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Commercial and industrial zoning and neighborhood disparities in billboard exposure: a field-verified statewide census in Rhode Island, USA

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Abstract

Background. Billboards stand on land that municipal zoning permits, and residents see their advertising without choosing to. Studies in large US cities have found more outdoor advertising in lower-income and minority neighborhoods. Most compared selected neighborhoods rather than every billboard in a jurisdiction, and zoning may account for part of the pattern. We estimated how billboard exposure was distributed across a US state and how much of its association with neighborhood disadvantage was accounted for by commercial and industrial zoning.

Methods. Between June and August 2024 we visited all 582 billboard panels listed in Rhode Island by Lamar Advertising and Clear Channel Outdoor, and coded the content of the 507 still standing and visible. We linked panels to 782 census block groups, American Community Survey estimates, statewide municipal zoning and land use maps from 1995 to 2020. Using negative binomial models, we divided the association between neighborhood disadvantage and panel counts into the part accounted for by commercial and industrial zoning and a remainder. We examined municipal clustering, alternative specifications and traffic volume. Because the zoning hypothesis arose during analysis, we treat this decomposition as exploratory.

Results. The most disadvantaged fifth of residents received 36.0% of annual billboard impressions (95% CI 18.2 to 57.3). For state environmental justice designation, the pre-specified primary exposure, the total association with panel counts was imprecise (incidence rate ratio 1.82, 95% CI 0.97 to 3.40), although its indirect effect through zoning was positive. Each standard deviation of disadvantage was associated with more panels (1.66, 1.22 to 2.27), and adjustment for zoning reduced this ratio to 1.24 (0.91 to 1.68). Zoning accounted for an estimated 57.8% of this association (24.6 to 160.5), mostly through industrial zoning, and between 27.8% and 61.7% across alternative specifications. Without Providence, which held 157 of the 507 panels, the total association was weaker and imprecise (1.37, 0.95 to 1.97). Content shares differed by under one percentage point between designated and non-designated block groups. Racial and Hispanic composition were not associated with panel counts net of disadvantage and zoning.

Conclusions. In Rhode Island, billboard exposure rose with neighborhood disadvantage. Commercial and industrial zoning accounted for between about a quarter and three fifths of that association, depending on specification. Neighborhoods differed in how much billboard advertising they received more than in what it advertised.

Keywords: Outdoor advertising, Billboards, Zoning, Land use, Environmental justice, Commercial determinants of health, Mediation analysis

1. Background

In New York City, block groups in predominantly Black neighborhoods held an average of four outdoor advertising panels per 1,000 residents [1]. Vacant lot area predicted panel density in those block groups, while the association with median household income did not reach significance [1]. Outdoor advertising for food and other products has been found to concentrate in lower-income or minority neighborhoods in several US cities [2-7]. Studies in a city in Northern England [8], in suburbs of Melbourne [9] and in central Scotland [10] have reported socioeconomic differences in outdoor advertising as well.

Experimental exposure to food advertising increased food intake in children, although not in adults [11]. Children from minority and socioeconomically disadvantaged backgrounds are more exposed to unhealthy food advertising [12], although evidence on socioeconomic differences in outdoor food marketing specifically is mixed [13]. Targeted marketing of products with health risks to groups defined as vulnerable raises equity concerns [14]. Research on the commercial determinants of health examines how the products and practices of commercial actors affect health and health equity [15, 16].

Most of these studies compared samples of neighborhoods chosen to contrast income or racial composition [2, 3, 5, 6, 9]. Those that recorded every advertisement covered a single city [8] or the subway stations of a single borough [7]. Findings on income and race have differed between settings. Household income, but not racial composition, was associated with unhealthy branded advertising in San Francisco and Oakland [5]. In New York City, sugary drink advertising was associated with the share of Black residents [6].

Zoning determines where each category of land use may go [17], which makes it a candidate explanation for these patterns. Lowery and Sloane compared seven identically zoned communities in Los Angeles and discussed zoning as a means of controlling where outdoor advertising is placed [2]. In New York City, industrially zoned areas carried higher environmental burdens, and noxious uses within them were concentrated in poor and minority neighborhoods [17]. Maantay attributed this concentration to the rezoning of affluent industrial areas for other uses and the expansion of industrial zones in poorer ones [17]. Whether locally unwanted land uses were sited in disadvantaged neighborhoods or whether residents with fewer options moved toward them remains debated [18, 19].

