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The acoustic environment is structured more by place and fine particulate matter more by time across Rhode Island communities

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Abstract

Environmental comfort in cities is shaped by several exposures at once, yet noise and air pollution are often combined into a single index of environmental quality. We measured the acoustic environment, fine particulate matter (PM2.5) and night-time illuminance at 144 sites across eight Rhode Island municipalities, sampling each in four day and night session types over 39 measurement days (531 site-sessions). Sound level and PM2.5 were uncorrelated and had different predictors. Sound was associated mainly with the built environment, rising near industrial land, and most of its variance lay between sites. PM2.5 was associated chiefly with day-to-day weather, falling with wind and rising with temperature and precipitation, and most of its variance lay between measurement days. Sound fell at night while PM2.5 rose. These patterns held under penalized regression and after accounting for spatial clustering, which itself reflected shared weather. Applying the same models to every measured quantity separated them consistently: the acoustic metrics and night-time light were structured mainly by place, and every air-quality metric mainly by time. In this setting the acoustic environment behaved more as a feature of place and PM2.5 more as a feature of time, suggesting the two are better characterized separately than combined.

Keywords: environmental noise; fine particulate matter; urban environment; built environment; meteorology; artificial light at night; spatial variation

Introduction

Human perception is fundamentally multisensory. Sound, air quality, temperature, and light all contribute to whether a place feels comfortable or stressful, and each has been linked to health and wellbeing in its own right. Together these domains shape what has been termed environmental comfort, the overall degree to which a setting supports the wellbeing of the people

in it, which is increasingly studied as a multidimensional construct rather than through any single exposure [1]. Environmental noise is associated with annoyance, sleep disturbance, and cardiovascular disease [2,3], and the World Health Organization now recommends limiting average road-traffic noise to protect public health [4]. Fine particulate matter (PM2.5) is one of the most consistent environmental risk factors for mortality and cardiopulmonary disease [5,6,7], and the WHO halved its recommended annual guideline value in 2021 in response to accumulating evidence of harm at low concentrations [8]. Because these exposures occur together in the same places, there is growing interest in characterizing the urban environment as a whole rather than one pollutant at a time, an ambition reflected in the exposome framework [9,10].

Much of the exposome literature operates on the premise that urban environmental stressors are co-occurring, mutually reinforcing, and therefore summarizable. Composite indices of environmental quality combine noise, air pollution, temperature, and greenness into single scores used for planning and for exposure assignment in epidemiology. Yet the empirical basis for combining them is thinner than the practice implies. Studies that have measured traffic noise and traffic-related air pollution together in the same locations have generally found only weak to moderate correlations, with substantial numbers of locations that are loud but relatively clean, or quiet but relatively polluted [11,12]. If two exposures that share a dominant source are only weakly coupled at the point of exposure, a single summary may obscure more than it reveals.

Part of the reason for this weak coupling may lie in how each exposure is distributed in space and time. Community noise is dominated by road traffic, structured by land use, and stable enough at a given location to be predicted from fixed features of the built environment [13,14,15]. Land-use regression models built from road type, traffic volume, building density, and vegetation routinely explain much of the spatial variation in measured sound across cities [13,14]. Fine particulate matter behaves differently within an urban area. A large share of urban PM2.5 is regional and secondary rather than emitted at the kerb, so concentrations tend toward spatial homogeneity across a metropolitan area while shifting from day to day with the weather [16,17]. Short-term measured PM2.5, in particular, reflects the meteorology of the measurement window as much as the characteristics of the location.

If that distinction holds, it has direct consequences for how environmental comfort should be measured. The sound environment of a site would be characterized by measuring that site, while its particulate environment would be characterized by measuring on many days or by modelling regional concentrations. A composite score built from a single visit would then mean something different for each exposure. The noise and soundscape literature already cautions against reducing the acoustic environment to a single sound-level number, treating it instead as something perceived in context [18,19,20], and reviews of indoor environmental quality emphasize that thermal, acoustic, air and visual conditions are distinct domains rather than facets of one thing [21]. Whether the distinction holds in practice, and how sharply, is an empirical question that requires measuring both exposures at the same places on the same occasions.

Here we address that question using a multi-domain measurement campaign across Rhode Island communities. We collected co-located measurements of the acoustic environment, fine particulate matter and night-time illuminance at 144 sites in eight municipalities, sampling each site across four session types defined by day type and time of day. Sound level can be summarized under different frequency weightings, and the A-weighting conventional in noise assessment de-emphasizes low-frequency energy, which is itself associated with annoyance and health effects and can dominate exposure near many urban sources [22]. We ask three questions. First, are sound level and PM2.5 correlated at the point of exposure? Second, are they predicted by the same features of the built environment and weather? Third, and most directly, is the variance in each attributable mainly to the site or to the day on which it was measured? Because the same protocol recorded several additional quantities at each visit, we carry every measured channel through the identical analysis, so that null results are reported on the same footing as positive ones and the specificity of any pattern can be judged directly.

Results

Measurements and study design

We analyzed 531 site-sessions from 144 sites, collected by 16 students on 39 distinct measurement days between 19 September and 16 November 2025. Sites were distributed across eight municipalities: Providence (92), Pawtucket (26), Warren (9), East Providence (8), Woonsocket (3), Central Falls (3), Cranston (2) and Barrington (1), with municipality assigned by geocoding site coordinates against census place boundaries (Fig. 1).

