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Quieter except on weekend evenings: Changes in street-level noise following pedestrianisation

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Abstract

Using open data from 7 permanent noise monitoring stations, our study assesses changes in street-level noise following the pedestrianisation of Barcelona's new "green axes" in 2023. We find that noise levels have diminished consistently for all study locations following pedestrianisation, with an average 24-hour reduction of -3.1 dB. However, this reduction overlooks potential qualitative changes to the soundscape caused by the shift from motorised traffic to pedestrian activity. We also report selected results from a resident survey assessing views on pedestrianisation (n = 1,211), regarding questions on street noise and its impacts on residents' homes. We find that residents of pedestrianised streets exhibit significantly different adaptive behaviours to street noise compared to those of neighbouring streets, reporting among others more frequent use of street-facing rooms and balconies.

Keywords: pedestrianisation; street noise; traffic noise; pre-post study; Barcelona.

1 Introduction

The negative impact of traffic noise on urban liveability is widely acknowledged, with a large body of public health literature pointing to the negative impacts of long-term exposure to high noise levels for both mental and physical health (Passchier-Vermeer and Passchier 2000; WHO, 2018). Although the European Noise Directive (END) stipulates a maximum threshold of 55 dB for 24-hour average outdoor noise levels and the World Health Organisation (WHO) recommends that road traffic noise does not exceed an average of 53 dB, such values are regularly exceeded in urban contexts. This is especially true in large cities with high population densities, where many or even most locations may exceed a severe noise pollution threshold of 65 dB (Kheirbek et al. 2014; Zannin, Diniz, and Barbosa 2002).

In this context, pedestrianisation and related traffic calming schemes can play an important role in reducing transportation noise from motorised traffic (Appleyard 1980; Litman 1999). Since potential traffic noise reductions tend to be seen as a somewhat collateral benefit of pedestrianisation, however, the implications of street transformation schemes for noise levels do not seem to have received the same level of scrutiny as their impacts on mobility (Cairns et al. 2002; Chung, Yeon Hwang, and Kyung Bae 2012; Hagen and Tennøy 2021; Aldred, Goodman, and Woodcock 2024), commercial activity (Özdemir and Selçuk 2017; Yoshimura et al. 2022), public space usage (Gehl 2013; Villani and Talamini 2021), or even air quality (Allirani, Dumka, and Verma 2024; Sánchez et al. 2021). To the best of the our knowledge, in fact only one before-and-after study has so far empirically assessed changes in noise levels following pedestrianisation using noise monitoring station data (van Soesbergen & Mulligan, 2024).

To address this research gap, the present article makes use of open data from Barcelona's network of permanent noise monitoring stations to evaluate changes in street-level noise following the conversion of four streets in the central Eixample district to semi-pedestrianised "green axes" in 2023. These new green axes (see Figures 1 and 2) are integral to Barcelona's long-term superblock vision, which aims to improve urban liveability, social cohesion, and public health by reallocating space from motorised traffic to public space and active mobility (Rueda 2019; Vidal Yañez et al. 2023; Nieuwenhuijsen et al. 2024). Importantly, potential changes in street-level noise deriving from of pedestrianisation include not only reductions in traffic noise, but also possible noise increases caused by higher levels of pedestrian activity and outdoor recreation. In the case of Barcelona's green axes, concerns have been voiced that traffic noise reductions following pedestrianisation may be counterbalanced by outdoor recreational noise associated with pedestrian activity (Nello-Deakin 2024). In the present paper, we seek to evaluate the extent to which such concerns are justified.

To complement this focus on objective noise data, we report selected results from a from a resident survey assessing views on pedestrianisation. While centred primarily on other topics, this survey included a limited set of questions about street noise and its impacts on residents' homes. Inspired by Appleyard's seminal *Liveable Streets* (1981), these questions explored the "adaptative behaviours" developed by residents in their own homes in response to street noise, such as avoiding the usage of rooms facing the main street, changing their function, or installing soundproof windows. The survey distinguished between residents of the following four street types:

- *Main*: Conventional streets with high traffic intensities (average daily traffic (ADT) >15,000)
- *Secondary*: Conventional streets with moderate traffic intensities (ADT < 15,000)
- *Consolidated pedestrianisation:* Semi-pedestrianised streets implemented before 2020
- *Recent pedestrianisation*: new green axes implemented in 2023

To summarise, our paper examines the following two questions:

- How have measurable noise levels changed following pedestrianisation, and how does this change vary between locations and time periods?
- Do residents of pedestrianised streets exhibit significantly different "adaptive behaviours" in response to street noise than residents of non-pedestrianised streets?

These questions, we argue, hold both academic and policy relevance for cities seeking to implement pedestrianisation schemes similar to Barcelona's, particularly for comparably dense cities with a benign climate and vibrant street life.

2 Street noise, traffic and pedestrianisation

Dating back to the pioneering work by Southworth (1969) on the sonic environment of cities, soundscapes have been recognised as an important but often overlooked urban characteristic with significant implications for urban planning, transportation, and public health (Raimbault and Dubois 2005; Kang et al. 2018). Existing research on urban noise is multidisciplinary, but public health perspectives have exerted a strong influence on public policy discourses and guidelines on the topic, with major syntheses and policy guidelines focusing on documenting population exposure to environmental noise and its negative implications for well-being and health (e.g. WHO 2011; WHO 2018; Basner et al. 2014). Based on an environmental noise management approach, such perspectives tend to see urban noise primarily as a source of environmental pollution to be reduced (Jennings and Cain 2013). Among other negative consequences, exposure to high noise levels tends to heighten stress levels, increase the risk of cardiovascular disease, worsen mental health, and cause significant sleep disruption, as demonstrated by an extensive body of literature in this area (Passchier-Vermeer and Passchier 2000; Ouis 2001; Chen et al. 2023; Arregi et al. 2024; WHO 2024). Likewise, traffic noise has also been shown to have a negative impact on housing prices (Wang et al. 2023; Morawetz et al. 2024).