We visited every billboard panel listed for Rhode Island, coded its content and linked it to statewide municipal zoning and to land use maps from 1995 onward. The first aim was to describe how billboard exposure was distributed across neighborhood disadvantage. A second aim was to estimate how much of the association between disadvantage and panel counts was accounted for by commercial and industrial zoning. Secondary aims were to compare advertising content between neighborhoods and to examine racial composition after accounting for disadvantage and zoning. Finally, we tested whether billboard exposure was associated with model-based tract health estimates, using negative control outcomes to examine confounding.

2. Methods

2.1. Setting

Rhode Island comprises 39 municipalities. Its 785 populated census block groups held 1,095,371 residents in the 2019 to 2023 American Community Survey [20].

2.2. Billboard inventory and field verification

We compiled all billboard panels listed for Rhode Island in the public inventories of Lamar Advertising Company [21] and Clear Channel Outdoor [22]. The inventories listed 582 panels with coordinates, face dimensions, media type, illumination and annual impression estimates. Impression estimates are audience figures supplied by the operators, and we did not validate them.

Trained student field teams visited every listed panel between June and August 2024. At each location they recorded whether the panel was standing and visible, photographed the advertisement and coded the advertiser, sponsoring industry, message, language and physical condition. Of the 582 listed panels, 73 no longer stood and 2 were standing but obstructed, which left 507 verified panels (hereafter panels) for analysis.

Visit dates were recorded for 565 panels, and 563 of these fell between June and August 2024. Two panels carried a recorded date of 29 June 2023. Seven other panels in the same block group were visited on 29 June 2024, so we treated the year as an entry error. Two verified panels had no recorded date. Excluding all four panels did not change the main estimate, with 57.8% of the association mediated with and without them.

2.3. Content coding

Coders assigned each advertisement to one of 31 sponsoring industries. The study team grouped these industries into consumer oriented, service oriented and mission driven categories (Additional file 1, Table S1). Two further measures were coded independently of industry. A panel was health related if it carried a health message, a definition that included every healthcare and health insurance advertisement. Public health messaging covered resources such as crisis hotlines and recovery services and information such as the health effects of vaping. The two health measures overlapped for 40 panels.

Three coders classified panels from a shared scheme. We did not double code a subset or calculate an inter-rater reliability statistic. As a check on consistency, we compared the codes given to each of the 76 advertisers that appeared on two or more panels, which together covered 401 panels.

2.4. Block groups, census data and designation

Block group boundaries came from 2023 TIGER/Line files [23]. American Community Survey 2019 to 2023 five-year estimates [20] gave population, median household income, educational attainment, housing tenure, unemployment, minority and Hispanic population shares and household limited English proficiency. Of 792 block groups, 785 had population and land area, and 782 had complete data for the models.

The Rhode Island Department of Environmental Management (RIDEM) designates Environmental Justice Focus Areas at census tract level using four criteria [24]. A tract qualifies if its median household income is no more than 65% of the statewide median. It also qualifies if minority residents make up 40% or more of its population, or if 25% or more of its households lack English proficiency. The fourth criterion covers tracts with a minority share of 25% or more in municipalities whose median household income is at most 150% of the statewide median.

We applied the four criteria at block group level, because billboard placement varies within tracts, and refer to block groups that met any criterion as designated. The source data record the fourth criterion under the minority label. We confirmed this by reconstructing the designation from the first three criteria. All 97 designated block groups that met none of the first three criteria had minority shares between 25% and 40%. The only two undesignated block groups in that range lay in Barrington and West Greenwich, consistent with the municipal income condition.

2.5. Zoning, land use and roads

Statewide municipal zoning came from the Rhode Island Geographic Information System (RIGIS) [25]. RIGIS assigns each zoning district to one of eight classes, namely residential, commercial, industrial, open space and conservation, public, agricultural, water and design district. For each block group we calculated the percentage of land area zoned commercial or industrial, and each class separately, by intersecting zoning polygons with block group boundaries.

We assigned each panel the zoning class of the polygon containing it. Of the 507 panels, 63 fell in small gaps between polygons, a median of 2 m from the nearest polygon (maximum 34 m), and took the class of that polygon.

To check whether the zoning pattern predated recent rezoning, we used RIGIS land use and land cover maps for 1995, 2003 to 2004, 2011 and 2020 [26]. For each year we calculated the percentage of block group area classed as industrial, and as commercial or industrial.

Primary and secondary roads came from 2023 TIGER/Line files [23], downloaded with the tigris package [27]. From these we calculated road length per square mile of block group area and the distance from each block group centroid to the nearest primary or secondary road. Bus stop density per square mile, calculated from Rhode Island Public Transit Authority stop locations [28], marked transit corridors.

2.6. Exposure measures

Exposure was measured as the number of panels in a block group and as annual impressions per resident. Impressions per resident were the sum of impression estimates for a block group's panels divided by its population. Panels per 10,000 residents are reported descriptively.

