forum acusticum 2026
8-12 September · Graz, Austria

BRIDGING COMMUNITY NOISE PERCEPTION AND THE ACOUSTIC ENVIRONMENT: INSIGHTS FROM A CITIZEN SCIENCE ACOUSTIC MONITORING NETWORK

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Abstract

Strategic noise maps based on sound emission and propagation modelling help identify overexposed areas using weighted annual average noise level indicators such as L_{den} and L_{night}. While providing large-scale, objective data to plan noise mitigation strategies, acoustic metrics retrieved from strategic noise maps can oversimplify and downplay characteristics of the acoustic environment linked to noise annoyance and sleep disturbance. To address this gap, the citizen science project De Oorzaak deployed a large-scale Internet-of-Things-based acoustic sensor network, for one year in Antwerp, Ghent, and Leuven, with 1,484 citizen scientists installing a Class-2 smart sound sensor outside their bedroom window for continuous six-week measurement periods. In parallel, a questionnaire was sent each week in order to get a detailed view of the respondents' noise perception. The resulting data will enable a finer-grained exploration of the acoustic environment, including time-varying patterns, and identifiable noise events and their sound sources. By linking these objective measurements with the subjective survey responses this study offers a more nuanced perspective on how environmental noise drives annoyance at the population level.

Keywords: *citizen science, environmental noise, acoustic sensor network, noise annoyance*

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1. Introduction

Strategic noise maps, produced through sound emission and propagation modelling, are the main policy tool used to identify overexposed areas and plan noise mitigation strategies under the European Noise Directive (END 2002/49/EC) [1], using weighted annual average indicators such as L_{den} and L_{night}, as also recommended by the World Health Organization (WHO) environmental noise guidelines [2]. While such indicators provide consistent, large-scale, objective data, they average the acoustic environment over a full year and can therefore oversimplify or downplay characteristics of the soundscape [3] that are closely linked to noise annoyance and sleep disturbance, such as peak levels, the recurrence of specific noise events, and the underlying noise source type or frequency content.

A citizen science (CS) approach, combining a dense network of sensors with the active participation of residents, has repeatedly been put forward as a way to complement strategic noise maps with finer-grained, longer-duration and more localised data, although earlier large-scale initiatives were typically limited to either smartphone-based or low-cost sensors [4], or a combination of a small number of high-quality reference stations with a larger but lower-quality citizen network [5]. Building on this approach, the citizen science project "De Oorzaak" ("the cause" or "case of the ear", in Dutch) was launched in 2023 in Flanders (Belgium), an initiative of the University of Antwerp, the Antwerp University Hospital (UZA) and the newspaper De Morgen, combining a large-scale smart sound sensor network with subjective surveys and a medical study on sleep and stress, as introduced in [6].

This paper focuses on the part of the project that links the objective acoustic measurements of the citizen sensor network to the subjective experience reported by the participants, both through a large, one-off survey on noise annoyance and through a set of weekly surveys repeated throughout each measurement period. The aim is to determine to what extent, and at which time scale, average noise indicators and identified noise events can explain the annoyance, fatigue, stress and sleep quality reported by residents at population level.

2. Methodology

2.1 Citizen sensor network

The citizen sensor network of De Oorzaak consisted of 400 smart sound sensors (type NP9 by Munisense, The Netherlands), each equipped with a Class II microphone and a custom-built mounting frame that compensates for façade reflection (approx. 5.7 dB), see Fig. 1.

Figure 1. Installation of the Munisense smart sound sensor with custom-built mounting frame: (left) figure from the instruction manual and (right) actual installation by a citizen scientist.

The sensors also contain a GPS module and a SIM card, so that no Wi-Fi connection is required. Citizen scientists installed these sensors outside their bedroom window in three major cities in Flanders (Antwerp, Ghent and Leuven), for one of six consecutive six-week measurement periods between April 2024 and April 2025. In total, 1,452 citizen sensor locations were obtained (746 in Antwerp, 500 in Ghent and 206 in Leuven, see Fig. 2); 89.7% of the installations fully complied with the installation protocol, and 60.4% of the sensors were mounted at the front façade of the dwelling, the remainder at a side or rear façade.

