

Urban Health Monitoring Using Environmental and Physiological Data: A Pilot Study [†]

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Abstract

Urban environments expose individuals to multiple stressors, including air pollution and noise, which significantly impact health by causing cardiovascular and respiratory diseases and sleep disruption. Effective monitoring of these stressors through intelligent sensing technologies can support the mitigation of long-term deterioration in both physical and mental health. In this context, this pilot study presents a multimodal approach that integrates environmental sensing and physiological monitoring to assess stress responses of the human body to urban conditions. Indoor and outdoor air quality were measured using smart sensor nodes that captured particulate matter (PM₁, PM_{2.5}, PM₄, PM₁₀), air temperature and relative humidity. The physiological response to urban noise exposure was evaluated using electrodermal activity (EDA) and heart rate variability (HRV) acquired via a wearable biomedical device, while sound pressure levels (dBA) were measured using a professional sound level meter. Preliminary results indicate that indoor particulate matter concentrations greatly exceeded outdoor levels, despite outdoor sensors being deployed in a high-traffic urban environment. Physiological analysis revealed increased tonic electrodermal activity under noise exposure, indicating increased sympathetic activation. Complementary HRV analysis showed elevated heart rate (HR), reduced parasympathetic activity, and increased sympathetic dominance under high-noise conditions, confirming a measurable physiological stress response to urban environmental exposure.

Keywords: urban environmental exposure; air quality monitoring; noise exposure; electrodermal activity (EDA); heart rate variability (HRV); physiological stress assessment



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1. Introduction

Urban environments are generally associated with increased risks to both physical and mental health, driven by factors such as poor air quality, elevated noise levels, and other environmental stressors. Among these, air pollution is recognized as one of the leading threats to human health, with particulate matter (PM) playing a central role in the development of respiratory disorders, cardiovascular diseases, and lung cancer [1].

In particular, fine particulate matter (PM_{2.5}), defined as airborne particles with an aerodynamic diameter smaller than 2.5 μm, represents a major public health concern due to its ability to penetrate deeply into the respiratory system and enter the bloodstream [2].

These particles originate from a wide range of sources, including traffic emissions and industrial combustion in outdoor environments, as well as indoor activities such as cooking, smoking, candle burning, and dust resuspension.

Importantly, pollutant concentrations in indoor environments can often exceed outdoor levels by a factor of two to five [3], a finding that is especially concerning given that individuals spend approximately 90% of their time indoors, especially at home [4]. This highlights the critical need for effective monitoring of key environmental parameters and increased public awareness in order to mitigate long-term health risks associated with chronic exposure.

In addition to air pollution, environmental noise constitutes a significant yet often underestimated urban stressor, with well-documented effects on both physical and mental health [5,6]. Chronic exposure to urban noise has been associated with increased stress levels, sleep disturbances, cognitive impairment, and a higher risk of cardiovascular and psychological disorders [7,8].

In this context, the assessment of physiological responses to environmental stressors has gained increasing relevance. Electrodermal activity (EDA), which reflects changes in skin conductance driven by sympathetic nervous system activation, provides a non-invasive and real-time measure of stress and arousal. The integration of EDA and heart rate variability (HRV) monitoring with environmental sensing enables the evaluation of how external factors such as urban noise influence human physiological states, offering valuable insights into the relationship between environmental exposure and mental health.

2. Materials and Methods

2.1. Air Quality Analysis

This study was conducted in a residential apartment located along one of the main arterial roads in Lisbon, characterized by high traffic density, including passenger vehicles, ambulances, and other emergency vehicles, due to its proximity to a major hospital. The area is also affected by aircraft noise, given its proximity to the city's airport, resulting in continuous exposure to environmental stressors for approximately 12 h per day. Additionally, the surrounding area is characterized by limited vegetation.

Air quality monitoring was performed in two distinct microenvironments within the same habitation: an outdoor location, represented by a balcony facing the main avenue; an indoor location, represented by the living room, the most frequently occupied area of the house. The outdoor sensor node was installed in a shaded area to minimize direct solar radiation effects on measurements. The indoor node was positioned at approximately 1.5 m above ground level, consistent with typical human breathing height. Prior to deployment, both sensor nodes were co-located and operated simultaneously for 24 h to ensure stabilization and consistency of measurements, enabling an initial calibration and validation of sensor agreement.

Data acquisition was conducted over a one-week period in April 2026, with measurements recorded at 1-min intervals. The monitored habitation was occupied by a single resident during this study.

