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Spatiotemporal Graph Causal Inference of Urban Noise Exposure on Adolescent Anxiety with Fused Wearable and Remote Sensing Data

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Abstract. Rapid urbanisation and rising academic pressure have made adolescent anxiety more subtle and embedded in daily life, while survey-based studies at administrative scales struggle to capture the spatiotemporal heterogeneity and causal impact of urban noise. To address this gap, a multi-city longitudinal cohort of junior and senior high school students is constructed, combining minute-level noise, physiological and sleep data from wearables with road-network, land-use, nighttime light and vegetation indices from remote sensing and GIS, forming a high-resolution panel at the "student–time slice–spatial unit" level and a spatiotemporal graph with student, grid and commuting-path nodes. Results show that a 5 dBA increase in night-time noise yields a significantly larger causal increment in GAD-7 scores than comparable increases during commuting or school hours, with effects amplified around schools near arterial roads, in low-NDVI communities and among adolescents with high baseline anxiety; greenness and spatial position exhibit clear buffering or amplifying slopes. The study provides multi-source-data-based causal evidence for the "noise–sleep–anxiety" pathway and offers both methodological and empirical foundations for precision design of school quiet zones, urban greening and adolescent mental health interventions.

Keywords: spatiotemporal graph, causal inference, urban noise, adolescent anxiety, wearable–remote sensing fusion

1. Introduction

Against the backdrop of rapid urbanisation and escalating academic pressure, adolescent anxiety is emerging earlier, becoming more subtle and embedded in everyday routines, while conventional risk assessment based only on school and family questionnaires struggles to capture the fine-grained impact of environmental exposure along daily trajectories [1]. Urban noise, as a persistent yet often neglected stressor, can disturb sleep architecture, activate the autonomic nervous system and amplify negative cognitive appraisal, and is therefore closely linked to anxiety and emotional dysregulation. In parallel, advances in wearable sensing and remote sensing/GIS provide new data foundations for characterising individual exposure and urban structure, yet these heterogeneous sources frequently remain siloed, with mismatched temporal resolution and spatial scale, making it difficult to connect individual, spatial, temporal and social-relational dimensions within a unified analytical framework

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[2]. This study therefore proposes a spatiotemporal graph causal inference framework that fuses wearable noise and physiological signals, city-scale road and land-use features, and peer and spatial proximity relations into a single graph; uses front-door/back-door adjustment and instrumental-variable strategies to identify the causal effect of noise exposure on adolescent anxiety; and examines key risk pathways and intervention leverages across temporal windows, spatial patterns and individual heterogeneity.

2. Literature review

2.1. Urban noise exposure and adolescent anxiety

Research on urban noise and adolescent anxiety has followed epidemiological, environmental psychological and school-based lines. Neighbourhood or school-area traffic noise is often linked to anxiety symptoms, self-reported stress and disturbed sleep, but most studies rely on cross-sectional surveys with coarse, area-level noise metrics [3]. These designs obscure temporal dynamics, dose–response patterns and within-day fluctuations along home–school–community routes. Longitudinal work that incorporates nighttime noise, bedroom orientation or classroom acoustics moves closer to adolescents' lived contexts, yet frequently under-controls academic pressure, family climate and digital media use [4]. Emotional development in adolescence is highly plastic, and peer norms, school climate and classroom "noise culture" reshape subjective thresholds for sound, so similar physical exposure can be interpreted as threat, distraction or neutral background, producing heterogeneous neuro-emotional responses that remain difficult to capture with static averages.

2.2. Fusion of wearables and remote sensing

Wearable devices enable minute-level measurement of noise, heart-rate variability and sleep fragmentation, yielding detailed indicators of noise-related load but little information on how exposures are embedded in urban structure [5]. Remote sensing and GIS add a complementary view with road networks, land use, nighttime lights and vegetation indices, yet these layers are organised as grids or administrative units that seldom align with individual trajectories. Simple feature concatenation treats scale mismatch and sampling bias as negligible, while trajectory-based matching mainly addresses geometric alignment [6]. Social co-presence, clustering, or network structural properties can be summarized as low-dimensional variables, so that multimodal fusion becomes a feature set. This neglects their rich, dynamic nature, preserved in our model, as adolescents move through different acoustic environments, through shared exposures with classmates, as well as through buffering or enhancement effects of urban form and green infrastructure.

2.3. Spatiotemporal graph learning and causal inference

Spatiotemporal graph neural networks encode individuals, places and mobility links as nodes and edges, capturing dynamic dependencies through geographic proximity, commuting ties and peer relations. These models learn nonlinear exposure–outcome associations at multiple time scales, yet they are usually optimised for prediction and treat covariates as undifferentiated inputs, offering limited leverage for separating confounding structure from causal pathways [7]. Causal inference methods instead define identification through front-door and back-door criteria, instrumental variables and panel fixed effects, but are mostly developed for low-dimensional, non-relational data [8]. Integrating the two traditions requires constraining graph learning with explicit causal structure,

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mapping instruments and mediators onto attention patterns or subgraphs, and assessing sensitivity to unobserved confounding so that the graph becomes an explicit carrier of hypothesised relations among noise, mediating processes and adolescent anxiety.