Meanwhile, environmental psychology and related disciplines have shown that subjective perceptions of noise can vary significantly between urban contexts, and is mediated or modified by visual urban environment characteristics such as street character (Young Hong and Yong Jeon 2020), building height (Montes González, Barrigón Morillas, and Rey-Gozalo 2023) or greenery (Cerwén, 2016; van Renterghem, 2019; Ren et al. 2023). In turn, sound environments influence people's activities and behaviour in outdoor spaces: compared to traffic sounds, for instance, natural sounds appear to promote greater levels of social interaction (Chen et al. 2024).

Despite extensive research on urban soundscapes, comparatively few studies have focused on empirically examining street-level noise in urban settings (McAlexander, Gershon, and Neitzel 2015; Ozturk et al 2025). Historically, many studies equated street-level noise with traffic noise, relying on traffic flow data to model predicted noise levels (Raimbault and Dubois 2005; Lionello et al. 2020). While motorised traffic indeed accounts for the overwhelming majority of noise pollution in most urban contexts, this risks disregarding other relevant noise sources, particularly in densely populated urban settings with low levels of car commuting (Kheirbek et al. 2014). As an example, McAlexander, Gershon, and Neitzel (2015) report measuring higher noise levels in intensively used pocket parks than on surrounding streets in dense Manhattan areas.

Before-and-after studies assessing changes in environmental urban noise levels during COVID-19 lockdowns also provide an interesting precedent for studying the impacts of traffic reduction on noise levels. Most of these studies reported significant reductions in noise levels (e.g. Aletta et al. 2020; Asensio et al. 2020; Rumpler et al. 2020), but paradoxically this reduction appears to have led to increased noise complaints in some contexts (Tong et al. 2021). In the specific case of Barcelona, a study by Bonet-Solà et al. (2024) found a mean reduction of -5.72 dB(A) across all sites of the city's noise monitoring network during lockdown. However, these results cannot be separated from the exceptional context of COVID-19 lockdown, which did not only drastically reduce motorised traffic but also all types of pedestrian and outdoor activities.

Against this backdrop, few studies seek to specifically assess the impacts of pedestrianisation on noise levels, which seem to be understudied compared to the impacts of pedestrianisation on other environmental externalities such as air pollution (e.g. Sánchez et al. 2021; Mueller et al. 2020). While noise reductions are often mentioned as an important potential benefit of pedestrianisation (Soni and Soni 2016;0 Keserü et al. 2016), surprisingly few empirical studies appear to have assessed this claim. In fact, the only direct precedent we have been able to find is a recent study by van Soesbergen and Mulligan (2024), who analysed the Strand–Aldwych pedestrianisation project in London. Using a dense monitoring network, they found that the removal of motorized traffic produced a sustained and statistically significant reduction in traffic noise levels. Chiquetto's (1997) study of the environmental impacts of a pedestrianisation scheme in Chester (UK) provides an earlier relevant precedent, but his study relies on modelled noise data based on traffic reductions rather than actual noise observations.

While not directly focusing on pedestrianisation, a before-and-after study by Stansfeld et al. (2009) reported a street-level reduction of 2-4 dB following the introduction of a new road bypass in three towns in North Wales (UK) but note that this did not amount to a significant difference in perceived noise annoyance. Finally, some studies have specifically studied noise in pedestrian areas, but not the impacts of pedestrianisation itself. For instance, Young Hong and Yong Jeon (2020) found higher noise levels to be associated with higher pleasantness in pedestrian-dominated commercial streets in Seoul, but with lower pleasantness in traffic-dominated streets in the CBD. Similarly, Meng and Kang (2015) found that the relationship between crowd density and acoustic comfort in commercial pedestrian streets appears to follow an inverted U shape, peaking at approximately 0.15 persons/m^2.

Through the present study, we seek to redress this dearth of research on the noise impacts of pedestrianisation. While no previous academic studies on this issue have been carried out in Barcelona itself, a technical report from the local public health agency (ASPB, 2021) reported an average daytime reduction of 3.5 dB (but no changes in nighttime noise levels) following the traffic calming of an intersection part of the Sant Antoni superblock. A key value of our study is its reliance on hourly data from permanent noise sensors, rather than short-term observations from temporary sensors. Likewise, through our survey questions we seek to follow Appleyard's (1981) footsteps by studying the adaptive behaviours developed by residents in their homes to cope with street noise, a research direction which appears to have spawned little further research despite its clear policy relevance.

3 Case study: Barcelona's new green axes

Our research focuses on the four new semi-pedestrianised "green axes" in the Eixample district of Barcelona, which were completed in mid-2023 as part of the city's wider superblock strategy (for a map of the study area, see **Figure 2** in the methods section). As shown in **Figure 1**, the new green axes entail a significant transformation of the existing street profile, creating a wide new shared space with increased vegetation and public seating, and eliminating through traffic by forcing motorised vehicles to turn at street intersections. In turn, this transformation builds upon previous tactical urbanism interventions which had already reduced traffic capacity to a single lane in 2020 in preparation for their definitive transformation (the traffic impacts of which have been previously evaluated in Nello-Deakin, 2022). As previous research has shown, the Eixample district has the highest average noise levels in the city because of its central location and high levels of motorised traffic on most streets (Lagonigro, Martori and Apparicio 2018).

Figure 1 *– Above: Consell de Cent Street before and after pedestrianisation. Below: Two of the new squares created at the intersection of two green axes. Source: Google Street View (upper left)/Authors*

The present paper builds on our previous research on the impacts of these green axes, including a qualitative examination of their implications for spatial equity between the new green axes and adjacent non-pedestrianised streets (Nello-Deakin 2024), and a representative survey assessing residents' views on the new green axes (Nello-Deakin et al. 2024). As we reported in Nello-Deakin et al. (2024), most residents consider having been benefited by pedestrianisation, regardless of whether they live on one of the new green axes or not. For the present article, a particularly relevant finding of this paper is that among residents of pedestrianised streets, noise reduction is the second most mentioned positive impact of pedestrianisation. At the same time, excessive tumult and street life is the most frequent negatively mentioned impact among the minority of residents who consider themselves to be adversely affected by pedestrianisation. This echoes planners' concerns that the new green axes might become excessively noisy as the result of human activity.

