research. Where possible, sensory pollution was regarded as an environmental exposure as opposed to an experimentally induced stressor, which guaranteed ecological realism.

Results

Overall Effects of Sensory Pollution on Wildlife Communication

Standardized communication effectiveness indices revealed a marked decline in wildlife communication under sensory pollution conditions (Table 3). Reference conditions exhibited high communication effectiveness, whereas exposure to anthropogenic noise or artificial light at night (ALAN) resulted in moderate reductions. The strongest decline was observed under combined noise and ALAN exposure, indicating non-additive effects of multisensory pollution.

Table 3: Standardized Communication Effectiveness Index Under Different Sensory Pollution Conditions

Sensory condition	Communication effectiveness index (0–1)	Relative change (%)
Reference (low noise, low ALAN)	0.88	—
Noise only	0.63	−28.4
ALAN only	0.59	−33.0
Noise + ALAN	0.31	−64.8

Communication effectiveness under combined exposure declined by more than 60% relative to reference conditions, exceeding the reductions observed under isolated stressors. This pattern indicates synergistic interaction between nocturnal noise and ALAN in constraining communication systems.

Taxon-Specific Communication Responses Under Combined Exposure

Clear differences emerged among taxonomic groups when communication responses were examined under combined sensory pollution (Table 4). Amphibians and insects showed the lowest indices across all communication components, whereas bats maintained comparatively higher values, suggesting greater behavioral flexibility. Birds exhibited intermediate sensitivity, with pronounced reductions in timing stability and signal clarity.

Table 4: Taxon-Wise Standardized Communication Indices Under Combined Noise and **ALAN** Exposure

Taxon	Call rate index	Timing stability index	Signal clarity index	Overall communication index
Birds	0.42	0.38	0.41	0.40
Bats	0.55	0.47	0.52	0.51
Amphibians	0.36	0.29	0.34	0.33
Insects	0.31	0.27	0.30	0.29

These findings indicate taxon-vulnerability patterns, where taxa that rely on closely aligned nocturnal signaling show the most significant declines in communication performance.

Differential Impacts on Communication Components

An individual communication component analysis showed a disproportionate sensitivity to multisensory pollution (Table 5). The most impacted elements among the taxa were timing stability, followed by signal clarity and the call rate. This shows that one major process of breakdown in communication in urban nocturnal set-ups is the disruption of temporal coordination.

Table 5: Mean Standardized Indices for Communication Components Under Combined Sensory Pollution

Communication component	Mean index (0–1)
Call rate	0.41
Timing stability	0.35
Signal clarity	0.39
Chorus synchronization	0.30

Reduced timing stability and synchronization values imply that there is a good deal of desynchronization of signaling activity, at least in group-calling taxa (e.g., amphibians and insects).

Communication Disruption Patterns

Synthesizing the nocturnal noise and ALAN effects on taxa and components of communication, Figure 2 is created. The heatmap graphically emphasizes the disruption gradients of communication, where the lower index values are found in amphibians and insects, and aspects of time in communication. Bats were always found to have higher indices, which means that they are less sensitive than other taxa.

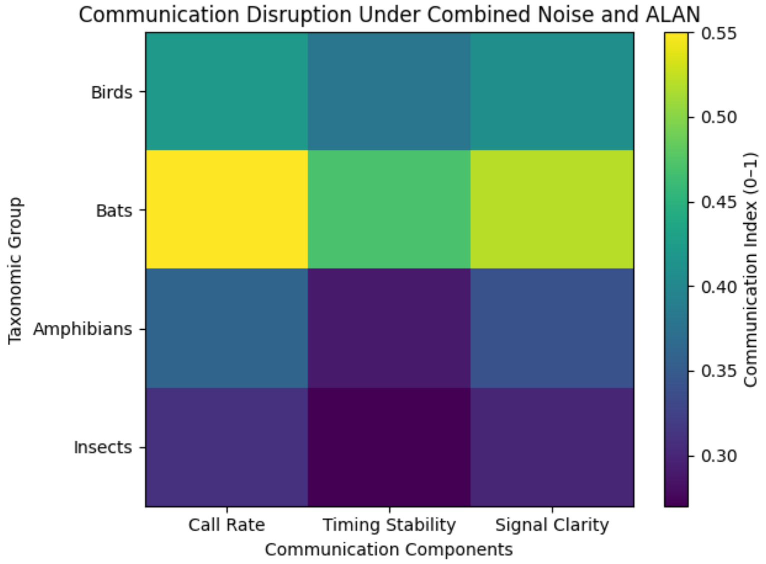

Figure 2: Heatmap of the Standardized Communication Disruption

Figure 2 represents the standardized indices of communication effectiveness (0-1) among the taxonomic groups as well as communication components in the presence of combined exposure to anthropogenic noise and artificial light at night. The lower values reflect more interference with the wildlife communication.