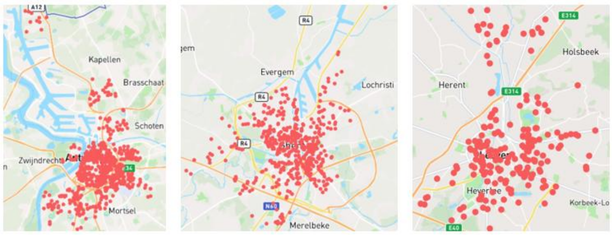

Figure 2. Sensor locations in Antwerp (left), Ghent (middle) and Leuven (right).

Sensors continuously measured third-octave sound levels and used an on-the-edge AI model, developed by ASAsense, to classify recognizable noise events by source category (road, rail and air traffic, construction, human voices, alarms and sirens, nature sounds, pets and abrupt sounds), without recording or transmitting any audio, ensuring a GDPR-compliant methodology. A noise event was defined as any one-second A-weighted level ($L_{Aeq,1s}$) exceeding the 15-minute moving A-weighted average ($L_{Aeq,m,15min}$) by more than 10 dB(A); each event was logged with its duration and assigned to a 5 dB(A) level category based on its L_{Amax}. In total, the smart sound sensor network collected over 60,000 sensor-days, or close to 1.47 million hours of acoustic data. From the available $L_{Aeq,1s}$ data, over 70 acoustic indicators were calculated.

2.2 Surveys

One of the first initiatives within De Oorzaak was to invite the citizen scientists to go for a soundwalk and answer a questionnaire based on the data collection procedure described in ISO 12913-2. A link to an online survey was published in the media, resulting in large public engagement. The results of over 4,500 answers spread over the Flemish region were combined with GIS data focusing on the effect of hearing nature sounds [7] or trying to explain the pleasantness and eventfulness using geospatial data [8]. This dataset is not further linked to the other datasets used, so it will not be discussed in detail in this paper.

A large-scale online survey on noise perception, the Large Sound Survey, was distributed through a large media campaign between November 2023 and May 2024, open to all Flemish residents older than 18; further details on its design and content are available in [9]. The survey was partly based on previous regional living-environment surveys, organized by the Flemish government, and partly on validated questionnaires for noise sensitivity, sleep quality, daytime sleepiness (Epworth Sleepiness Scale, ESS, introduced in [10]), fatigue (Fatigue Assessment Scale, FAS, developed in [11]) and stress (Perceived Stress Scale, PSS-10, introduced in [12]). Of the 17,988 respondents who started the survey, 10,138 completed it in full, including 2,189, 1,676 and 642 respondents living in Antwerp, Ghent and Leuven respectively, allowing a direct link to the sensor-based acoustic data in these three cities.

In parallel, all sensor participants received a set of weekly online surveys throughout their six-week measurement period: an intake survey on dwelling characteristics, followed by six weekly follow-ups combining a fixed, recurring block on general noise appreciation, source-specific annoyance, sleep quality, ESS and stress, with a rotating thematic module (e.g. hyperacusis, functional sleep outcomes, anxiety/depression screening, occupational noise, tinnitus). In total, 1,460 unique participants completed more than 10,000 weekly questionnaires, with a per-wave response rate between 75% and 100% and a retention rate generally above 75% (Table 1).

Table 1. Overview of the De Oorzaak datasets used in this study.

Dataset	Count
Citizen sensor locations : Antwerp / Ghent / Leuven	746 / 500 / 206
Total citizen sensor locations	1,452
Large Sound Survey – completed responses (Flanders-wide)	10,138
Large Sound Survey – completed responses (3 cities)*	4,507
Weekly survey participants	1,460
Weekly survey responses collected	> 10,000

** Sum of Antwerp (2,189), Ghent (1,676) and Leuven (642).*

3. Results

3.1 Acoustic environment characteristics

Across the full measurement period, a clear contrast emerged between front and non-front façades: 56.1% of front-façade locations remained below an L_{den} of 60 dB(A), against 89% at the side or rear; for L_{night}, 51.0% of front-façade locations stayed below 50 dB(A), against 80.7% at the back. The average front/non-front difference amounted to 5-6 dB(A) for L_{den} and 4-5 dB(A) for L_{night}, while the average L_{den}-L_{night} gap was 8-9 dB(A). Differences between the three cities were small and not statistically significant for either indicator (p-value between 0.117 and 0.816).

Within a single six-week measurement period, the average difference between the loudest and quietest day at a given location was 10.2 dB(A) for L_{den} and 10.8 dB(A) for L_{night} (12.3 dB(A) for the daytime-only L_{day}), with some locations varying by more than 20 to 30 dB(A); the difference between working days and weekends/holidays was markedly smaller (1.3 dB(A) for L_{den}, 0.7 dB(A) for L_{night}), see Fig. 3. The loudest hour of the day was, on average, between 11:00 and 12:00, and the quietest between 02:00 and 04:00, although the timing of the loudest hour varied considerably more across locations than that of the quietest one.