Indeed, Barcelona's previous experiences with the pedestrianisation of certain streets since the early 2000s (both in the Eixample area and other neighbourhoods) has shown that some of them can become a hub for outdoor recreation and nightlife, leading to an excessive concentration of bars and cafe terraces, and becoming a source of significant neighbourhood conflict. In this context, the City's 2010-2020 Noise Pollution Plan[1] designated certain special areas requiring specific regulations and monitoring, which the new 2022-2030 Plan extended by designating specific locations as "nighttime acoustically stressed areas". Critically, these correspond to lively pedestrian-dominated areas which constitute recreation and nightlife hotspots, rather than locations with high traffic noise. While the new green axes do not form part of these special areas, they have also been the focus of awareness campaigns which seek to discourage anti-social behaviour, including excessive noise (as evidenced by the billboard on the image below left in **Figure 1**). Likewise, specific regulations have been introduced limiting the number the types of new businesses which can open along the new green axes, mainly focusing on cafes and tourist-oriented uses.

4 Methods

4.1 Noise sensor data

Our primary analysis relies on data from Barcelona's municipal sensor network *Sentilo* (i.e. "sensor" in Esperanto), which includes mainly noise sensors, but also other types of monitoring stations (e.g. meteorological data, pedestrian counts). An overview of the key characteristics of this noise monitoring network can be found in

[1] Available in Catalan at https://bcnroc.ajuntament.barcelona.cat/jspui/handle/11703/86217

Camps (2015). As of late 2024, hourly noise data for individual noise sensors has been made publicly available on Barcelona's Open Data portal for the period 2015-2023. This noise sensor network does not seek comprehensive spatial coverage but rather focuses on potentially problematic or sensitive locations which may be exposed to excessive noise levels. This includes streets with high levels of motorised traffic, but also pedestrian-dominated streets and squares and high levels of pedestrian activity and nightlife. In this respect, and as discussed in the previous section, the *Sentilo* network forms part of the city's ongoing efforts to monitor and to reduce noise pollution.

Given the municipality's interest in monitoring the impact of the new green axes transformations on noise levels, noise sensors were installed at key locations in June 2022, i.e. prior to their (semi-)pedestrianisation in 2023. These locations include the four new squares created at the confluence of the green axes, and three other locations situated along an individual green axis (see **Figure 2** for a map of the new green axes, and **Figure 3** for an example of a sensor). These noise sensors were temporarily uninstalled between April-June 2023 because of the pedestrianisation roadworks, but the sensors were reinstalled at the same location between June-August 2023 once the new axes had been completed. The exact date intervals for which data is available vary slightly between individual locations depending on installation date, but provide a common period for all locations which makes it possible to compare the evolution of noise levels before and after pedestrianisation.

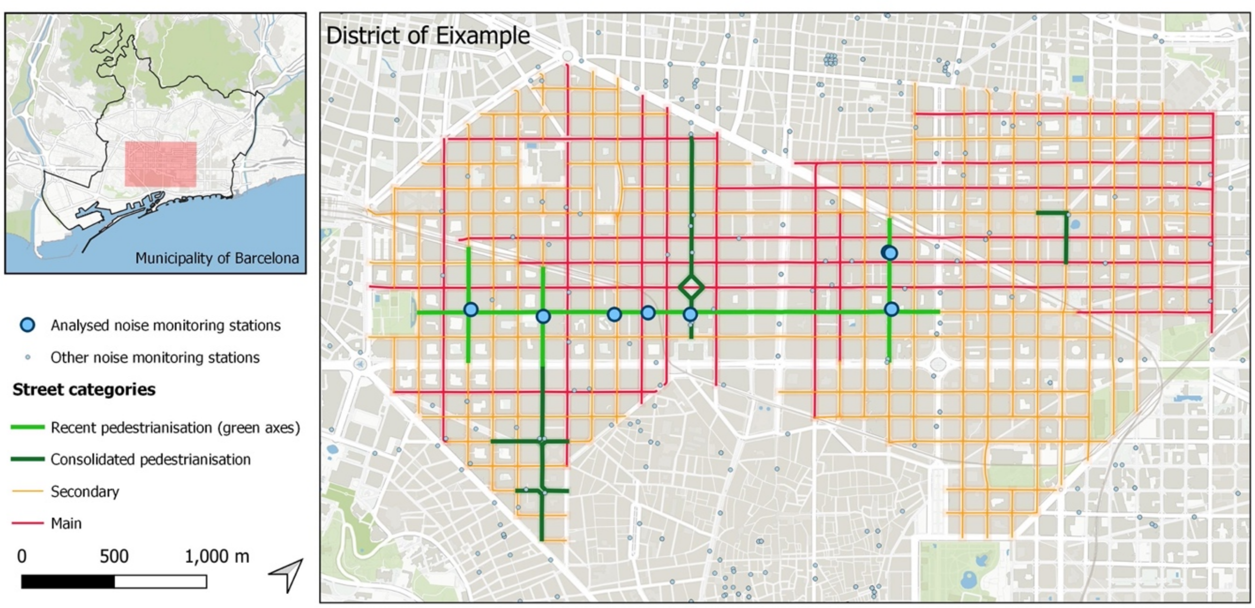

Figure 2 *– Study area, including noise monitoring stations and streets included in resident survey.*

Figure 3 *– Rocafort-Consell de Cent Square with visible noise sensor on lamppost.*

All noise sensors correspond to the TA120 model manufactured by CESVA, designed for permanent continuous noise monitoring in urban settings. According to the manufacturer's specifications, these sensors are certified as class 1 according to IEC 61672-1 standards, with a resolution of 0.1 dB and a measurement range of 28-120 dB (A). They rely on a ½″ condenser microphone, have a nominal sensitivity of 24.0 mV/Pa, and are protected against outdoor elements (IP65).

We aggregated hourly noise data for each station into daily averages, both over a 24-hour period (i.e. day-evening-night noise level, commonly abbreviated as **Lden**)and different parts of the day (Day (**Ld**) /Evening (**Le**)/Night (**Ln**), defined respectively as 07:00-21:00/21:00-23:00/23:00). Following the method used by the Municipality of Barcelona, the Lden measure includes a penalty of +5 dB for the evening period (Le) and +10 dB for the night period (Ln). Since decibels are logarithmic units, in all cases we transformed noise data to linear values before calculating averages, subsequently reconverting it into decibel format. Throughout the study, all decibel measurements refer to A-weighted decibels (dB(A)). While this is by far the most common weighting method for environmental noise exposure, it is important to be aware that it is not without limitations in capturing certain types of sounds (e.g. loud instantaneous bursts or low-frequency sounds) (Houser et al. 2021).