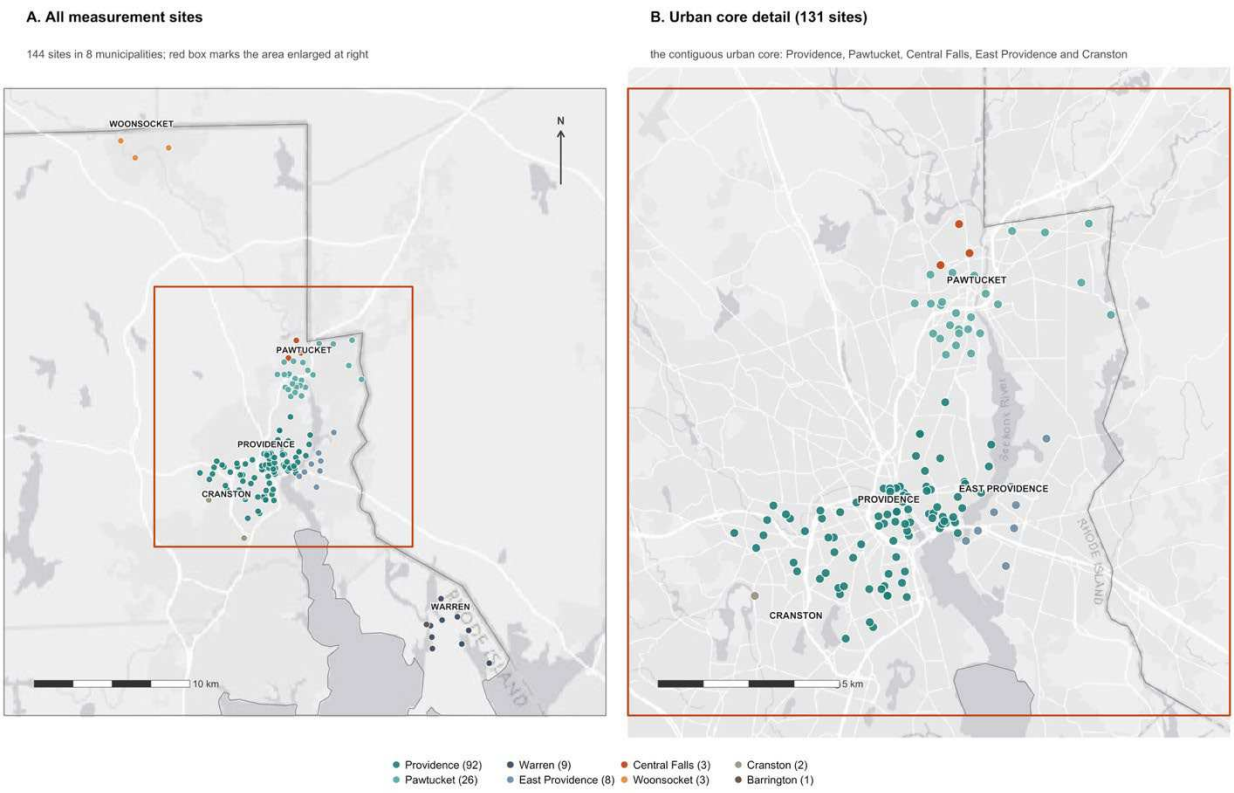


Figure 1. Measurement sites across Rhode Island communities. (a) All 144 sites, coloured by municipality, with the red box marking the area enlarged in (b). (b) The contiguous urban core of Providence, Pawtucket, Central Falls, East Providence and Cranston. Sites were sampled across 531 site-sessions on 39 measurement days between 19 September and 16 November 2025.

Each site was scheduled for four session types, weekday daytime, weeknight, weekend daytime and weekend night; 531 of the 576 scheduled sessions yielded co-located sound and air measurements. Measured levels spanned a wide range (Table 1). Site-session sound level had a median LAeq of 59.0 dBA (interquartile range 54.2 to 64.5) and PM2.5 a median of 3.0 µg/m³ (1.6 to 5.2), concentrations that are low in absolute terms and consistent with generally clean regional air during the campaign. Night-time illuminance was recorded during night sessions only, with a median of 0.00 foot-candles and a maximum of 4.50 across 182 sessions. Aircraft were noted in 56 of 491 sessions with a completed field sheet (11.4%).

Table 1. Study design and summary statistics for the principal measured variables across 531 site-sessions. Values are median (interquartile range) and range unless otherwise indicated.

Variable	Median (IQR)	Range
Sites	144	–
Site-sessions analysed	531	–
Measurement days	39	–
Unique students	16	–
Measurement period	19 Sep – 16 Nov 2025	–
LAeq, dBA	59.0 (54.2–64.5)	36.0–79.9
LCeq, dB	70.7 (65.9–74.5)	47.8–102.2
LZeq, dB	74.4 (69.4–78.7)	52.3–103.1
PM2.5, µg/m³	3.0 (1.6–5.2)	0.1–21.6
PM10, µg/m³	5.0 (2.6–8.8)	0.1–36.6
Air quality index	12 (6–21)	1–70
TVOC, mg/m³	0.02 (0.01–0.02)	0.01–1.75
HCHO, mg/m³	0.02 (0.01–0.02)	0.01–0.57
Temperature, °F	63.1 (57.3–68.4)	42.0–100.5
Relative humidity, %	47.4 (37.2–59.9)	21.1–80.5
Illuminance, Fc (night only, n = 182)	0.00 (0.00–0.53)	0.00–4.50

Sessions by type: weekday daytime 132, weekend daytime 140, weekend night 128, weeknight 131. Aircraft were observed in 56 of 491 sessions with a completed field sheet (11.4%).

Acoustic level and PM2.5 are uncorrelated

Across all site-sessions, sound level and PM2.5 showed little correlation (r = -0.05, 95% confidence interval -0.14 to 0.03, p = 0.24 against log-transformed PM2.5; r = -0.02 untransformed). When sites were divided at the median of each exposure, the four combinations were close to equally common: 139 site-sessions were loud and relatively clean (26.2%), 128 loud and relatively polluted (24.1%), 126 quiet and clean (23.7%) and 138 quiet and polluted (26.0%), a distribution indistinguishable from uniform (chi-square p = 0.80; Fig. 2).