The sensor nodes used in this study were developed by the authors and previously described in [9]. Each node is part of an IoT-based sensing network, built around the ESP32-S2 platform. Particulate matter concentrations were measured using the SPS30 sensor (Sensirion, Stäfa, Switzerland), capable of detecting PM_1 , $PM_{2.5}$, PM_4 , and PM_{10} , with a measurement range of 1–1000 $\mu g/m^3$ and a resolution of 1 $\mu g/m^3$. Temperature and relative humidity were monitored using the Si7021 sensor (Silicon Labs, Austin, TX, USA), providing an accuracy of ± 0.4 °C for temperature and $\pm 3\%$ for relative humidity within the

specified operating ranges. A GPS module was included to provide time synchronization across sensor nodes.

Given the fixed deployment configuration, all sensor nodes were powered via standard electrical outlets. Data were processed locally by the microcontroller and transmitted via Wi-Fi to a smart gateway implemented using a Raspberry Pi 5, running an MQTT broker/server. Data were simultaneously stored both locally (on microSD cards within each node and gateway) and remotely in a centralized database.

2.2. Noise Exposure Analysis

To evaluate the impact of urban noise exposure on physiological stress, environmental sound levels were measured using a sound level meter Tenma 72-13420 (Tenma, Leeds, UK). Measurements were performed three times per day, with each session lasting 5 min, over the course of one week.

The recorded sound levels were categorized into two primary environmental conditions:

- Noise exposure (window opened): 70–80 dBA (mean $\approx$ 75 dBA);
- Window closed (moderate noise exposure): 36–50 dBA (mean $\approx$ 45 dBA).

To assess physiological responses, EDA and photoplethysmography (PPG) signals were acquired from the resident using a Shimmer3 GSR+ (Shimmer Research Ltd., Dublin, Ireland) device. This unit includes two electrodes for skin conductance measurement and a PPG sensor for cardiovascular monitoring. Signals were acquired at a sampling frequency of 128 Hz and transmitted via Bluetooth to a computer for offline analysis.

Experimental Protocol

The participant was a healthy young adult, with no reported medical conditions and no consumption of alcohol or caffeine on the day of data collection. During all sessions, the participant remained seated in a relaxed upright position under spontaneous breathing conditions and was instructed to remain still during the measurements in order to minimize motion artifacts. Additionally, the participant remained with eyes closed to minimize external sensory stimulation. Ambient humidity was maintained at approximately 56% during the experimental sessions and all tests were conducted in the morning. The PPG sensor was placed on the index finger of the left hand, while the GSR electrodes were attached to two fingers of the opposite hand.

Physiological data were collected for 10 min under three experimental conditions:

1. Window closed (light to moderate noise, $\sim$ 45 dBA);
2. Noise (window opened, $\sim$ 75 dBA);
3. Silence condition (achieved using Sony WH-1000XM4 headphones (Tokyo, Japan) with noise-cancelling feature);

For each session, the last 5 min of data were used for analysis to ensure signal stabilization. The results presented correspond to the average values across all sessions per condition.

HRV parameters were derived from the PPG signal through peak detection and interbeat interval extraction using the Python library SciPy (version 1.7.3). These intervals were then analyzed using Kubios HRV Scientific software (version 4.1.0). The extracted parameters included Mean HR, Mean RR, SDNN, RMSSD, PNS index, and SNS index. The PNS and SNS indices are normalized measures representing parasympathetic and sympathetic nervous system activity, respectively. For EDA analysis, the tonic component (Skin Conductance Level, SCL) was extracted to assess sustained sympathetic activation.

3. Results and Discussion

This section presents preliminary evidence of the indoor and outdoor air quality analysis based on data acquired from the developed sensor nodes, alongside an assessment of physiological responses to urban noise exposure. The analysis integrates environmental measurements, including particulate matter concentrations, with biometric indicators such as EDA and HRV, in order to evaluate the combined impact of environmental stressors on human health.

3.1. Air Quality Monitoring

A temporal analysis of particle concentration was made to assess the dynamic behaviour of air quality in the different environments (Figure 1). Variations in particle levels reflect the influence of environmental factors such as urban activity and meteorological conditions, as well as ventilation conditions and human activity in indoor environments. To highlight periods with more pronounced variations in particle concentration, Figure 1 presents PM_{2.5} data from four selected days that are representative of higher levels of indoor activity, during which more noticeable fluctuations in particle concentration were observed. The WHO 24-h reference threshold is included as a benchmark for assessing exposure levels [10].