In the Results, we provide the two following outputs:

1) A visual evolution of daily noise levels throughout the whole study period (June 2022 to December 2023).

2) A numerical comparison of average noise levels between pre- and post-intervention periods (1 July- 17 November 2022 vs. 1 July-17 November 2023). By selecting the same calendar period for both years and an averaging noise values over multiple months, we have sought to reduce seasonal effects and account for small temporal data gaps in some monitoring stations (**Figure 5** in results section). We chose these calendar periods because they aligned with the (re-)installation dates of noise sensors, and the start date of permanent traffic changes caused by the implementation of the new green axes (18 November 2022)[2].

All calculations, analyses and graphs were conducted in R, relying primarily on the "tidyverse" (v 2.0.0) and "gtsummary" (v 2.5.0) collections of packages.

4.2 Resident survey

To complement noise sensor data, we draw upon an intercept street survey assessing views on pedestrianisation among residents in the Eixample district, which we

[2] While permanent traffic changes were only implemented on 18 November 2022, noise data from late August to November 2022 might be slightly affected by preliminary roadworks which began on 16 August 2022. Figure 6 in the Results hints at a potential increase in positive outliers for daytime (Ld) noise levels during this period, but averaging data across months minimises their potential effect.

conducted in September 2023 as part of a research project assessing impacts and perceptions of the new green axes. The main results of the survey regarding residents' views on the new green axes have previously been published in Nello-Deakin et al. (2024), to which we refer the reader for a complete description of survey characteristics. While not its main focus, this survey included a limited number of questions asking residents about the main sources of street noise and their impact on street noise and its impact on residents' homes, which have not been previously analysed in Nello-Deakin et al. (2024). The survey was carried out by an independent research company on our behalf, and took approximately 10 minutes to complete. It is based on a sample of 1,211 residents, with quotas for gender and age designed to be representative of the district population. As described in the Introduction, the survey also classified respondents based on the type of street they lived on (see **Figure 2**) into the following street categories: *main* (average daily traffic >15,000), secondary (average daily traffic <15,000), *consolidated pedestrianisation* (semi-pedestrianised streets implemented before 2020) and recent pedestrianisation (new green axes). The survey included respondent quotas for each type of street (see Table 2 in Results), oversampling respondents in the *recent pedestrianisation* and *consolidated pedestrianisation* categories to guarantee reliable results for these categories.

In the Results, we compare differences in the main reported sources of street noise between the residents of pedestrianised vs. non-pedestrianised streets; likewise, we compare how street noise conditions the usage and frequency of use of street-facing rooms and balconies. In the context of Barcelona and given its benign climate, street-facing balconies are a common feature of most apartments and are strongly appreciated for a variety of purposes, from offering a vantage point to get some fresh air or contemplate the street, providing space for plants and greenery, to practical uses such as storing bulky items (e.g. bicycles) or hanging the laundry. Anecdotal observational evidence suggests that balconies on heavily trafficked streets appear to be less used than those on calmer streets, a hypothesis we wanted to test in this survey. To assess the statistical significance of these differences, we employ Chi-square analysis, complemented by adjusted residual tests to identify values that deviate significantly from expected frequencies (either positively or negatively).

5 Results

5.1 Noise monitoring stations

Figure 4 offers a visual comparison of average noise levels across all monitoring stations before and after pedestrianisation, categorized by time of day. To complement this figure, in **Table 1** we provide summary results of a paired t-test of average before-and-after noise levels for all monitoring stations, which confirms that noise reductions are statistically significant ($p<0.05$) for all time periods. As can be seen, post-intervention daily average noise levels (Lden) are significantly lower (-3.1 dB) than pre-intervention ones, dropping from 69.4 to 66.3 dB. The largest decrease (-4.7 dB) occurs during daytime (Ld), while evening noise levels present the smallest decrease (-1.2 dB).

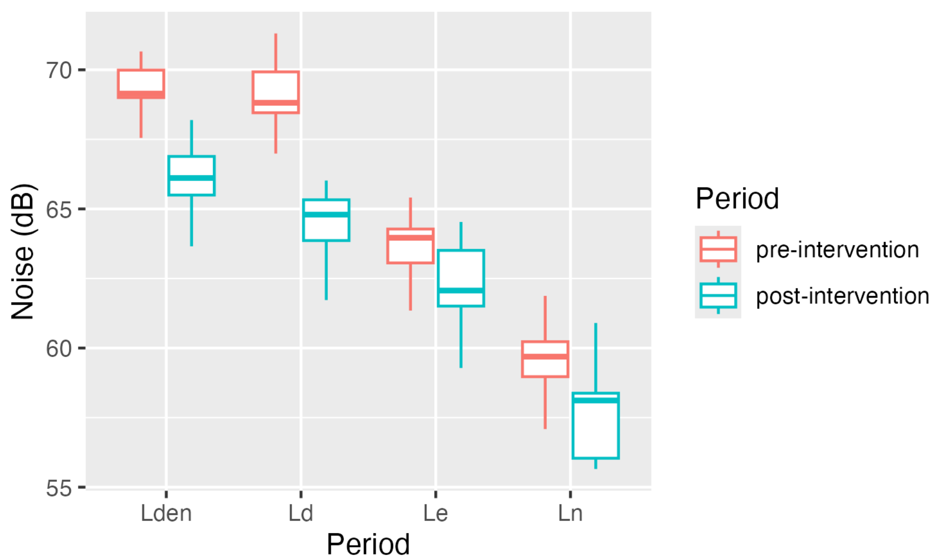

Figure 4 *– Average pre- and post-intervention noise levels across all analysed monitoring stations, categorised by time of day: 24-hours (Lden), Day (Ld), Evening (Le), and Night (Ln).*

Period	dB (A) – pre-intervention	db (A) – post-intervention	Difference (post – pre)	T	df	95 % CI Lower	95% CI Upper	p-value
Lden	69.4	66.3	-3.1	9.93	6	2.43	4.03	0.000
Ld	69.3	64.6	-4.7	7.39	6	3.15	6.27	0.000
Le	63.8	62.6	-1.2	2.67	6	0.11	2.59	0.037
Ln	59.8	58.0	-1.8	5.08	6	1.00	2.87	0.002