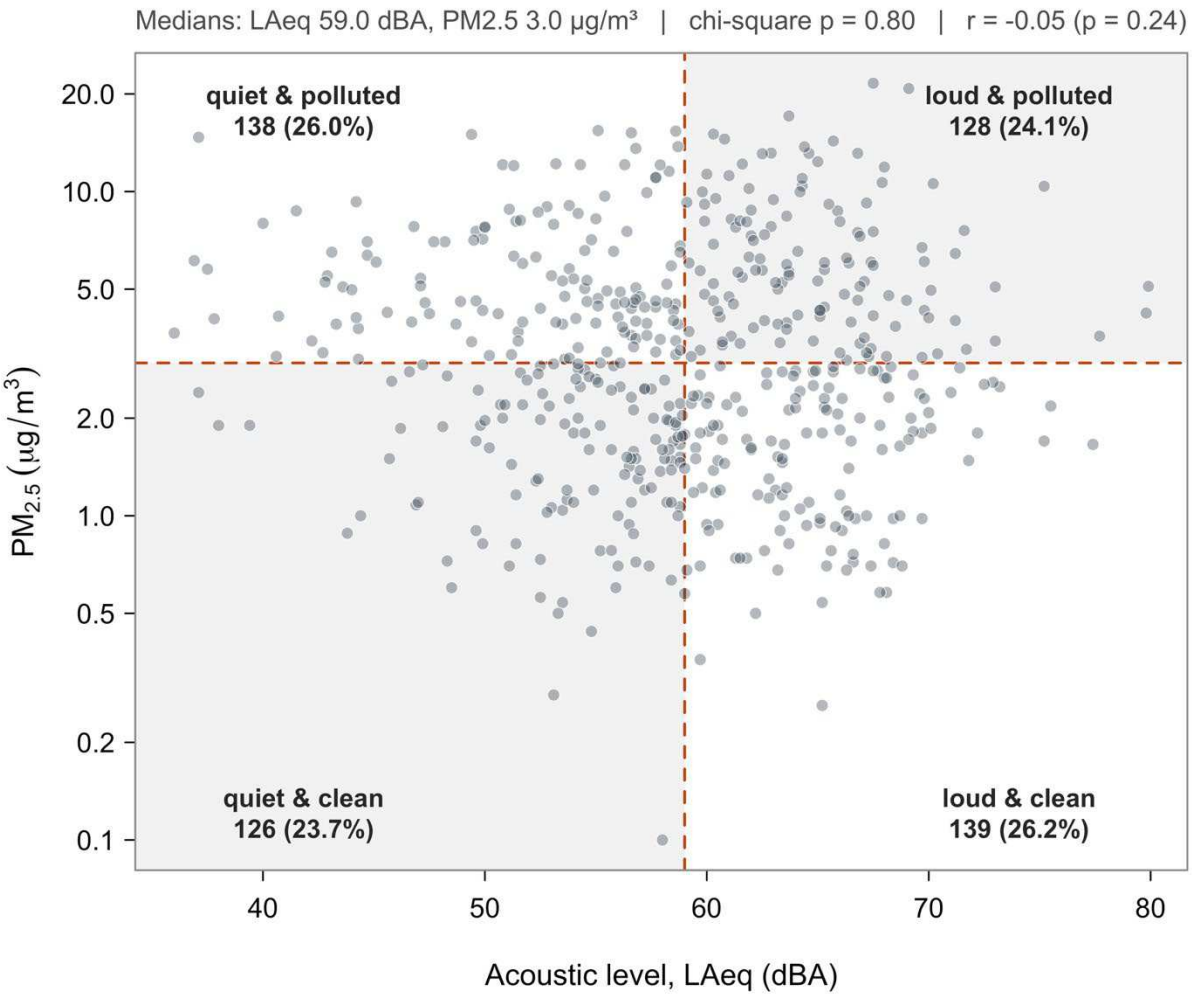


Figure 2. Independence of sound level and fine particulate matter across 531 site-sessions. Dashed lines mark the median of each exposure; labels give the count and percentage of site-sessions in each quadrant. The four combinations occurred at close to equal frequency (chi-square p = 0.80), and the two exposures were uncorrelated (r = -0.05, p = 0.24).

Knowing whether a location fell in the louder half of the sample told us little about whether it fell in the more polluted half. The pattern was not specific to PM2.5. Sound level was similarly uncorrelated with coarse particulate matter (r = -0.03), the air quality index (r = -0.03), total volatile organic compounds (r = -0.07) and formaldehyde (r = -0.08). Within the air-quality instrument, by contrast, the reported metrics were nearly redundant: PM10 correlated with PM2.5 at r = 0.998, the air quality index with PM2.5 at r = 0.993, and formaldehyde with total

volatile organic compounds at r = 0.978, so these are best regarded as alternative expressions of two underlying signals rather than independent measurements.

Acoustic level is associated with the built environment; PM2.5 with weather

To ask what predicts each exposure, we fitted linear mixed-effects models with the same set of 16 standardized predictors, a random intercept for site and a fixed effect for session type, separately for sound level and log-transformed PM2.5 (Table 2; Supplementary Table S1). Collinearity among the predictors was modest, with a maximum variance inflation factor of 7.45 and none above 10.

Table 2. Standardized coefficients (standard errors) from linear mixed-effects models of acoustic level and log-transformed PM2.5, with the same 16 predictors entered into both, a random intercept for site, and a fixed effect for session type. Significance is evaluated at a single threshold, alpha = 0.05.

Predictor	LAeq β (SE)	LAeq p	log PM2.5 β (SE)	log PM2.5 p
Bars/drinking places (400 m)	−0.81 (1.09)	0.460	−0.031 (0.057)	0.592
Restaurants (400 m)	−0.33 (1.18)	0.779	0.100 (0.062)	0.108
Industrial (400 m)	1.65 (0.80)	**0.040**	0.013 (0.042)	0.755
Distance to nearest fuel station	−0.92 (0.67)	0.171	−0.032 (0.035)	0.370
Distance to nearest auto-body/paint	0.53 (0.67)	0.435	0.030 (0.035)	0.391
Total businesses (400 m)	0.44 (0.74)	0.550	−0.010 (0.040)	0.811
Traffic proximity (500 m)	1.01 (0.57)	0.080	−0.059 (0.030)	0.054
Nearest-road AADT	0.83 (0.47)	0.080	0.064 (0.025)	**0.010**
Heavy-vehicle traffic (800 m)	0.52 (0.55)	0.346	0.029 (0.029)	0.320
TRI facilities (800 m)	−0.45 (0.71)	0.528	−0.048 (0.038)	0.206
Distance to nearest TRI facility	0.63 (0.91)	0.491	0.012 (0.048)	0.807
Impervious surface % (400 m)	0.95 (0.74)	0.204	−0.034 (0.039)	0.387
Tree canopy % (400 m)	−1.31 (0.75)	0.081	−0.092 (0.040)	**0.022**
Temperature (daily)	−0.02 (0.26)	0.939	0.113 (0.023)	**<0.001**
Wind speed (daily)	0.67 (0.27)	**0.014**	−0.213 (0.024)	**<0.001**
Precipitation (daily)	−0.32 (0.23)	0.169	0.083 (0.021)	**<0.001**

Session-type effects (reference weekday daytime): LAeq −4.69 dBA on weeknights ($p < 0.001$) and −2.38 dBA on weekend nights ($p < 0.001$); log PM2.5 +0.60 on weeknights and +0.52 on weekend nights (both $p < 0.001$).

Sound level rose with the built environment. It was significantly higher near industrial land (1.65 dBA per standard deviation, p = 0.04), and the associations with traffic proximity (1.01 dBA, p =

0.08), nearest-road traffic volume (0.83 dBA, $p = 0.08$) and tree canopy (-1.31 dBA, $p = 0.08$) were of similar magnitude and consistent direction without reaching the 0.05 threshold. Systematic measurements across Portland, Oregon, similarly found the highest levels near major roads and highways and in industrial areas [23]. Among the weather variables, only wind speed was associated with sound level (0.67 dBA per standard deviation, $p = 0.01$); temperature and precipitation were not. For PM2.5 the pattern was close to the reverse. The strongest associations were meteorological: concentrations fell with wind speed (-0.21 log units per standard deviation, $p < 0.001$) and rose with temperature (0.11, $p < 0.001$) and precipitation (0.08, $p < 0.001$). Two built-environment terms also reached significance, nearest-road traffic volume (0.064, $p = 0.01$) and tree canopy (-0.092, $p = 0.02$), although as shown below neither survived penalization, whereas the two leading acoustic predictors did.

The positive association between precipitation and PM2.5 runs counter to the scavenging effect expected on physical grounds and most plausibly reflects the sensitivity of low-cost optical particle sensors to ambient humidity, which rises during and after rainfall. We return to this in the discussion of instrument performance below and in the limitations.