Road traffic was the dominant identified noise source overall (37.5% of all classified noise events), see Fig. 4, followed by construction-related sounds (20.2%). Priority vehicles (sirens/alarms) were comparatively rare but dominated the loudest events, accounting for 50.4% of all events above 85 dB(A), while nature sounds occurred predominantly at lower noise levels and pets and abrupt sounds were the least frequent and least reliably recognised categories. Some city-specific patterns emerged: Antwerp recorded more loud (> 70 dB(A)) air-traffic events, Ghent more rail-traffic and construction events, and Leuven more human-voice events, particularly at night.

The ten loudest locations per city, almost all situated along arterial or ring roads, measured 13-15 dB(A) above the city average and were dominated by road traffic and sirens above 70-80 dB(A); the single loudest points were found along the A12 in Antwerp (L_{den} 75.6 dB(A), L_{night} 67.7 dB(A)) and at the R4/E40/E17 interchange in Ghent (L_{den} 76.8 dB(A), L_{night} 68.7 dB(A)). The ten quietest locations, scattered across residential areas away from those roads, measured 8-10 dB(A) below average; several of them still registered a comparatively high share of brief air-traffic events that barely move an energy-averaged indicator such as L_{den}.

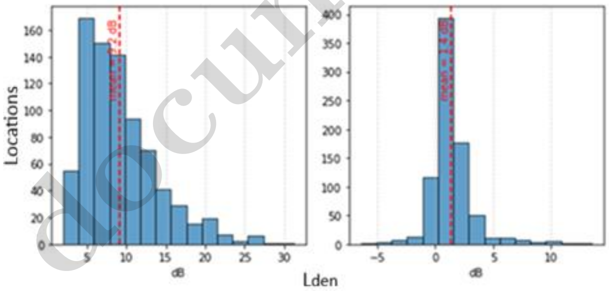

Figure 3. Histograms showing the dynamic range for sensors placed at the front: (left) difference in L_{den} between the loudest and quietest days and (right) difference in L_{den} between working and non-working days.

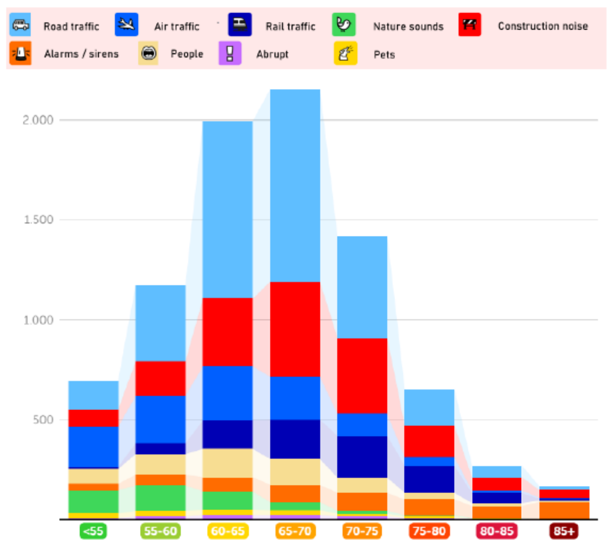

Figure 4. Histograms showing the total duration of identified noise events per 5 dBA range [visualization by De Morgen]

3.2 Linking the acoustic environment to community noise perception

In the Large Sound Survey, road traffic again emerged as by far the most disturbing source of environmental noise across Flanders, based on the percentage of respondents classified as highly annoyed (%HA, sum of very and extremely annoyed): passenger cars (26.2%), trucks (24.7%) and mopeds/scooters/motorcycles (22.9%) occupied the top three places of the resulting ranking (Table 2), followed by construction/demolition activities (12.9%), buses (9.8%) and priority vehicles (9.1%); human activity in public space, roadworks, unidentified humming and pets each accounted for around 7%. This pattern aligns well with the sensor-classified breakdown of noise events from Fig. 4, where the same two source categories, road traffic and construction, also dominated. Annoyance levels in the survey were considerably higher than in the Flemish reference living-environment survey (35.8% vs. 14.8% %HA), which is consistent with a degree of self-selection bias among an opt-in, noise-focused survey population.

Table 2. Top 10 most disturbing noise sources (%HA).