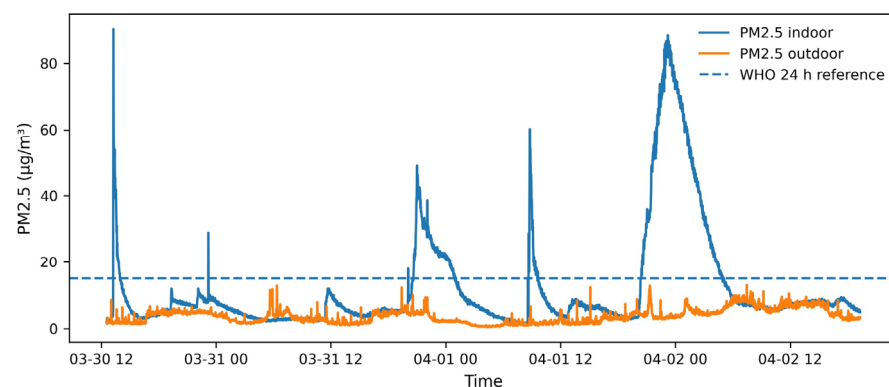


Figure 1. PM_{2.5} time series with WHO reference threshold (15 µg/m³).

Two of the observed elevated concentrations, around 8 pm, coincided with documented candle-burning activities in the non-ventilated indoor environment. These events resulted in sustained increases in PM_{2.5} concentrations, supporting the role of indoor combustion sources as significant contributors to particulate exposure. This suggests limited air exchange and highlights the importance of ventilation in mitigating indoor air pollution. In addition, other observed spikes were associated with cooking activities, with emissions propagating from the kitchen to the living area where the sensors were located. This indicates that particulate matter generated in adjacent indoor spaces can significantly impact air quality in connected environments, particularly in the absence of adequate ventilation.

To have a more quantitative comparison of PM_{2.5} and PM₁₀ concentrations across the different environments, Figure 2 presents boxplots summarizing the distribution of such concentrations.

The analysis shows that indoor particulate matter concentrations exhibit higher median values and greater variability compared to outdoor measurements. For PM_{2.5}, median indoor concentrations (~6–7 µg/m³) were approximately twice those observed outdoors (~3 µg/m³), with indoor values reaching peaks above 15 µg/m³. A similar pattern was observed for PM₁₀, indicating that indoor environments are subject to both higher baseline concentrations and episodic pollution events.

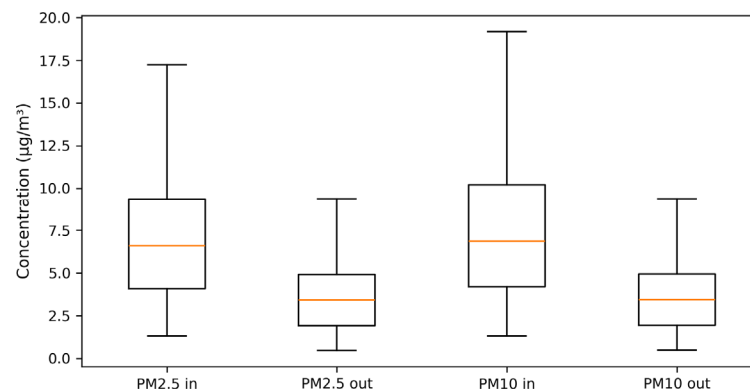


Figure 2. Distribution of indoor and outdoor particulate matter (PM₁₀ and PM_{2.5}).

A correlation matrix with the different measured parameters highlights weak relationships between indoor and outdoor particulate matter concentrations, indicating limited coupling between the two environments (Figure 3). This suggests that indoor air quality was not primarily influenced by ambient outdoor conditions in this case but was instead influenced by local factors, including indoor emission sources and ventilation dynamics. Overall, the results highlight the importance of adequate ventilation in indoor environments to promote air renewal and reduce particle accumulation. In situations where natural ventilation is limited or not feasible, the use of air purification systems may represent an effective alternative to improve indoor air quality.