Acoustic variance is greater across sites; air-quality variance across days

The two models also differed in where their variance came from (Fig. 3).

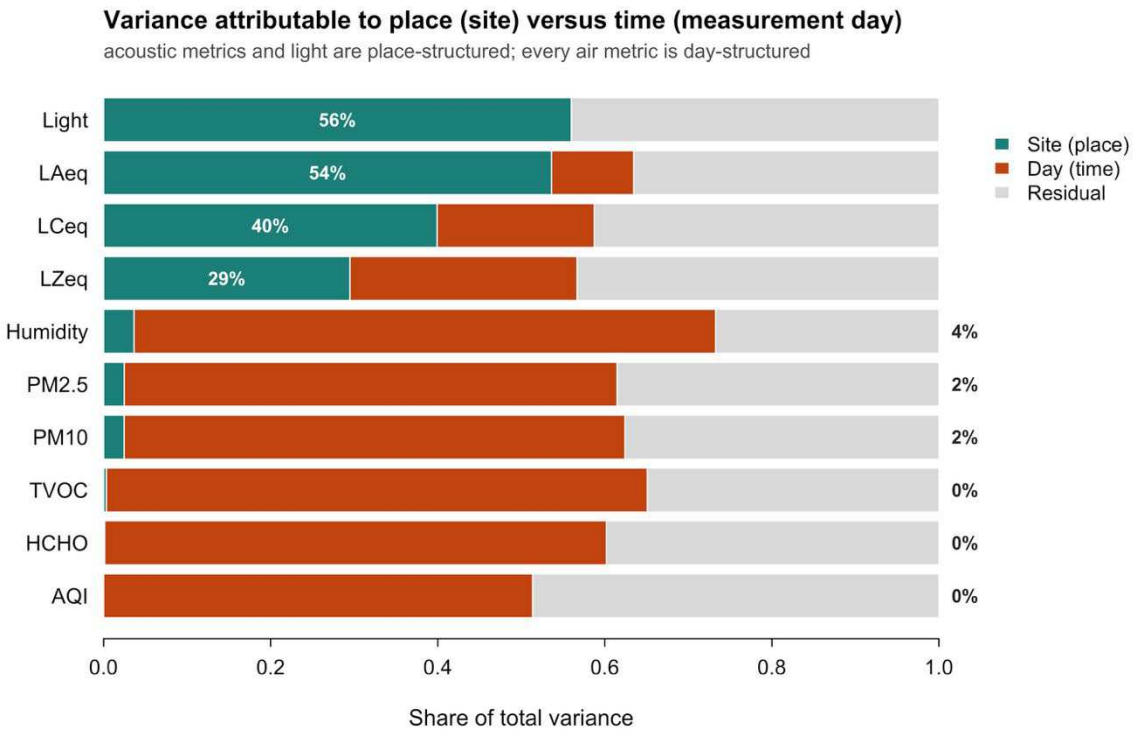


Figure 3. Variance in each measured quantity attributable to the measurement site and to the measurement day, from intercept-only models with crossed random effects. Percentages give the site share. Acoustic metrics and night-time light are structured mainly by place; every air-quality metric, and relative humidity, is structured mainly by time.

For sound level, the conditional R^2 of 0.64 far exceeded the marginal R^2 of 0.31 (Table 3), indicating that site identity, that is, the persistent differences between one measurement location and another that the measured predictors did not capture, accounted for a substantial share of variation beyond the 16 predictors. The random intercept for site had a standard deviation of 4.48 dBA against a residual standard deviation of 4.70 dBA, so between-site differences were comparable in magnitude to all remaining within-site variation combined. Automobile counts recorded independently on the field sheets, and not used in any model, correlated with measured sound level (Spearman $\rho = 0.65$), consistent with the site effect reflecting real differences between locations.

For PM2.5 the structure was reversed. Adding a random effect for the day of measurement showed that the day explained roughly three times as much variance as the site: the day-level standard deviation was 0.381 log units against a site-level standard deviation of 0.120. In

intercept-only models fitted to every measured quantity, the contrast was consistent and ordered (Table 4). Between-site differences accounted for 54% of the variance in LAeq, 40% in LCeq and 29% in LZeq, and 56% of the variance in night-time illuminance, but only 2.5% in PM2.5 and in PM10, 0.3% in total volatile organic compounds, 0.1% in formaldehyde and essentially none in the air quality index. Conversely, the measurement day accounted for 59% of the variance in PM2.5 and between 51% and 65% for the other air-quality metrics, against 10% for LAeq and none for illuminance. Every quantity measured through the air-quality instrument, including relative humidity, was structured mainly by time; every acoustic metric, and light, was structured mainly by place. Mapping site means shows the same contrast: sound level varied systematically between locations, whereas PM2.5 did not (Fig. 4).

Sound level carried the same spatial signature under all three frequency weightings, though not equally. Between-site differences accounted for 54% of the variance in the A-weighted level, 40% in the C-weighted level and 29% in the unweighted level, so the place-bound character of the acoustic environment weakens as more low-frequency energy is admitted. The gradient is informative rather than incidental: low-frequency sound propagates further and is less attenuated by the built fabric, so it is less tightly tied to the immediate surroundings of a site. Wind speed showed the corresponding gradient in the driver models, rising from 0.67 dBA per standard deviation for LAeq ($p = 0.01$) to 0.93 for LCeq ($p < 0.001$) and 2.05 for LZeq ($p < 0.001$). A windscreen was fitted at every measurement, so this is unlikely to be microphone self-noise, and it is consistent with wind influencing the propagation of low-frequency sound.

The two exposures move in opposite directions between day and night

Time of day affected the two exposures in opposite directions. Relative to weekday daytime, sound level fell by 4.69 dBA on weeknights ($p < 0.001$) and by 2.38 dBA on weekend nights ($p < 0.001$), while weekend daytime was indistinguishable from weekday daytime (0.12 dBA, $p = 0.85$). PM2.5 moved the other way, rising by 0.60 log units on weeknights and 0.52 on weekend nights (both $p < 0.001$). Median PM2.5 was 4.50 µg/m³ at night against 1.99 µg/m³ by day. Because measured humidity was also markedly higher at night (55.9% against 38.0%), we tested whether the nocturnal rise was an artefact of sensor response to humidity by adding on-site temperature and relative humidity to the model. The night coefficient fell only slightly, from 0.503 to 0.451, so the great majority of the nocturnal increase persists after adjustment and is

more consistent with the shallower night-time boundary layer than with instrument response alone.

Wind direction, coastal position and comparison with regulatory monitors

Because the sampled area lies at the head of Narragansett Bay, we examined whether wind direction structured the air-quality results. Days on which the fastest two-minute wind came from the south or south-east, that is, up the bay, carried higher particulate concentrations than days with northerly or north-westerly wind (median 3.51 against 2.10 µg/m³; 0.21 log units, $p < 0.001$), while sound level was unrelated to wind direction ($p = 0.41$). Sites in the coastal municipalities of Warren, Barrington and East Providence were about 6 dBA quieter than inland sites ($p < 0.001$) but did not differ in PM2.5 ($p = 0.29$), and the interaction between coastal position and wind direction was not significant, indicating that the wind-direction effect operated across the sampled area rather than only at the shore.