2.7. Disadvantage index

We summarized neighborhood disadvantage with the first principal component of four standardized block group variables, following Messer and colleagues [29]. Its four inputs were relative median household income, the percentage of adults with less than a high school education, the percentage of renter-occupied homes and the percentage unemployed. Relative income was block group median household

income divided by the median across block groups. The first component explained 53.9% of their variance, with loadings of −0.57 for income, 0.50 for education, 0.56 for renter occupancy and 0.33 for unemployment (Additional file 1, Table S2). We scaled the index to a mean of 0 and a standard deviation (SD) of 1, with higher values indicating more disadvantage. Racial composition and limited English proficiency were left out of the index so that they could be examined separately. Population-weighted quintiles of the index each held about 20% of residents.

2.8. Statistical analysis

Cumulative impressions were plotted against cumulative population, with block groups ranked from most to least disadvantaged. The concentration index summarizes this curve and is negative when exposure concentrates among the disadvantaged [30]. We estimated impressions per resident in each quintile with 95% confidence intervals (CI) from 1,000 bootstrap resamples of block groups [31, 32].

The zoning hypothesis arose during analysis, after adjustment for zoning attenuated the associations between neighborhood characteristics and panel counts. Before fitting the mediation models, we fixed in a written plan the exposures, mediator, outcome, confounders, estimation methods, secondary analyses and sensitivity analyses. The plan named state designation as the primary exposure and the disadvantage index as the secondary exposure. We report both and treat the decomposition as exploratory.

As the mediator we used the percentage of block group area zoned commercial or industrial. We combined the two classes because 384 of the 507 panels stood on land in one of them. Panel counts were modeled with negative binomial regression, with the logarithm of block group population as an offset, and we report incidence rate ratios (IRR) [33, 34]. All models adjusted for the logarithm of population density, road length per square mile, the logarithm of distance to the nearest major road and bus stop density. We did not adjust for the density of commercial businesses, because zoning determines where businesses may locate [17] and adjusting for them would remove part of the pathway under study.

Each exposure's total association with panel counts was estimated first, followed by its direct association after adding the mediator. The proportion mediated was the difference between the total and direct log IRR divided by the total, with 95% CI from 1,000 bootstrap resamples of block groups [31, 32]. We also fitted counterfactual mediation models [35, 36], with linear regression for the mediator and for the logarithm of 1 plus impressions per resident. From these we estimated the average causal mediation effect (ACME), the average direct effect and the proportion mediated with 1,000 bootstrap simulations. We based conclusions about mediation on the indirect effect, which does not require a statistically significant total effect [37].

For sensitivity to unmeasured confounding of the zoning and billboard relation, we calculated the residual correlation between the mediator and outcome models at which the ACME would equal zero [35]. To separate the two zoning classes, we entered commercial and industrial zoning as mediators one at a time and together, with bootstrap intervals. We repeated the decomposition with land use from each mapping year in place of current zoning.

Sensitivity analyses replaced the mediator with commercial zoning alone and with commercial, industrial and design districts combined. We refitted the models as spatial lag models of the logarithm of

1 plus impressions per resident, with row-standardized weights from the five nearest block group centroids [38, 39]. Further analyses excluded the 63 panels assigned to the nearest zoning polygon, omitted each municipality in turn and excluded the four panels with uncertain dates.

Because zoning is set by municipalities, we repeated the main estimates with a cluster bootstrap that resampled the 39 municipalities [40]. We also fitted a multilevel negative binomial model with a random intercept for municipality. To estimate the indirect effect on the scale of the panel count models, we also used the product method for a log-linear count outcome with a linear mediator [41]. Under this method the natural indirect effect ratio is the exponential of the product of the exposure coefficient in the mediator model and the mediator coefficient in the outcome model. The method assumes no interaction between exposure and mediator, which we tested. We calculated E-values for the association of zoning with panel counts [42].

Three further analyses examined how the main models were specified. First, we replaced the population offset with an area offset, with log population as a covariate. We also fitted models with no offset and with log population and log area as covariates. Second, we rebuilt the disadvantage index without renter occupancy, which may partly reflect urban form, and used relative income alone. Third, we added two traffic measures from the 2024 Highway Performance Monitoring System as confounders [43]. One was the percentage of block group area within 660 feet of an Interstate, freeway, expressway or other principal arterial, the corridor in which federal law controls outdoor advertising [44]. The other was the logarithm of the highest annual average daily traffic on any road touching the block group.