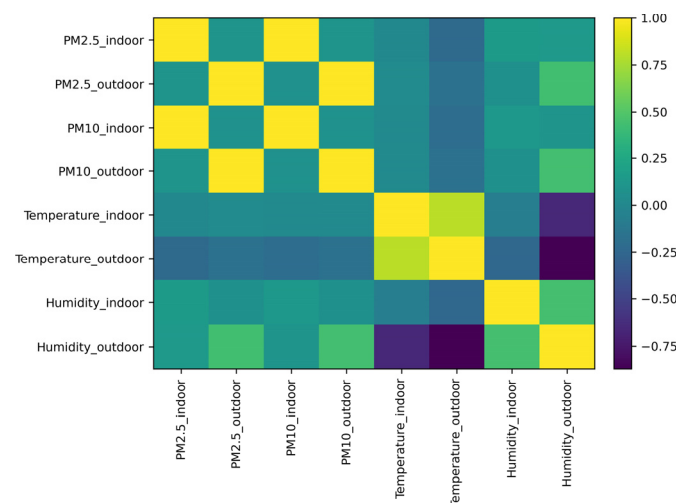


Figure 3. Correlation matrix (PM, Temperature, Humidity).

3.2. Noise Exposure and Physiological Stress

Physiological data were collected under three distinct conditions: silence, moderate noise exposure with the window closed, and higher noise exposure with the window open. These conditions were intended to capture the varying levels of urban noise exposure in a typical residential environment located in a high-traffic environment.

Exposure to urban noise (70–80 dBA) was associated with increased electrodermal activity. Figure 4 presents the electrodermal activity time series, expressed in skin resistance (kΩ), from a representative session. It reveals lower baseline values and greater temporal variability under noise conditions compared to silent and closed-window environments. As skin resistance is inversely related to conductance, this pattern reflects increased electrodermal activity. These patterns are consistent with increased sympathetic nervous system activation. Quantitative analysis further supported this observation, with higher tonic skin conductance levels (SCL) under noise exposure, as demonstrated in Figure 5. These

results already suggest that urban noise may induce a physiological response consistent with stress-related arousal.

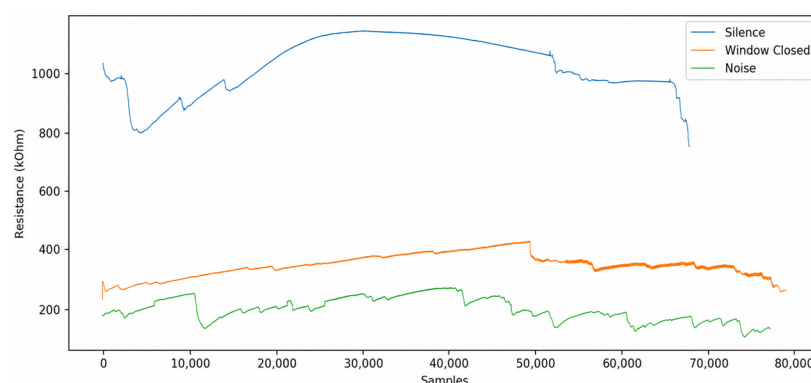


Figure 4. GSR time series from one experimental session.

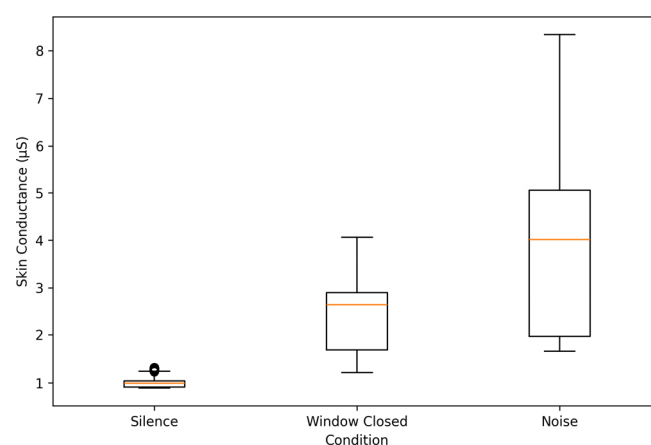


Figure 5. Average distribution of tonic skin conductance (SCL) across experimental conditions.

Table 1 summarizes the EDA metrics across the three experimental conditions. A clear increase in both central tendency and variability is observed with increasing levels of noise exposure. The silence condition had the lowest mean and median conductance values (0.996 μS and 0.992 μS , respectively), reflecting a baseline physiological state with minimal sympathetic activation. In contrast, the window-closed condition showed a substantial increase in EDA (mean = 2.422 μS), indicating elevated physiological arousal even under light to moderate noise exposure. The highest values were observed under the noise condition, with a mean of 3.850 μS and a median of 4.014 μS , approximately four times higher than the silence baseline. This condition also exhibited the greatest variability, as indicated by the highest standard deviation (2.47 μS) and interquartile range (3.090 μS), suggesting more heterogeneous and pronounced physiological responses. These results indicate that increasing noise exposure is associated with both higher levels of sympathetic activation and greater variability in physiological response.