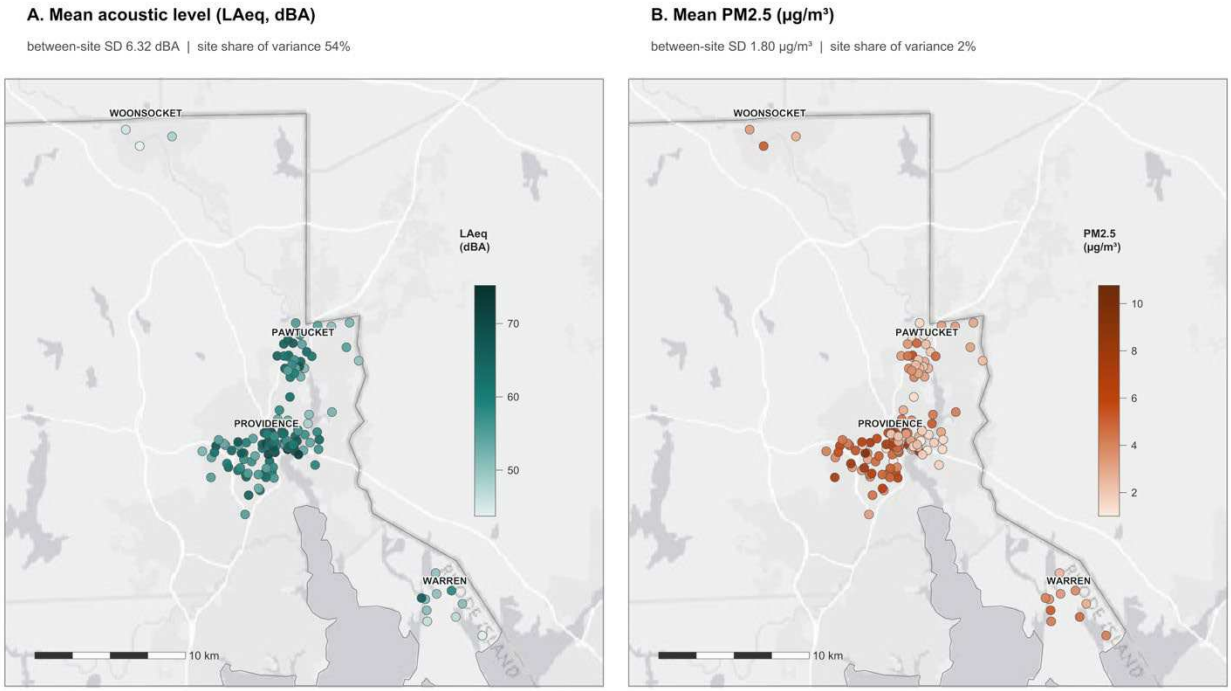


Figure 4. Site mean values mapped across the study area. (a) A-weighted sound level, which varies systematically between locations. (b) Fine particulate matter, which does not. Subtitles give the between-site standard deviation and the share of total variance attributable to site for each exposure.

To characterize the performance of the portable air-quality instrument, we compared our daily mean PM2.5 with the daily mean across the six Rhode Island federal reference and equivalent method monitors operating during the campaign, on the 39 days when both were available (Supplementary Fig. S1). The two agreed moderately and significantly ($r = 0.58$, 95% confidence interval 0.33 to 0.76, $p < 0.001$), with a regression slope of 1.20 (standard error 0.28) and a mean bias of -0.59 $\mu g/m^3$, our instrument reading slightly low. This supports the use of these measurements for relative comparison across sites and sessions, which is how they are used here, and not as estimates of absolute concentration.

The patterns are robust

Several checks supported these conclusions (Table 3; Supplementary Tables S2 to S5). First, when we replaced the full model with penalized regression at site level, the acoustic model retained industrial land, traffic proximity and tree canopy and no weather term, while the PM2.5 model retained wind speed and precipitation together with a single weak land-use term, the count of restaurants within 400 m. Second, residual spatial autocorrelation was absent for sound (Moran's $I = 0.03$, $p = 0.23$) but present for PM2.5 when only a site random effect was included ($I = 0.11$, $p = 0.006$); it disappeared once the measurement day was added ($I = 0.02$, $p = 0.31$), indicating that the apparent clustering in air quality reflected shared weather on shared days rather than fixed spatial structure. Third, collapsing each exposure to a single site-level mean and refitting with ordinary least squares reproduced the built-environment associations in direction for every predictor and in significance for most; the weather terms are not interpretable in that specification because averaging to one value per site removes the day-to-day variation on which they act. Fourth, varying the radius used to define the business, traffic, industrial and land-cover predictors between 250 m, 400 m and 800 m left both patterns intact, with wind speed significant for sound at every radius and wind speed, temperature and precipitation significant for PM2.5 at every radius (Supplementary Table S2).

Table 3. Summary of robustness analyses: variance structure, spatial autocorrelation of model residuals, and predictors retained under penalized regression.

Evidence	Finding
Acoustic variance structure	Conditional $R^2 = 0.64$ vs marginal $R^2 = 0.31$; site SD = 4.48 dBA, residual SD = 4.70. Site-dominated.

Evidence	Finding
Air variance structure (+ day RE)	Day SD = 0.381 vs site SD = 0.120 (3.2×); conditional R^2 = 0.66, marginal R^2 = 0.26. Day-dominated.
Moran's I — acoustic residuals	I = 0.028, p = 0.231. No residual spatial clustering.
Moran's I — air residuals (site only)	I = 0.112, p = 0.006. Spatial clustering present.
Moran's I — air residuals (+ day RE)	I = 0.016, p = 0.314. Clustering removed once measurement day is included.
Lasso (λ_{1se}) — acoustic	Industrial land, traffic proximity and tree canopy retained; no weather term retained.
Lasso (λ_{1se}) — air	Wind speed and precipitation retained, with one weak land-use term (restaurants, 400 m).

Table 4. Partition of variance between measurement site and measurement day for every exposure measured, from intercept-only models with random effects for site and day. Shares sum with the residual to one.