Table 1 *– Summary of paired t-test results (average before-and-after noise levels for all monitoring stations).*

In **Figure 5**, we provide a trendline of the evolution of average noise levels for individual monitoring stations between June 2022 and December 2023, including not only the pre- and post-intervention periods but also the intermediate period of roadworks during the first half of 2023. As shown, pre-intervention noise levels generally range from 65 to 70 dB. Most stations present a slightly decreasing trend in noise levels prior to the implementation of traffic changes in November 2022 (dashed vertical line). During the first half of 2023, however, noise levels increased for most monitoring stations, plausibly because of the noise impacts of roadworks and their accompanying effects on motorised traffic. The final post-intervention phase (solid vertical line) results in a substantial reduction in noise levels across all studied locations. This reduction seems to be particularly marked for the monitoring stations located in newly created squares (solid colour lines), which are situated at the confluence of new two pedestrianised streets and are accordingly further removed from streets with through motorised traffic.

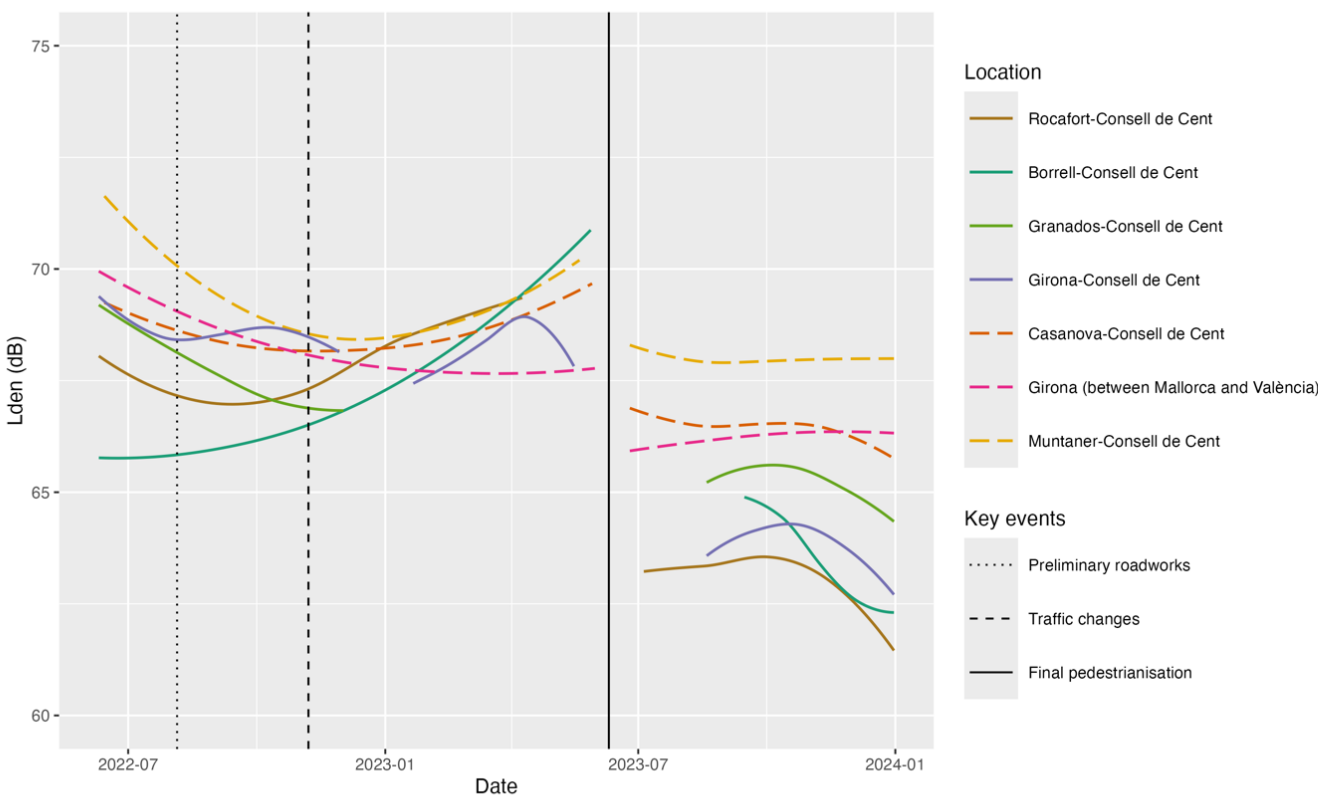

Figure 5 *– Trendline of daily average noise levels for analysed monitoring stations between June 2022 to December 2023 (continuous line = new squares; dashed line = remaining stations).*

Figure 6 offers a more granular temporal perspective of noise evolution for individual stations, classified by time of day and including a dot plot of average daily noise levels.

In accordance with previous figures, the data display a clear overall reduction in noise levels across all time periods and stations following pedestrianisation, with daytime noise levels (Ld) presenting the most significant reductions. However, during the first half of 2023 (roadworks stage), we can observe that noise levels generally increased during the daytime compared to the pre-intervention stage, but decreased during the evening and night periods.