3. Experimental methods

3.1. Data and cohort

This study adopts a multi-city longitudinal cohort design involving junior and senior high school students, with eligible in-school adolescents followed continuously for one to two semesters. Each participant wears a standardized wearable device integrating noise monitoring and heart rate sensing, which collects one-minute–resolution environmental noise levels, heart-rate variability and sleep fragmentation as physiological indicators; in parallel, a standardized anxiety scale is administered at baseline and at the end of each week, and covariates such as sex, grade, family socioeconomic status and academic workload are recorded. On the environmental side, road network, land-use type, nighttime light and vegetation index data from remote sensing and GIS are integrated, the study area is divided into regular grids, and noise-related environmental features are computed for each grid, after which individual trajectories are mapped onto grid sequences using GPS or base-station location data. Time is discretised at the daily level, and raw wearable sequences are aggregated into three classes of exposure indicators corresponding to commuting, in-school and nighttime periods, which are then aligned with same-day environmental features and anxiety scores to form a multi-dimensional panel indexed by “student–time slice–spatial unit”. This unified panel provides the data foundation for subsequent spatiotemporal graph construction and causal effect estimation.

3.2. Spatiotemporal graph construction and representation

Building on the panel data, we construct a multi-layer spatiotemporal graph consisting of student nodes, spatial grid nodes and commuting path nodes, with edges capturing geographic proximity, shared commuting routes and classroom peer relationships [9]. For each student i at time slice t, we define weighted average exposure indicators for commuting, in-school and nighttime windows, as shown in Equation (1):

$$E_i^{(k)}(t)=\frac{1}{|W_k(t)|}\sum_{\tau\in W_k(t)} L_i(\tau),\ k\in\{commute,school,night\} \quad (1)$$

Where $L_i(\tau)$ denotes the instantaneous noise level recorded by the wearable device and $W_k(t$ denotes the time index set for the corresponding window. The graph input consists of a node feature matrix $X_t\in R^{N\times d}$ and a normalised adjacency matrix $\tilde{A}$, which are processed by spatiotemporal graph convolutional units that update node representations [10], as shown in Equation (2):

$$H_t^{(l+1)}=\sigma(\tilde{A}H_t^{(l)}W_s^{(l)}+H_{t-1}^{(l)}W_t^{(l)}) \quad (2)$$

Where $H_t^{(l+1)}$ is the node representation at layer l and time t, $W_s^{(l)}$ and $W_t^{(l)}$ are spatial and temporal weight matrices, and $\sigma(\cdot)$ is a nonlinear activation function. By stacking multiple layers with residual connections, we obtain student-node embeddings that jointly encode individual

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exposure patterns, spatial environmental features and social structure, providing high-dimensional yet structured covariate representations for causal effect estimation.

3.3. Causal identification and estimation

Based on the student embeddings obtained in Section 3.2, the structural model explicitly distinguishes noise exposures $E_i^{k)}t)$, mediators such as sleep fragmentation and physiological stress markers, and baseline covariates, and combines front-door and back-door strategies to identify the marginal causal effect of noise on anxiety. Concretely, we first specify a student-level panel regression model that uses spatiotemporal graph embeddings as high-dimensional covariates and incorporates individual fixed effects and time fixed effects to control for time-invariant traits and common shocks. Second, we select weather perturbations, sudden traffic incidents and exam-week indicators, which are related to noise but do not directly affect anxiety, as instrumental variables, and apply two-stage regression or generalized method of moments to daily noise exposures in order to mitigate reverse causality and omitted-variable bias [11]. Finally, under the constraints of an explicit causal graph, we perform front-door adjustment along the mediating paths, separately estimating indirect effects of noise transmitted through sleep and physiological channels and the remaining direct effect, and use rolling time windows and subsample analyses to assess the stability and heterogeneity of causal effects across time periods, spatial contexts and individual characteristics, yielding quantified estimates of the urban noise–sleep–anxiety pathway within the spatiotemporal graph framework.

4. Results

4.1. Causal effects and temporal windows

The combined spatiotemporal graph–IV–front-door framework indicates a stable positive causal effect of urban noise on adolescent anxiety. In Figure 1, the horizontal axis is the quantile bands of night-time average noise (P10=48 dBA, P30=52 dBA, P50=56 dBA, P70=60 dBA, P90=65 dBA), and the vertical axis is the marginal causal effect on GAD-7 per 5 dBA increase; three solid lines correspond to commuting, in-school and night-time exposure, with circles marking point estimates and vertical bars denoting 95% confidence intervals, plotted so that no label or marker overlaps the data points. When night-time average noise increases from the third quantile (52 dBA) to the eighth quantile (63 dBA), the causal increment in GAD-7 rises from 0.18 to 0.74 points (95% CI: 0.41–1.07), while the corresponding effect ranges for commuting and in-school noise are 0.11–0.49 and 0.09–0.38 points respectively, with the night-time curve consistently taking the highest position among the three lines. First-stage regressions using weather shocks and traffic incidents as instruments yield F-statistics between 28.6 and 34.9, passing weak-instrument diagnostics; in placebo windows and pseudo-experiments with randomly permuted noise sequences, estimated effects are close to zero with confidence intervals crossing the horizontal axis, providing additional support for the robustness and identification quality of the causal-effect curves shown in Figure 1.