Outcome	N	Site share	Day share	SD site	SD day	Site:day ratio
LAeq	531	0.536	0.098	5.68	2.43	5.45
LCeq	531	0.399	0.188	4.66	3.20	2.12
LZeq	531	0.295	0.272	4.40	4.23	1.08
log PM2.5	531	0.025	0.590	0.10	0.50	0.04
log PM10	531	0.025	0.599	0.12	0.57	0.04
Air quality index	531	0.000	0.514	0.00	10.21	0.00
TVOC	531	0.003	0.648	0.01	0.11	0.01
HCHO	531	0.001	0.601	0.00	0.03	0.00
Temperature	531	0.004	0.719	0.76	9.56	0.01
Relative humidity	530	0.036	0.696	2.87	12.55	0.05
Illuminance (night)	182	0.560	0.000	0.55	0.00	–

Discussion

Across communities measured repeatedly by day and night, the acoustic environment and fine particulate matter behaved differently in ways that were consistent across every analysis we conducted. They were uncorrelated at the point of exposure. They were predicted by different factors, sound by the built environment and PM2.5 chiefly by weather. Their variance was concentrated differently, sound between sites and PM2.5 between days. They moved in opposite directions between day and night. Each of these is a separate line of evidence, and they point the same way: in this setting sound behaved more as a feature of place and short-term particulate matter more as a feature of time.

We state that comparison in relative terms deliberately. Neither exposure is purely spatial or purely temporal, and our own results show as much. Sound varied with wind speed, and more

strongly as lower frequencies were admitted, which is what one would expect if wind affects the propagation of sound rather than only its generation. Sound also fell substantially at night, a temporal pattern as large as many of the built-environment associations. PM2.5, for its part, retained a small but non-zero between-site component and was associated with nearest-road traffic volume. The claim supported by these data is therefore one of degree, and the degree is large: a site-to-day variance ratio of about 5.5 for A-weighted sound against about 0.04 for PM2.5.

The contrast in variance structure is the clearest expression of this. Sound behaves largely as a property of the measurement location: knowing where a site is tells you much about how loud it will be, and a single visit provides a reasonable characterization. Short-term PM2.5 behaves largely as a property of the day: knowing when a measurement was taken tells you more than knowing where. That asymmetry is not a statement about which exposure matters more, but about what a measurement of each represents. It also explains why the same design supports confident spatial inference for one exposure and not the other. Traffic contributes to both exposures, and nearest-road traffic volume was associated with PM2.5 as well as with sound; the difference lies in what happens after emission. Sound attenuates over tens of metres and is shaped by the local built fabric, whereas particulate mass mixes and is transported at regional scale.

The spatial-autocorrelation result reinforces this reading. Air-quality measurements at nearby sites resembled one another, which might be taken as evidence of spatially structured pollution, but that resemblance vanished once the measurement day was included. Nearby sites were often visited on the same day, and it was the shared day, not the shared location, that made their readings alike. Applying the same models to every measured quantity supports the same conclusion from another direction: relative humidity, which has no plausible relationship to the built environment of a site, was structured by day exactly as the particulate metrics were, while night-time illuminance, which is a property of fixed infrastructure, was structured by site even more strongly than sound.

The opposite day-night patterns fit the same logic. Sound falls at night as activity and traffic decline, a well-documented pattern that underlies separate night-time noise guidance [24] and one driven by human behaviour at a fixed place. PM2.5 rises at night as the boundary layer

shallows and disperses less, a temporal pattern driven by atmospheric physics across the whole region. That the nocturnal rise in PM2.5 survived adjustment for on-site temperature and humidity argues that it is a genuine feature of the atmosphere rather than an artefact of sensor response, although the sensor's humidity sensitivity is separately evident in the precipitation association.

These findings bear on how environmental comfort is assessed. There is appeal in summarizing the many attributes of a place in a single score, and environmental comfort is by definition a multidimensional idea. Our results do not argue against that framing, but they do bear on how its components should be measured. If the acoustic and particulate components of a composite index are structured so differently, a score built from a single visit carries different meaning for each: a well-characterized estimate of the site's sound environment alongside an estimate of the region's air quality on one particular day. We would add that environmental comfort, as we use the term, refers to measurable environmental determinants of comfort rather than to comfort as experienced. Several of the exposures considered here have objective consequences that do not depend on perception, such as noise-induced microawakenings during sleep, and a framework built on measured conditions should not be read as reducing those effects to subjective impressions.

The practical implication is that the two exposures call for different measurement designs. Characterizing the sound environment of a neighbourhood is well served by measuring many locations, even briefly. Characterizing its particulate environment is better served by measuring repeatedly over time, or by drawing on the long-term modelled estimates the regional literature relies on. A programme that applies one design to both will characterize one of them poorly.

Several features of the design bound the interpretation, and three deserve emphasis because they constrain the central claim rather than merely qualifying it.

First, and most importantly, this is a study of one compact region measured over part of a single autumn. PM2.5 in an urban area is dominated by regional and secondary contributions, so a single-city design offers limited spatial contrast in particulate matter almost by construction, whereas sound varies over tens of metres. Part of the contrast we report may therefore reflect the spatial scale of the study as much as any intrinsic property of the two exposures. A study spanning a larger region, or one including a dominant local particulate source, would likely find

more spatial structure in PM2.5. Our finding should be read as a statement about what these two exposures look like when measured at neighbourhood scale in a mid-sized coastal metropolitan area in autumn, not as a general law. The wind-direction effect in particular reflects the study area's position at the head of Narragansett Bay, and a landlocked setting might show a different meteorological signature. The seasonal window is narrow for the same reason: the campaign ran from September to November, so winter heating emissions and summer photochemistry are unrepresented.

Second, the particulate measurements come from a low-cost optical instrument rather than a reference monitor. Our comparison against the regulatory network showed moderate agreement, a near-unity slope and a small negative bias, which supports relative comparison across sites and sessions but not the interpretation of absolute concentrations. The positive association between precipitation and PM2.5, which runs counter to the expected scavenging effect, is the clearest sign of the instrument's humidity sensitivity and should be read as a property of the measurement rather than of the atmosphere. Our conclusions rest on relative structure, and the variance decomposition in particular is unaffected by a constant multiplicative bias, but any absolute value reported here should be treated accordingly.

Third, sites were selected purposively rather than at random. Students chose locations relevant to a public health topic and sampled at varying distances from it, which produced wide coverage of built environments but not a probability sample of any municipality. Measurement locations were not standardized with respect to distance from the kerb, proximity to reflecting surfaces or exposure to wind, and this micro-siting variation contributes to the between-site variance we attribute to place. That works against us in one direction and for us in another: it inflates apparent site-level differences in sound, but it applies equally to the air-quality measurements, which nonetheless showed almost no between-site variance.

Further bounds apply. Exposures were short spot measurements rather than continuous monitor records, a trade-off that buys broad spatial coverage at the cost of long averaging at any one point, and which bears more heavily on PM2.5, whose signal is dominated by day-to-day weather, than on sound, whose short-sample measurements are known to track longer-term levels well [12]. Our meteorological data come from a single regional station, so within-area variation in weather is not captured. We did not measure ultrafine particles, nitrogen dioxide or other

traffic-related pollutants with sharper spatial gradients than particulate mass; had we done so, the spatial contrast between the acoustic and air-quality domains would plausibly have been smaller, and we regard that as an open question rather than one our data settle. Finally, 45 of the 576 scheduled sessions were not completed, concentrated in two data collectors rather than in particular sites or conditions.