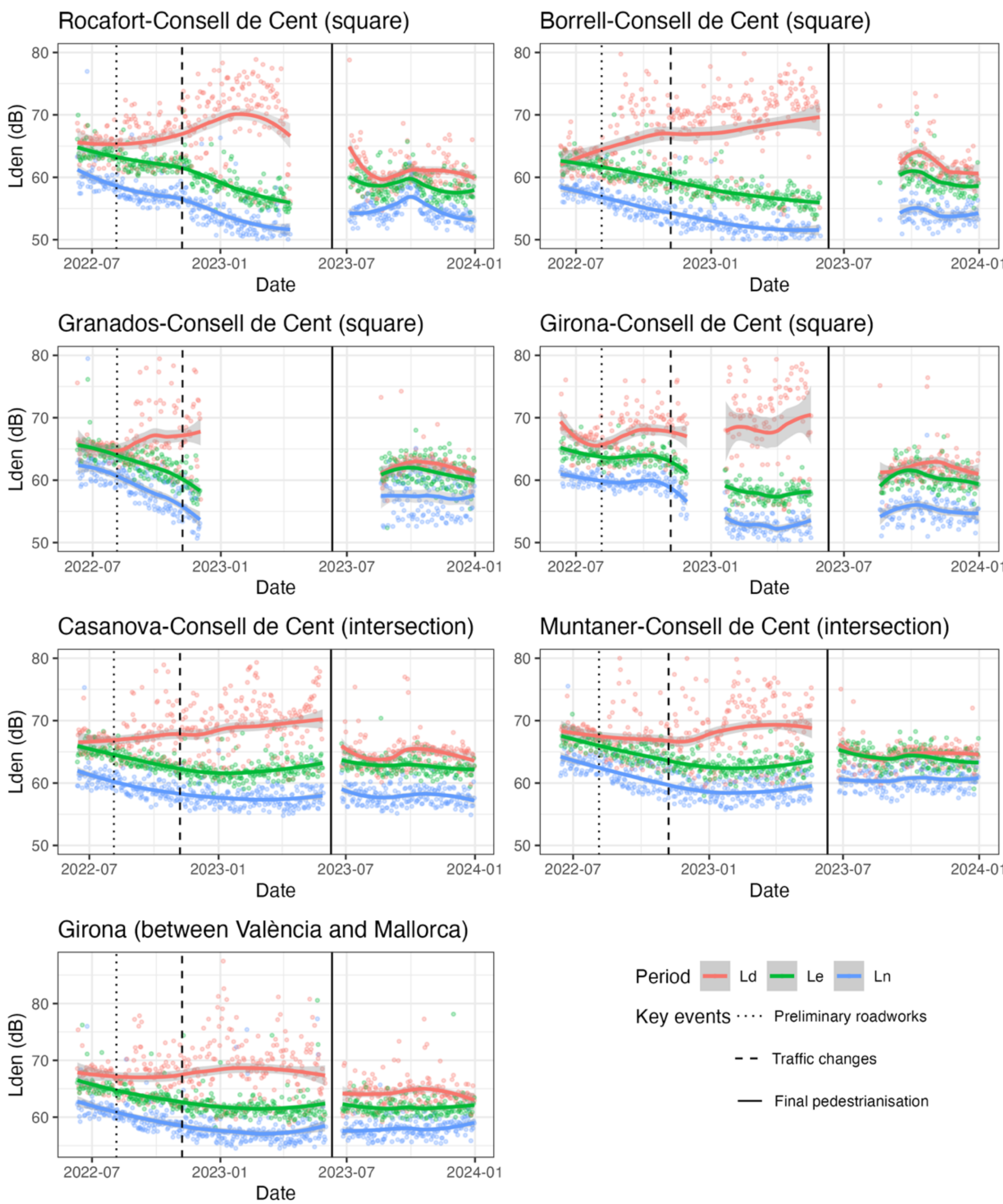

Figure 6 *– Dot plot and trendline of average daily noise levels for individual noise monitoring stations, categorised by time of day: Day (Ld), Evening (Le), and Night (Ln).*

Lastly, **Figure 7** compares average pre- and post-intervention hourly noise levels across all stations, distinguishing between weekdays and weekends. This figure highlights how the largest noise reductions following pedestrianisation are to be found during the central daytime hours (approximately between 08:00-18:00). Before pedestrianisation, weekday noise levels peaked between 08:00-12:00, surpassing an average of 70 dB. Post-intervention data shows a significant drop in daytime peak noise levels, decreasing to about 65 dB. Overall, the morning and afternoon noise peaks appear to be somewhat less prominent in the post-intervention period; a plausible explanation for this is that pedestrian activity tends to be less concentrated around peak hours than motorized traffic. Weekend daytime noise levels exhibit a similar change, but the decrease is slightly less pronounced. While weekday daytime noise levels are clearly higher than weekend daytime noise levels for the pre-intervention period, in the post intervention period this is no longer always the case.

An important exception to the overall reduction in noise is to be found in the evening period (from around 20:00 to 23:00). While the results show a small reduction in noise levels during weekdays, evening post-intervention noise levels during weekends show no significant reduction compared to pre-intervention levels. Higher levels of pedestrian activity and outdoor recreation during weekend evenings offer a plausible explanation for trend, even if our study is unable to confirm this hypothesis.

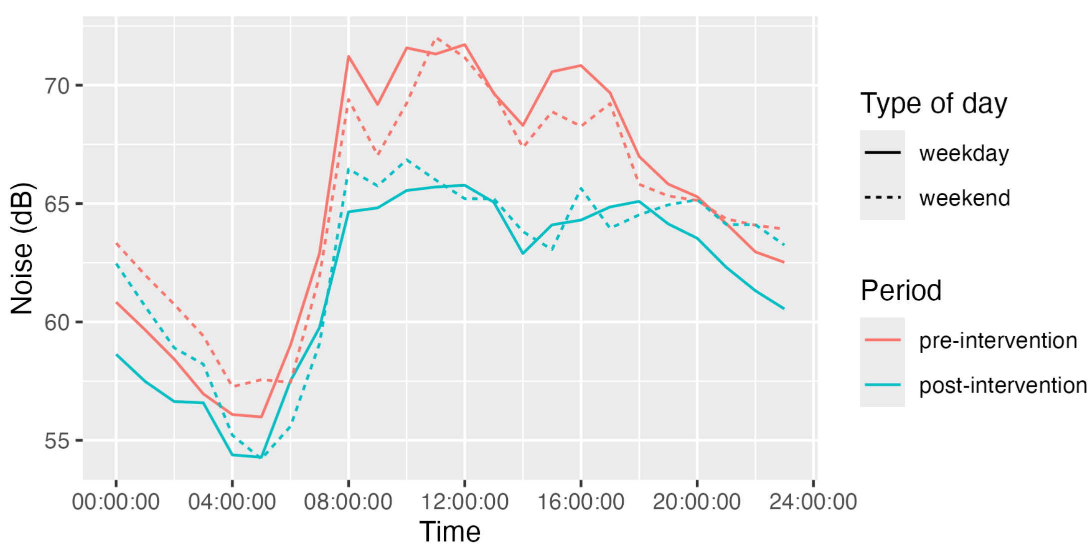

Figure 7 *– Hourly average noise levels for all stations, according to type of day and period.*

5.2 Survey findings

In Table 2, we provide an overview of key characteristics of survey respondents. Our sample exhibits a balanced gender and age distribution, since it included specific quotas designed to be representative of the Eixample district population. In accordance with the design of the survey sample, equal proportions (33.0%) of participants live on principal and secondary streets, while a smaller proportion of respondents (17.3%) reside on recently pedestrianised streets (17.3%) – i.e. new green axes – and consolidated pedestrianised streets (16.7%). Questions related to street noise were only asked to the subsample of respondents (68.2%) that have at least one room directly facing the main street.