For comparison with earlier studies, we modeled panel counts on each of seven neighborhood characteristics separately. Each model was fitted in three steps, adjusting first for population density and bus stops, then adding roads, then adding zoning. We corrected the fully adjusted *P* values across the seven characteristics with the Benjamini and Hochberg procedure [45]. Minority and Hispanic population shares were each tested net of the disadvantage index and zoning, with correction across the two tests.

We compared content as the percentage of panels within each stratum, because raw counts would differ with panel volume alone. Differences were tested with Fisher exact tests, corrected across the five content measures [45]. To test similarity directly, we used two one-sided tests at equivalence bounds of 5 and 10 percentage points, with 90% CI [46]. We also compared a group of health-harming products defined in advance, made up of alcohol, cannabis and lottery advertising, with and without food and beverage advertising.

A linear mixed model of log annual impressions per panel, with a random intercept for block group, tested whether the reach of individual panels differed by neighborhood [47, 48]. The model adjusted for designation, distance to the nearest major road, media type, population density and bus stops.

Census tract health estimates came from the 2025 release of PLACES [49]. The Centers for Disease Control and Prevention derives these estimates from Behavioral Risk Factor Surveillance System data by multilevel regression and poststratification [50]. Because they are modeled partly from tract demographics, we included negative control outcomes [51]. Primary outcomes were obesity, binge drinking, current smoking and depression. Negative controls were loss of all teeth, arthritis and cancer other than skin cancer, which we judged unlikely to be affected by billboard exposure. Each prevalence

was regressed on the logarithm of 1 plus impressions per resident across 246 tracts, unadjusted and adjusted for the disadvantage index, zoning and population density. Correction was applied across the four primary outcomes [45].

Analyses used R 4.6.0 [52] with sf 1.1.3 [53], tigris 2.2.1 [27], spdep 1.4.2 and spatialreg 1.4.3 [39], MASS 7.3.66 [34], mediation 4.5.1 [36], lme4 2.0.6 [47], lmerTest 3.2.1 [48], boot 1.3.32 [31, 32], ggplot2 4.0.3 [54] and patchwork 1.3.2 [55]. Random seeds were fixed for all resampling.

3. Results

3.1. Field verification and coding

Of the 582 listed panels, 507 (87.1%) were standing and visible. The operator inventories therefore overstated the panel count by 14.8% and the number of block groups with any panel by 10.5%, at 147 compared with 133. Attrition was similar in designated and non-designated block groups, at 13.7% and 10.4% (Fisher $P = 0.29$). The 507 panels accounted for 99.8 million annual impressions and stood in 133 of 785 block groups (16.9%) (Fig. 1).

Among the 76 advertisers on two or more panels, 98.7% received the same industry code on every panel and all received the same category. The single inconsistency in industry was the state health department, coded as both healthcare and health insurance (Additional file 1, Table S12).

3.2. Distribution of exposure

Billboard exposure was concentrated among disadvantaged residents (Fig. 2a). The most disadvantaged 20% of residents received 36.0% of annual impressions (95% CI 18.2 to 57.3) and 36.5% of panels, and the most disadvantaged half received 67.5% of impressions. A concentration index of −0.336 (95% CI −0.482 to −0.160) summarized this concentration.

Impressions per resident rose across quintiles of disadvantage, from 17.2 per year in the least disadvantaged quintile (95% CI 3.8 to 39.0) to 164.4 in the most disadvantaged (87.0 to 257.9) (Table 1, Fig. 2b). Designated block groups held 44.7% of residents and received 71.6% of impressions, or 146.0 impressions per resident compared with 46.7 in non-designated block groups (Table 2). Among designated block groups, those meeting the low income criterion received between 187.8 and 382.4 impressions per resident, compared with 79.2 in block groups designated on the minority criterion alone.

Table 1. Block group characteristics and billboard exposure by population-weighted quintile of the disadvantage index