Within those bounds, the central result held across several independent lines of analysis. Acoustic and air-quality measurements were uncorrelated at the point of exposure; they were predicted by different variables; their variance was attributable to different levels; they moved oppositely between day and night; and the spatial clustering in air quality was explained by shared measurement days rather than shared locations. Carrying every measured quantity through the same model separated them the same way, with a negative control behaving as a negative control should.

The place-bound structure held across the frequency spectrum, but it weakened as lower frequencies were admitted, from 54% of variance between sites for the A-weighted level to 40% for the C-weighted and 29% for the unweighted level. The low-frequency content of the sound environment, indexed by the difference between C-weighted and A-weighted levels, had a median of 10.6 dB and was largest at the quietest sites and at sites with the least traffic (Supplementary Note). Low-frequency energy is therefore a pervasive background characteristic of the acoustic environment rather than a signature of nearby traffic, and because it is the component least attenuated by distance and by the built fabric, it is also the component least tied to the immediate surroundings of a site. That gradient offers a physical account of why the place-bound structure of sound weakens with frequency weighting, and it suggests that studies using low-frequency metrics should not assume the spatial stability that A-weighted measurements support.

In this setting the acoustic environment and fine particulate matter were organized along different axes, one predominantly spatial and one predominantly temporal. Characterizing environmental comfort well will mean measuring its dimensions in ways suited to each rather than assuming that one design serves them all.

Methods

2.1. Study area and design

Measurements were collected at 144 outdoor sites in Rhode Island, United States. Sites were distributed across eight municipalities: Providence (92 sites), Pawtucket (26), Warren (9), East Providence (8), Woonsocket (3), Central Falls (3), Cranston (2) and Barrington (1). Municipality was assigned by geocoding site coordinates against United States Census Bureau place boundaries rather than from field records. The sampled area therefore comprises the contiguous urban core of Providence, Pawtucket and Central Falls, together with adjacent East Providence and Cranston, the separate urban centre of Woonsocket approximately 25 km to the north, and a coastal cluster in Warren and Barrington on the eastern shore of Narragansett Bay.

Each site was scheduled for measurement during four session types defined by day type and time of day: weekday daytime, weekday nighttime, weekend daytime and weekend nighttime. Daytime sessions covered approximately 07:00 to 19:00 and nighttime sessions approximately 19:00 to 07:00. Measurements were collected between 19 September and 16 November 2025, on 39 distinct measurement days. The campaign therefore samples a single autumn season, which we return to in the limitations.

2.2. Site selection

Sites were selected purposively rather than at random, and we describe the procedure in full because it bounds the inferences the design can support. Students enrolled in a graduate environmental health course each selected a minimum of eight sites within the urban centres named above. Within that constraint, each student chose a topic of public or environmental health relevance to the community, identified a location central to that topic, and then placed sites at varying distances from it. Topics included bus stops in downtown Providence, neighbourhoods surrounding a new professional soccer stadium in Pawtucket, residential areas near colleges, laundromats, public school locations, parks at differing distances from waterways, and coastal exposure in Warren.

This produced a sample that spans a wide range of built environments, from dense commercial blocks to residential streets and open parkland, but that is not a probability sample of any municipality. The distribution of sites relative to roadways reflects that design: the median distance from a site to the nearest mapped road was 47.1 m, with an interquartile range of 11.0 m to 119.7 m and a full range of 0.5 m to 663.5 m. Students were instructed to select sites with varying built environments, but no numerical rule was imposed on distance to the kerb,

proximity to reflecting facades, or degree of shelter, and we treat the resulting micro-siting variation as part of the measured between-site variance rather than as a controlled factor.

2.3. Instrumentation and calibration

Sound was measured with an NTi Audio XL2 sound level meter fitted with an M2211 microphone, MA220 preamplifier and ACO7052 capsule. This configuration is Class 1 (Type 1) for frequency response, with typical intrinsic noise of 21 dB(A) SPL at 20 mV/Pa and a maximum sound pressure level of 144 dB SPL at 3% distortion at 1 kHz. Meters were calibrated annually by the manufacturer, with a calibration certificate issued for each device; the certificates record that each meter completed the periodic tests of IEC 61672-3 with traceability in accordance with ISO/IEC 17025. The measurement range was set to 30 to 130 dB at every site, and a foam windscreen was fitted to the microphone for every measurement.

Air quality was measured with a Temtop LKC-1000S+ portable monitor, calibrated annually by the manufacturer. The instrument reports fine particulate matter, coarse particulate matter, total volatile organic compounds, formaldehyde, temperature and relative humidity, together with an instrument-derived air quality index; the set of reported pollutants was determined by the instrument rather than selected in advance. Its stated measuring range is 0 to 999 μg/m³ for PM2.5 and PM10 at a display resolution of 0.1 μg/m³, and 0 to 5 mg/m³ for formaldehyde and total volatile organic compounds at a resolution of 0.01 mg/m³. Manufacturer specifications give an operating range of 0 to 50 °C and 0 to 90% relative humidity. This is a low-cost optical instrument rather than a reference or equivalent method monitor, and no independent detection limit is published for it. We state this prominently because it bounds the interpretation of every particulate result reported here: the instrument supports relative comparison across sites and sessions, not regulatory-grade absolute concentration. Section 2.7 reports a direct comparison against regulatory monitors.

Illuminance was measured with a REED Instruments R1630 light meter logging through the REED Smart Series application, version 1.8.9, at a storage interval of 10 s in foot-candles at a resolution of 0.1. A subset of sessions was recorded at a 1 s storage interval and was averaged to the common interval during processing. A further subset was recorded in lux rather than foot-candles, and those values were converted during cleaning by dividing by 10.764.

All three instruments were mounted on tripods at a height of approximately 1.4 m (4.5 ft), standardised across sites.

2.4. Measurement protocol

At each site-session the sound level meter recorded for a fixed 5 min interval using the instrument's single timer mode, which counts down and stops recording automatically, so the averaging period is identical across all sessions. Sound was summarised as the equivalent continuous level under A-, C- and Z-weightings (LAeq, LCeq, LZeq). Air quality was logged over the same 5 min window and summarised as the session mean. Illuminance was recorded during nighttime sessions only and summarised as the session mean.

Median session start times were 14:22 for weekday daytime sessions, 14:22 for weekend daytime, 20:44 for weeknight and 21:13 for weekend night. Including equipment set-up and take-down, time on site typically ranged from about 10 to 25 min, of which the 5 min instrument window forms the measurement period.