Total	1,211 (100%)
Age groups	
18-29	207 (17.1%)
30-44	340 (28.1%)
45-59	270 (22.3%)
60-74	237 (19.6%)
75+	157 (13.0%)
Gender	
Women	651 (53.8%)
Men	559 (46.2%)
Non-binary/other	1 (0.1%)
Street type	
Recent pedestrianisation	209 (17.3%)
Consolidated pedestrianisation	202 (16.7%)
Secondary	400 (33.0%)
Main	400 (33.0%)
Rooms directly facing main street	
No	385 (31.8%)
Yes, with at least one balcony or terrace	764 (63.1%)
Yes, without any balcony or terrace	62 (5.1%)

***Table 2** – Key characteristics of survey respondents (n=1,211)*

The main source of street noise reported by survey respondents varies significantly by type of street of residence, as shown in **Table 3**. On main streets, motorised traffic is the predominant noise source according to 81.3% of respondents, which is significantly higher than for other types of streets. In contrast, recreation and people is the most commonly reported source of street noise for residents of pedestrianised streets (both recent and consolidated). Other noise sources (e.g. roadworks, rubbish collection) are also reported more frequently on recently pedestrianised streets (32.9%) compared to other street types.

	Recent pedestrianisation	Consolidated pedestrianisation	Secondary	Main
Traffic	14.8%$^-$	19.3%$^-$	53.9%	81.3%$^+$
Recreation and people	52.3%$^+$	60.0%$^+$	26%	7.0%$^-$
Other	32.9%$^+$	20.7%	20.1%	11.7%$^-$
Total	100%	100%	100%	100%

a. 385 missing cases correspond to individuals without street-facing rooms; 5 cases correspond to "Don't know / No answer".

Pearson Chi-Square= 257.288, df=6, p<0.001.

Adjusted residuals test: $^-$Significantly lower than expected, $^+$Significantly higher than expected.

Table 3 *– Main reported source of street noise by street type (n=821[a]).*

As shown in **Table 4**, the comparative prevalence of soundproof windows varies significantly between residents of pedestrianised and non-pedestrianised streets. On main streets, up to 62% of respondents report that that all their windows are soundproof or double-glazed, compared to 44.1% on recently pedestrianised streets. This pattern likely reflects pre-existing differences in traffic levels rather than the effects of pedestrianisation, but it demonstrates a clear relationship between traffic intensity and soundproof window adoption. The reported impact of noise on room usage further illustrates these differences. Residents of main streets are more likely to report that noise conditions their usage of the room or rooms facing the main street (59.0%), a value significantly higher than for other street types; conversely, this proportion is lowest among residents of recently pedestrianized streets. Compared to residents of pedestrianised streets, a greater proportion of residents of main and secondary streets also report using the room(s) facing the main street less frequently because of street noise, but this difference is not statistically significant.

	Recent pedestrianisation	Consolidated pedestrianisation	Secondary	Main
Sound-proof windows[a]				
No	52.4%⁺	42.80%	37.60%	34.3%⁻
Yes, some windows	3.40%	2.10%	5.20%	3.70%
Yes, all windows	44.1%⁻	55.20%	57.20%	62.0⁺
Total	100.0%	100.0%	100.0%	100.0%
Modifies use[b]				
No	53.3%⁺	50.00%	46.1%	40.5%⁻
Yes	46.7%⁻	50.00%	53.9%	59.0%⁺
Total	100.0%	100.0%	100.0%	100.0%
Modifies frequency[c]				
No	69.3%	68.5%	61.3%	61.0%
Yes	30.7%	31.5%	38.7%	39.0%
Total	100.0%	100.0%	100.0%	100.0%

a. n=811; 385 missing cases correspond to individuals without rooms to analyzed street; 15 cases correspond to "Don't know / No answer". Pearson Chi-Square= 16.31787, df=6, p=0.0121
c. n=824; 385 missing cases correspond to individuals without rooms to analyzed street; 2 cases correspond to "Don't know / No answer". Pearson Chi-Square= 7.48, df=3, p=0.058
d. n=824; 385 missing cases correspond to individuals without rooms to analyzed street; 2 cases correspond to "Don't know / No answer". Pearson Chi-Square= 4.963, df=3, p=0.175
Adjusted residuals test: ⁻Significantly lower than expected, ⁺Significantly higher than expected.

Table 4 *–Prevalence of soundproof windows and reported impacts of street noise on usage of room(s) facing main street, classified by street type.*

Lastly, **Table 5** displays residents' reported frequency of use of street-facing balconies/terraces according to street type. Residents of consolidated pedestrianised streets report the highest daily or near-daily usage (68.3%), followed by those of recently pedestrianised streets; by contrast, balconies/terraces are used least frequently by residents of main streets, and to a lesser degree by those of secondary streets. This suggests that pedestrianisation may spur residents to use their balconies more frequently a result of their reduced exposure to negative traffic externalities (i.e. noise, air pollution).

	Recent pedestrianisation	Consolidated pedestrianisation	Secondary	Main
Rarely or never	13.8%	15.1%	15.6%	19.9%
Occasionally (weekly or monthly)	23.4%	16.5%[-]	24.2%	31.4%[+]
Daily or nearly daily	62.8%	68.3%[+]	60.2%	48.8%[-]
Total	100.0%	100.0%	100.0%	100.0%

a. 447 missing cases correspond to individuals without balcony/terrace to analysed street; 3 cases correspond to "Don't know / No answer".

Pearson Chi-Square= 17.577, df=6, $p<0.05$.

Adjusted residuals test: [-]Significantly lower than expected, [+]Significantly higher than expected.