#	Source	%HA (n)
1	Passenger cars	26.2% (2,659)
2	Trucks	24.7% (2,509)
3	Mopeds / scooters / motorcycles	22.9% (2,324)
4	Construction / demolition	12.9% (1,311)
5	Buses	9.8% (995)
6	Priority vehicles (sirens)	9.1% (922)
7	People in public space	7.4% (752)
8	Roadworks	7.1% (719)
9	Unidentified humming/buzzing	7.0% (706)
10	Pets	7.0% (706)

General noise annoyance reported in the survey increased systematically and significantly with both L_{den} and L_{night} measured at the respondent's sensor location ($p<0.001$ between most annoyance categories, except between "very" and "extremely" annoyed), see Fig. 5, as well as with the number of loud events (> 70 dB(A)) per day.

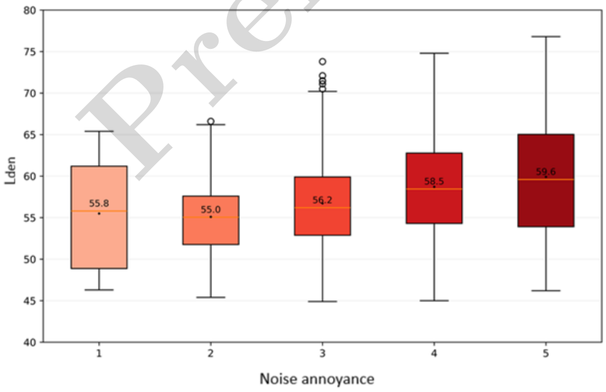

Figure 5. Correlation between general noise annoyance and L_{den} (answer categories: 1 not at all, 2 not, 3 moderately, 4 very and 5 extremely annoyed).

For specific sources, however, the link with event duration was source-dependent: no significant relationship was found for road traffic or construction noise, both near-continuous at busier locations and therefore poorly captured by duration and noise events alone, whereas rail traffic, air traffic, human voices and especially priority vehicles all showed a significant, positive relationship between event duration and the corresponding source-specific annoyance (Fig. 6).

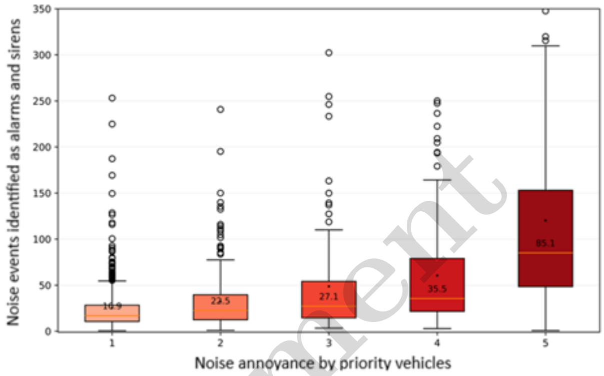

Figure 6. Correlation between specific noise annoyance by priority vehicles and the average duration per day of noise events identified as alarms and sirens (answer categories: 1 not at all, 2 slightly, 3 moderately, 4 very and 5 extremely annoyed).

A similar pattern emerged for sleep: residents who reported always keeping their bedroom window closed at night measured significantly higher L_{night} values and more (loud) night-time events than those who left it open, and the duration of events classified as rail or tram noise correlated with how often residents reported being woken up by trains or trams (the same pattern held for road traffic, but not for air traffic or neighbour noise). No relationship was found between L_{night} or event counts and self-reported sleep onset latency or duration. General annoyance also correlated significantly with fatigue (FAS) and stress (PSS-10) (Kruskal-Wallis, $p<0.001$ for both), see Fig. 7, but not with daytime sleepiness (ESS); as such relationships can run in both directions, an already fatigued or stressed respondent may also tolerate noise less and therefore report more annoyance.

Quality-of-life satisfaction in the immediate neighbourhood, finally, was markedly higher in Leuven (68.5%) than in Ghent (55.8%) and Antwerp (46.4%), broadly mirroring the cities' acoustic and traffic profiles, while the presence of nature sounds, and birdsong in particular, was consistently associated with higher quality of life and lower noise annoyance.