Field observations were recorded on a standardised sheet at each session. Aircraft were recorded as present or absent and, where present, counted for the duration of the 5 min window, with students instructed to note aircraft either seen or heard; at least one aircraft was noted in 56 of 491 sessions with a completed sheet (11.4%). Rail noise was not a designated field and was captured only in open-ended site notes. Observers also recorded vehicle counts, land use, street lighting and tree presence.

2.5. Data completeness and verification of measurement dates

The design specified 576 site-sessions (144 sites by four session types). Of these, 531 had co-located sound and air measurements and form the analysis set. The 45 missing sessions were not distributed evenly across sites or conditions: 30 belonged to a single student and 10 to a second, with the remaining five spread across three others. This pattern reflects course attrition rather than site or exposure characteristics. Twenty-three students enrolled at the start of the semester, 16 had submitted data by the final progress report, and data already collected by students who did not complete the full schedule were retained. Missing sessions were slightly more common at night (29 of 45) than during the day (16 of 45).

Measurement dates were verified before analysis. The field records contain separate date fields for the sound and air instruments, and these disagreed for 132 of 536 sessions. We adjudicated each disagreement using two independent criteria: consistency between the recorded date and the day of week implied by the session label, and the timestamps written inside the corresponding raw instrument files. The sound-instrument date was consistent with the session label for 529 of 536 sessions, against 517 of 576 for the air-instrument date, and raw file timestamps supported the sound-instrument date in all 45 cases where they could discriminate. We therefore adopted the sound-instrument date as the measurement date, falling back to the air-instrument date where the former was absent or failed the day-of-week check. All daily meteorological variables were joined on this verified date.

2.6. Built environment and meteorological predictors

Each site was characterised by a common set of spatial predictors derived from public and licensed data. The predictors were chosen before analysis to represent the source categories identified in the land-use regression literature for noise and in the traffic-related air pollution literature, namely traffic volume and proximity, industrial and commercial land use, point sources of emissions, and vegetation and impervious cover, and the same set was entered into both models without modification. Business and land-use counts, comprising drinking places, restaurants, total businesses and industrial premises within 400 m and distances to the nearest fuel station and auto-body or paint facility, were derived from the Data Axle USA establishment database and classified by industry code. The total business count is a superset that includes the drinking places, restaurants and industrial premises counted separately; across the 144 sites those three categories together account for 9.3% of the total business count, and the total is greater than or equal to their sum at every site.

Road traffic exposure was derived from the Federal Highway Administration Highway Performance Monitoring System 2023 release, Rhode Island layer. For each site we computed a distance-weighted traffic proximity measure within 500 m, the annual average daily traffic of the nearest road, and summed heavy-vehicle traffic within 800 m; all functional road classes present in the source data were included. Toxic-release facilities were drawn from the United States Environmental Protection Agency Toxics Release Inventory and summarised as counts within

800 m and distance to the nearest facility. Tree canopy and impervious surface within 400 m were derived from the National Land Cover Database.

Daily meteorological data were obtained from the National Oceanic and Atmospheric Administration Global Historical Climatology Network daily record for the Providence T. F. Green station (USW00014765), the single reference station serving the study area, and joined to each site-session by verified date. Variables comprised maximum and minimum temperature, average wind speed and precipitation, with daily mean temperature computed as the average of the daily maximum and minimum. Because the study area lies at the head of Narragansett Bay, we additionally extracted the direction of the fastest two-minute wind and classified days as onshore (100 to 200 degrees), offshore (280 to 20 degrees) or other.

2.7. Comparison with regulatory monitors

To characterise the performance of the portable air quality instrument we compared our measurements against regulatory monitors. Daily mean PM2.5 from all Rhode Island federal reference and federal equivalent method monitors was obtained from the United States Environmental Protection Agency Air Quality System for the study period, comprising six monitors in Providence, Pawtucket, East Providence, Cranston and two additional locations. Our site-session measurements were averaged to a daily mean and compared with the corresponding daily mean across the regulatory network on the 39 days with data from both sources (Supplementary Table S6).

2.8. Statistical analysis

All analyses were conducted in R [25]. The independence of sound level and particulate matter was assessed by Pearson and Spearman correlation across all site-sessions and by cross-classifying sessions at the median of each exposure into four categories, tested with a chi-square test of equal proportions.

To identify predictors of each exposure we fitted linear mixed-effects models using the lme4 package [26]. The 16 spatial and meteorological predictors described above were standardised to zero mean and unit variance and entered simultaneously into models with identical structure for each outcome, with a random intercept for site and a fixed effect for session type, weekday daytime as reference. PM2.5 was analysed as $\log(x + 1)$ because its distribution was strongly

right-skewed, and correlations are also reported untransformed. Collinearity among predictors was assessed by variance inflation factor; the maximum was 7.45 and no predictor exceeded 10. Statistical significance was evaluated at a single threshold of 0.05, and we emphasise the magnitude of the standardised coefficients alongside it.

To partition variance between place and time, intercept-only models with crossed random intercepts for site and for measurement day were fitted to every measured quantity, and variance components were expressed as shares of the total. Marginal and conditional R^2 for the predictor models were computed following Nakagawa and Schielzeth [27,28].

Three robustness analyses were performed. First, penalised regression with the lasso [29] was fitted at site level for each exposure, selecting the penalty by cross-validation and reporting predictors retained at the more conservative one-standard-error penalty. Second, spatial autocorrelation in model residuals was tested using Moran's I [30] on site-aggregated residuals with neighbours defined by five nearest neighbours; for the particulate model this was evaluated both with a site random effect alone and with measurement day additionally included. A small number of sites share identical coordinates, which the neighbour construction treats as coincident. Third, both outcomes were collapsed to a single mean per site and refitted with ordinary least squares.

Ethics declarations

This study involved measurement of the physical environment and did not involve human participants, identifiable private information, or biological samples. Institutional review board approval was therefore not required.

Data availability

The de-identified measurement data and site characteristics supporting the findings of this study are available in Zenodo at https://doi.org/10.5281/zenodo.23003091 (ref. 31). Business and land-use counts were derived from the Data Axle USA establishment database under licence and cannot be redistributed by the authors; they are available from Data Axle under licence. Meteorological data are from the NOAA Global Historical Climatology Network (station USW00014765) and regulatory PM2.5 data from the US Environmental Protection Agency Air Quality System, both publicly available.

Code availability

The R code used for all analyses and figures is available in Zenodo at https://doi.org/10.5281/zenodo.23003091 (ref. 31).

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636 **Author contributions**

E.D.W., S.L. and S.V.M. conceptualized the study. S.V.M. developed the methodology and software, carried out the investigation, and performed the formal analysis and visualization. E.D.W. acquired funding and provided resources. E.D.W. administered the project, and E.D.W. supervised the work. E.D.W., S.L. and S.V.M. curated the data and validated the results. S.V.M. wrote the original draft, and E.D.W., S.L. and S.V.M. reviewed and edited the manuscript.

Competing interests

The authors declare no competing interests.

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