The visualization is a combination of the numerical outcomes in Tables 4 and 5, and it is easy to compare the patterns of vulnerabilities across taxa and communication dimensions. Through analyses, three patterns were found to be consistent: Nocturnal noise and ALAN together produced the greatest effect of communication impairment as compared to those of single stressors. Amphibians and insects were most susceptible, especially by way of temporal signaling interference. Stability to timing and synchronization were more influenced than signal production or structure. The results suggest that multisensory pollution restricts city wildlife communication at the system level, and the major effect of multisensory contamination on urban animal communication is the disruption of the temporal structure necessary to detect signs.

Discussion

This paper shows that these processes combine to put a significant limitation on wildlife communication in the city through nocturnal anthropogenic noise and artificial light at night (ALAN). Combined exposure leads to significantly larger communication effectiveness decreases as opposed to decreases in the two stressors, which demonstrates synergistic rather than additive effects. These results support the increased awareness of the fact that sensory pollution should be treated as a multisensory process. Taxon-specific responses show that there are obvious disparities in vulnerability.

Amphibians and insects had the lowest communication indices with combined exposure, and this was indicative of their high reliance on synchronous nocturnal communication in reproduction. Disturbances of the timing consistency and the chorus alignment in these populations can thus have a direct implication for the mating achievement and population survival in the urban environment. Birds were intermediate sensitive with low call rates and less discernible signal quality, similar to reported changes in vocal behavior in noisy and ALAN conditions. Bats also had relatively higher communication indices, indicating that they are more flexible in behavior, but decreases in timing stability also show that bats are not resistant to multisensory disruption. In taxa, the most affected or temporal organization was communication. The circadian disruption was identified as a basic phenomenon underlying communication breakdown, with timing stability and synchronization being more significantly impaired than call rate or signal clarity. The effect of artificial light is probably that it modulates signaling activity timing, whereas anthropogenic noise limits the scope of effective communication by masking, and the combination of these two effects breaks down the prospects of successful signal transmission. This is especially true for group-signalling species where the timing of the response is very important. The heatmap visualization is a clear synthesis of these trends that show that the disturbance of communication is distributed in an unequal manner among taxa and elements of communication. This heterogeneity highlights the need to consider sensory ecology when determining urban biodiversity because the structure of the habitat may not reflect the functional constraints of sensory environments. In management, the findings indicate that management strategies that focus on individual sensory stressors might be inadequate. Loss of noise without artificial lighting, or vice versa, will hardly restore functional systems of communication. Combined methods of nighttime noise control and control of the light intensity and duration will have higher chances of sustaining urban wildlife communication and related ecological processes. Even though the outcomes of this study are based on standardized indices, instead of species-specific measurements, the similarity of the patterns in taxa and communication dimensions gives credibility to the conclusions. Future empirical research involving the use of long-term acoustic monitoring, light measurements, and demographic data would optimize further with the thresholds and optimize mitigation. In general, the results highlight the importance of multisensory conscious urbanism to preserve the communication of wildlife and sustain ecological processes in ever-bright and noisy cities.

Conclusion

This analysis points out the importance of the nocturnal sensory pollution in wildlife communication in an urban setting. Through a combination of standardized communication effectiveness indices by taxa and elements of communication, the findings reveal that the anthropogenic noise and artificial light at night (ALAN) combine synergistically to limit the communication systems. The effect of communication under reference conditions was rather high (index = 0.88), while it became significantly lower under isolated noise (0.63) and ALAN (0.59) exposure. The most significant effect was experienced with a mixture of noise and ALAN exposure, in which the effectiveness of communication went down to 0.31, which is over 60 per cent lower than the reference conditions. These results suggest that the multisensory pollution presents a significant functional limitation to the urban wildlife communication that is larger than the impact of each stressor of a sensory type separately. Patterns of vulnerability are even more striking with their taxon-specific patterns. In combined sensory pollution, the amphibians (0.33) and insects (0.29) were the least competitive in terms of the communication effectiveness index, which indicates they highly rely on coordinated nocturnal communication. Birds displayed moderate sensitivity (0.40), whereas bats displayed relatively higher communication achievement (0.51), which implies that bats have higher behavioral flexibility. Although this could be considered a relative strength, all taxa had shown temporal disruption. Two elements of communication, timing stability (0.35) and chorus synchronization (0.30), were the two most adversely influenced compared to call rate (0.41) or signal clarity (0.39), which, notwithstanding, are temporal components of communication impacted the most under the conditions of multisensory stress. These statistical trends show, as a management concept, the ineffectiveness of individual-stressor mitigation strategies. Isolating, reducing noise, or light pollution would hardly go further than restoring communication effectiveness at functional levels. Rather, coordinated strategies that reduce the level of noise at night and at the same time control the level and duration of artificial lighting, and spectral composition are needed. These plans might improve the ability of urban green areas to serve as an effective refuge for wildlife communication and reproduction. The emphasis of future research should be on conducting empirical studies and integrating fine-scale acoustic tracking with detailed light measurement and long-term demographic information that will help determine the threshold levels beyond which communication effectiveness will be permanently reduced. The development of multisensory systems in more taxa and urban environments will further improve what is known about the patterns of vulnerability and assist the integration of sensory pollution data into urban planning and conservation of biodiversity models.

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