At the weekly time scale, however, these links were considerably weaker: week-to-week variation in measured noise levels at a given location was modest, and no clear population-level relationship was found between weekly L_{den}/L_{night} and the matching week's self-reported noise appreciation or specific annoyance, despite the dataset comprising over 10,000 weekly responses. Sensor side (front vs. rear) remained linked to lower general appreciation and higher stress, and general appreciation, specific annoyance and stress remained mutually correlated as expected. The direct, weekly link between measured sound levels and self-reported perception, however, only became clearly visible at the coarser, six-week averaging window used in §3.1.

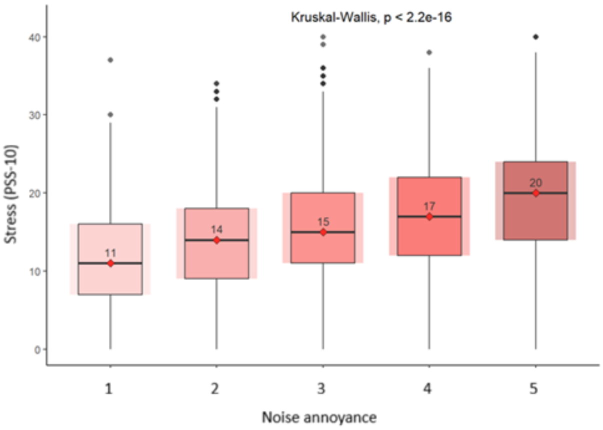

Figure 7. Correlation between general noise annoyance and stress (PSS-10) (answer categories: 1 not at all, 2 not, 3 moderately, 4 very and 5 extremely annoyed).

4. Discussion and conclusions

These results confirm that average noise indicators such as L_{den} and L_{night}, computed over several weeks or even simulated over a year, remain meaningful: higher long-term averages are systematically associated with more noise annoyance and a less favourable acoustic experience. At the same time, they explain only part of that experience. Loud, repeated and source-identifiable events, in particular from rail traffic, air traffic, human voices and priority vehicles, correlate more strongly with noise annoyance, sleep behaviour, fatigue and stress than near-continuous sources such as road traffic and construction noise, whose presence is almost constant once a location is busy, and whose annoyance is therefore not well captured by event duration alone. This nuance is consistent with the project's own conclusion that average indicators explain only part of how environmental noise is experienced, and that peak, recurring and source-specific events deserve more weight in assessing the impact of environmental noise [13].

The same nuance also held across time scales: the positive relationship between measured noise levels and self-reported noise annoyance was clear when comparing six-week averages across markedly different locations (e.g., loudest vs. quietest), but largely disappeared when looking at week-to-week fluctuations at a single location, where natural variation in exposure proved too limited, given the available sample, to produce a detectable population-level effect.

From a policy perspective, these findings support the need for legally binding and locally appropriate noise limits, and the exploration for complementing the existing strategic indicators used under the WHO/END guidance with other acoustic descriptors, that explicitly account for peak levels, event recurrence and source character rather than annual averages alone [13]. Future work includes refining the AI-based source recognition, further analyzing the year-round sensor dataset for specific noise sources (e.g., tram or airplane noise), and re-examining the weekly survey-sensor link on smaller, more homogeneous subsets of participants.

A number of limitations should be kept in mind when interpreting these results. The Large Sound Survey was an opt-in survey rather than a representative sample, so the self-selection bias noted in §3.2 means its absolute annoyance levels cannot be generalised to the Flemish population as a whole, even though the relative ranking of noise sources and the correlations with measured levels are expected to be more robust. Furthermore, all reported associations are correlational rather than causal: fatigue, stress and noise sensitivity can plausibly act in both directions, increasing reported annoyance may act as both antecedents and consequences, and a longitudinal or experimental design would be needed to disentangle these pathways. Finally, the present analysis is limited to Antwerp, Ghent and Leuven. Extending the same sensor-and-survey methodology to smaller cities, suburban and rural areas would help establish whether the patterns identified here, in particular the limited explanatory power of the duration of road traffic noise and the stronger role of rail, air and human-voice events, generalise beyond a large-city context.

Acknowledgments

The authors gratefully acknowledge the more than 10,000 citizen scientists who contributed to De Oorzaak, as well as the project partners, University of Antwerp, Antwerp University Hospital (UZA) and newspaper De Morgen, and the supporting industry and government partners, including the Flemish government (Departement Omgeving, Departement Zorg en Agentschap Wegen en Verkeer), Orange Belgium, Lantis, Natus, De Lijn, Sorama, the cities of Ghent and Leuven, and the Province of Antwerp. Last but not least, the authors thank Munisense and ASAsense, and all involved colleagues from UAntwerp for their valuable support during the entire project.

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