Table 1. EDA summary (SD—Standard Deviation; IQR—Interquartile Range).

Condition	Mean (μS)	Median (μS)	SD (μS)	IQR (μS)
Silence	0.996	0.992	0.13	0.129
Window Closed	2.422	2.629	1.16	1.213
Noise	3.850	4.014	2.47	3.090

Regarding HRV analysis, presented in Table 2, a progressive shift toward sympathetic dominance across conditions was obtained. Compared to silence, both closed-window and

noise conditions exhibited increased heart rate and elevated SNS index values. The highest sympathetic activation (SNS = 1.36) and lowest parasympathetic activity (PNS = −1.35) were observed under traffic noise exposure when the window was opened, indicating a pronounced stress response. These findings suggest that even moderate environmental noise can induce measurable autonomic changes, while higher noise exposure results in a clear imbalance between sympathetic and parasympathetic activity. Although SDNN was higher in the Window Closed condition, other indicators, such as heart rate, SNS index, and PNS index, showed a consistent trend across conditions, and as SDNN reflects overall autonomic variability rather than specific parasympathetic activity, this finding does not necessarily indicate increased relaxation. Additionally, the increase in electrodermal activity, as measured, supports this shift toward sympathetic dominance under noise exposure.

Table 2. Summary of heart rate variability (HRV) parameters across experimental conditions.

Parameter	Unit	Silence	Window Closed	Noise
Mean HR	bpm	80.0	86.7	88.0
Mean RR	ms	750	695	680
SDNN	ms	46.1	61.0	53.8
RMSSD	ms	36.2	37.2	35.6
PNS index	–	−0.99	−1.25	−1.35
SNS index	–	1.04	1.14	1.36

Overall, EDA revealed increased tonic conductance under noise conditions, reflecting heightened sympathetic arousal. In parallel, HRV analysis showed increased HR across several exposure sessions and reduced parasympathetic activity under the noise exposure session with the window open. Together, these findings strengthen the evidence that urban environmental exposure, particularly noise, is associated with measurable physiological stress responses.

4. Conclusions

This work presents an indoor air quality and urban noise exposure within a residential environment located in a high-traffic urban area. The preliminary results demonstrate that indoor particulate matter concentrations consistently exceeded outdoor levels. Indoor air quality was characterized not only by higher baseline concentrations but also by pronounced short-term peaks associated with indoor activities such as cooking and candle use. This finding reinforces existing evidence that indoor air quality is not solely determined by outdoor pollution levels but is strongly influenced by indoor emission sources and ventilation conditions. Additionally, physiological monitoring revealed clear autonomic responses to noise exposure. Electrodermal activity analysis showed increased tonic conductance under noise conditions, indicating elevated sympathetic activation. Heart rate variability analysis further confirmed this trend, with increased heart rate, reduced parasympathetic activity, and a shift toward sympathetic dominance, particularly under high-noise exposure to urban traffic when the window is opened. This is consistent with previously reported autonomic responses to acoustic stress, indicating that even short-term exposure to urban noise can trigger measurable physiological changes.

5. Limitations and Future Work

This preliminary study presents some limitations and therefore requires further investigation. First, the experimental procedure was based on a single participant, which limits the generality of physiological findings. In addition, the monitoring period was

relatively short, and longer-term measurements will be necessary to capture variability across different weeks and behavioral patterns.

For this reason, this pilot study will consider, as future work, expanding the dataset and extending monitoring periods, as well as exploring the real-time integration of environmental and physiological data to enable intelligent environments with actuation capabilities aimed at exposure mitigation and health risk assessment.

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Institutional Review Board Statement: This study involved an adult volunteer participating in a minimal-risk proof-of-concept experiment. The participant provided informed consent prior to participation. No patients or vulnerable populations were involved.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EDA	Electrodermal Activity
GSR	Galvanic Skin Response
SCL	Skin Conductance Level
SCR	Skin Conductance Response
HRV	Heart Rate Variability
HR	Heart Rate
RR	R-R Interval
SDNN	Standard Deviation of Normal-to-Normal Intervals
RMSSD	Root Mean Square of Successive Differences
PNS	Parasympathetic Nervous System
SNS	Sympathetic Nervous System
PPG	Photoplethysmography
PM	Particulate Matter
IoT	Internet of Things
MQTT	Message Queuing Telemetry Transport
dBA	A-weighted Decibels

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