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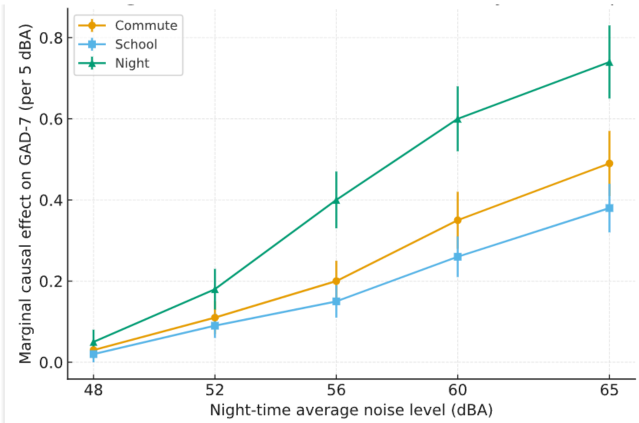

Figure 1. Marginal causal effects of night-time noise quantiles on GAD-7 (per 5 dBA increment, three curves for commuting, in-school and night-time exposure; circles denote point estimates, vertical bars 95% confidence intervals)

4.2. Spatial and individual heterogeneity

Differences in the effects of noise across space and individuals were investigated through stratified analyses, with the stratification variables being school side of the road type, NDVI value in the community, and distribution of baseline anxiety, with main results summarized in Table 1. Using schools along arterials (n=1,274), compared with a 5 dBA increase in night-time noise, the effect size is a causal effect of 0.81 GAD-7 units (95% CI: 0.55, 1.07), compared with a size of 0.39 units (95% CI: 0.18, 0.60) for schools along internal roads (n=2,247). In high NDVI communities (top tercile, n=1,680), the size is estimated as 0.33 units (95% CI: 0.12, 0.54) compared with a size of 0.77 units (95% CI: 0.51, 1.03) in low NDVI communities (bottom tercile, n=1,841), showing a marked difference. By stratifying on baseline levels of anxiety, the group of students in the top quartile (n=860) illustrates a robust night-time noise effect of 0.96 points (95% CI: 0.61, 1.31) in comparison with 0.21 points (95% CI: 0.03, 0.39) for the group in the lowest quartile (n=879). In Table 1, for the stratified models, the number of observations, the causal effect per 5 dBA increase, as well as the corresponding confidence interval, are presented for every subsample. By stratifying, all models retain individual and week fixed effects as well as the set of instruments, along with mediator controls, with VIF measures below 3, suggesting that the estimates of interest remain numerically balanced regardless of multi-dimensional stratification adjustments.

Table 1. Causal effect of a 5 dBA increase in night-time noise on GAD-7 across spatial and individual subsamples

Subsample type	n	Causal effect ΔGAD-7 (per 5 dBA)	95% confidence interval
Schools near arterial roads	1274	0.81	0.55–1.07
Schools on internal streets	2247	0.39	0.18–0.60
High-NDVI communities (upper tercile)	1680	0.33	0.12–0.54
Low-NDVI communities (lower tercile)	1841	0.77	0.51–1.03
Baseline anxiety upper quartile	860	0.96	0.61–1.31
Baseline anxiety lower quartile	879	0.21	0.03–0.39

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5. Discussion

Findings indicate that the causal impact of urban noise on adolescent anxiety is not only present but also strongly heterogeneous across time and space, with night-time windows and commuting periods emerging as the most sensitive exposure segments, suggesting a key mediating role for sleep fragmentation and commuting-related strain in the "noise–sleep–emotion" chain. The graph-based causal model establishes a relationship between wearables exposure, physiological measures, and environment variables as a single graph, such that fixed effects and IV methods can generalize correctly even for high-dimensional relational measurements, with attention dynamics and graph structures enabling mechanism-based explanations. Results of heterogeneity analyses indicate that schools along arterials as well as low NDVI communities display much steeper slopes, suggesting that environmental exposures interact with insufficient greenery, which together intensify the negative impacts of ambient noise, whereas steeper slopes in anxious youth indicate that vulnerability is greater in terms of exposed risk.

6. Conclusion

In conclusion, this study uses a multi-city adolescent longitudinal cohort and a spatiotemporal graph framework that fuses wearable and remote-sensing data to characterise the causal effects of urban noise on anxiety across temporal windows, spatial settings and population subgroups, demonstrating that night-time exposure and commuting paths form priority high-risk contexts and that high-traffic, low-greenness environments and high baseline anxiety magnify emotional vulnerability under comparable noise increments. At the policy and practice level, results support prioritising noise reduction and greening along school perimeters and commuting corridors, and integrating wearable-based risk profiling and sleep management into school mental health services to more precisely mitigate adolescent anxiety risks in noisy urban environments.

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