Table 4 *– Reported frequency of use of balcony/terrace by street type (n=761[a]).*

6 Discussion

Our results suggest that pedestrianisation has clearly reduced ambient street noise levels for all studied locations, particularly during daytime hours. These findings confirm that reducing or eliminating motorised traffic plays a critical role in reducing noise pollution in urban contexts, leading to an improvement in environmental quality which can be seen as a key benefit of pedestrianisation.

At the same time, average noise levels after pedestrianisation on the new green axes clearly continue to exceed recommended maximum values from both the EU and the WHO (55 and 53 dB respectively), with only the four new squares formed at the intersection of two green axes falling below the Municipality of Barcelona's own maximum threshold of 65 dB for residential mixed-use areas (Lden). This attests to the difficulty of reducing noise levels to the standards recommended by international guidelines, which arguably may not offer a realistic target in the context of a densely populated Mediterranean city (at least in the foreseeable future). Indeed, previous research has found that 94.7% of Barcelona's population is exposed to noise values above EU guidelines (Lagonigro et al. 2018).

Importantly, our results suggest that concerns that reductions in traffic noise might be counteracted by a corresponding increase in noise from outdoor recreation and pedestrian activity are not substantiated, at least for the monitored study locations. However, the shift of the main source of noise from motorised traffic to pedestrian activity has entailed a change in the temporal distribution of noise levels. While daytime noise levels during the pre-intervention period are generally higher on weekdays than during the weekend, in the post-intervention we find that this situation is often reversed, with higher noise levels during the weekend than on weekdays. This situation is particularly pronounced on weekend evenings, which are in fact the only period for which noise levels have not diminished after pedestrianisation. This suggests that outdoor recreational activities now constitute the main source of noise on the new green axes, which could potentially become excessive during specific time periods or at specific locations if the new green axes become subject to an intensive use of public space.

It is also possible that for a comparable objective dB(A) intensity level, background traffic noise is perceived as less irritating or disruptive than more irregular or variable sounds associated with pedestrian activity (shouting, music, etc.). Echoing the findings of Lee and Jeong's (2021) study of urban noise during the COVID-19 lockdown in London, reductions in traffic noise might also lead to a heightened perception of other noise sources such as neighbours. For these reasons, it would be valuable to complement our focus on objective noise data with on-the-ground research examining resident's subjective noise perceptions, including more qualitative approaches. Ideally, a fully-fledged noise monitoring strategy for the new green axes would go beyond simple noise abatement, instead seeking to think more holistically about the soundscape of the new pedestrianized axes (Morawetz, Klaiber, and Zhao 2024; Raimbault and Dubois 2005). Since visual elements such as greenery can also influence noise perception (Ren et al. 2023; Gidlöf-Gunnarsson and Öhrström 2007), plans for street pedestrianisation could also seek to incorporate specific urban design and greening strategies to maximise acoustic comfort and reduce noise perception.

In contrast to other streets dominated by traffic noise, our survey findings show that people and recreation are by far the most common source of noise on pedestrianized streets. Both for residents of pedestrianised and non-pedestrianised streets, use of their own home is significantly conditioned by street noise, with many residents using the rooms/balconies facing the main street less frequently than they would in absence of excessive street noise. In line with Appleyard's (1981) pioneering research in this area, these "adaptation strategies" are stronger in streets with higher traffic levels, suggesting that pedestrianisation benefits residents by allowing them to make a fuller use of their homes. As previous research has found (Litman 1999; Wang et al. 2023; Morawetz et al. 2024), such noise reductions may ultimately contribute to raise local property values on pedestrianised streets, thereby raising concerns that the new green axes may inadvertently contribute to processes of "green gentrification" (Anguelovski et al. 2023).

Lastly, our study has three main limitations that are worth reiterating. Firstly, the locations of the studied noise sensors were not planned for the specific purposes of the present study and only cover selected points within the new pedestrianised streets, and which may introduce some level of spatial bias. Secondly, our before-and-after analysis is constrained by the (re)-installation dates of the noise sensors, which prevented us from comparing longer time periods. This is especially true for the relatively short period of available post-intervention data, which limits insights into the long-term evolution of noise levels following pedestrianisation. Accordingly, it would be desirable to revisit our results in a few years' time to monitor long-term noise trends and assess whether the noise reductions reported in the present study are maintained. Finally, the restricted scope of the questions related to street noise are an important limitation of our survey findings: these questions did not seek to capture the richness of residents' subjective noise perceptions, and only provide simple insights into the adaptive behaviours developed by residents to cope with street noise. In this respect, we suggest that more detailed research on the adaptive responses developed by residents in response to street noise could constitute a promising avenue for future study. This is especially true since despite its clear conceptual appeal and relevance for urban policy, we have been unable to find any more recent studies which further pursue Appleyard's (1981) notion of "adaptive behaviours".

7 Conclusions

Based on a pre-post comparison of noise levels from seven permanent monitoring stations over multiple months, our study has demonstrated that the pedestrianisation of four new "green axes" in Barcelona has resulted in a statistically significant reduction in average street noise levels for all time periods. Average reductions are largest during daytime hours and smallest during the evening, with reductions also somewhat more pronounced on weekdays compared to weekends. Notably, noise reductions are significantly larger at monitoring stations located in the new squares formed at the intersections of two green axes, compared to those located along a single green axis. While this belies concerns that noise from pedestrian activity may exceed traffic noise, results from our resident survey confirm that noise from people and recreation are now dominant on the new green axes. From a policy perspective, this suggests that it is important to actively monitor noise levels on the new green axes, which could risk becoming excessive at times of high pedestrian and recreational activity (e.g. weekend evenings in summer) in the absence of mitigation measures (e.g. awareness campaigns, limiting opening hours of café terraces). This monitoring could be valuably complemented by citizen science approaches, both as a means of incorporating more qualitative soundscape evaluations and fostering public participation in knowledge production (Radicchi et al. 2018).

Our survey findings also underscore broader benefits of pedestrianisation related to reductions in street noise: residents of recently pedestrianised streets report using street-facing rooms and balconies more than residents of main streets. Nevertheless, almost half of residents of pedestrianised streets still report that street noise affects the use of their indoor home spaces, serving as a reminder that noise levels on the new pedestrianised green axes remain well above EU and WHO recommended thresholds. This calls for further efforts to integrate noise mitigation strategies into pedestrianisation and traffic calming schemes.

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