Characteristic	Q1, least disadvantaged	Q2	Q3	Q4	Q5, most disadvantaged	All
Block groups, n	137	151	160	160	174	782
Residents, n (% of total)	219,030 (20.1)	217,654 (19.9)	218,502 (20.0)	218,435 (20.0)	218,754 (20.0)	1,092,375 (100.0)
Median household income, $, median (IQR)	141,433 (127,012 to 169,922)	107,171 (96,149 to 117,910)	86,260 (78,972 to 97,572)	73,728 (61,084 to 86,359)	50,538 (39,330 to 63,641)	88,099 (64,664 to 112,925)
Less than high school, %, median (IQR)	2.5 (1.1 to 4.9)	4.6 (1.9 to 8.4)	6.6 (2.7 to 10.1)	10.1 (5.8 to 15.4)	24.4 (15.8 to 34.5)	7.4 (2.8 to 15.7)
Renter occupied, %, median (IQR)	7.1 (2.6 to 11.8)	17.2 (9.8 to 27.0)	29.5 (21.7 to 40.3)	50.8 (35.0 to 61.0)	72.2 (58.7 to 82.6)	32.3 (14.3 to 57.3)
Unemployed, %, median (IQR)	1.7 (0.0 to 3.8)	3.0 (1.2 to 5.1)	4.0 (1.3 to 8.2)	5.1 (1.3 to 9.4)	9.0 (2.6 to 15.0)	3.9 (0.9 to 8.5)
Minority, %, median (IQR)	9.0 (5.3 to 15.4)	12.7 (6.6 to 23.0)	17.6 (8.9 to 31.8)	34.6 (16.6 to 52.3)	66.8 (41.5 to 86.3)	20.8 (9.6 to 48.6)
Hispanic, %, median (IQR)	2.0 (0.0 to 4.7)	4.1 (1.2 to 8.7)	5.6 (1.4 to 13.8)	13.4 (5.0 to 29.8)	39.9 (19.4 to 63.3)	7.0 (1.8 to 25.8)
Designated, n (%)	8 (5.8)	35 (23.2)	55 (34.4)	110 (68.8)	160 (92.0)	368 (47.1)
Area zoned commercial, %, mean (SD)	2.4 (6.1)	4.7 (6.8)	7.0 (9.5)	8.5 (9.5)	12.4 (12.2)	7.3 (9.8)
Area zoned industrial, %, mean (SD)	2.5 (7.1)	4.2 (9.4)	8.7 (15.6)	10.0 (16.6)	11.2 (17.3)	7.6 (14.5)
Block groups with any panel, n (%)	10 (7.3)	17 (11.3)	27 (16.9)	31 (19.4)	48 (27.6)	133 (17.0)
Panels, n (% of all)	29 (5.7)	51 (10.1)	108 (21.3)	134 (26.4)	185 (36.5)	507 (100.0)
Panels per 10,000 residents	1.32	2.34	4.94	6.13	8.46	4.64
Annual impressions per resident (95% CI)	17.2 (3.8 to 39.0)	50.5 (12.5 to 120.4)	97.3 (34.3 to 196.4)	127.3 (41.3 to 252.4)	164.4 (87.0 to 257.9)	91.3 (59.1 to 130.2)

Quintiles each hold about 20% of residents. Confidence intervals for impressions per resident are from 1,000 bootstrap resamples of block groups. IQR, interquartile range. American Community Survey 2019 to 2023 estimates.

Table 2. Billboard exposure by state designation and by criteria met

A. By designation

	Non-designated	Designated
Block groups	417	368
Residents	605,805	489,566
% of residents	55.3	44.7
Panels, n (%)	181 (35.7)	326 (64.3)
Panels per 10,000	2.99	6.66
Impressions, millions	28.3	71.5
% of impressions	28.4	71.6
Annual impressions per resident	46.7	146.0

B. By criteria met

Criteria met	Block groups	Residents	Panels, n	Panels per 10,000	Annual impressions per resident
Low income, limited English, minority	26	31,429	49	15.59	382.4
Low income, minority	85	110,902	118	10.64	255.8
Low income	26	33,173	23	6.93	187.8
Minority only	213	291,042	121	4.16	79.2
Limited English, minority	18	23,020	15	6.52	77.7
Non-designated	417	605,805	181	2.99	46.7

Designation follows the four RIDEM criteria applied at block group level. The minority label includes block groups qualifying under the fourth criterion, with minority shares of 25% to 40%. Analysis of 785 block groups with population and land area.

3.3. Zoning

Most panels stood on commercial or industrial land (Fig. 1b, c). Of the 507 panels, 384 (75.7%) stood in one of these two classes, 81.9% in designated block groups and 64.6% in non-designated block groups (Fisher $P < 0.001$).

Commercial and industrial zoning increased with disadvantage (Fig. 2c). Each SD of the index was associated with 5.55 more percentage points of block group area zoned commercial or industrial (95% CI 4.04 to 7.05). The industrial share rose by 3.14 percentage points per SD (1.85 to 4.43), and the commercial share by 2.41 (1.58 to 3.23) (Additional file 1, Table S3).

3.4. Zoning and the association between disadvantage and billboards

Each SD of disadvantage was associated with a 66% higher rate of panels per resident (IRR 1.66, 95% CI 1.22 to 2.27). Adding zoning to the model reduced the association to an IRR of 1.24 (0.91 to 1.68) (Table 3, Fig. 3a). By the difference method, zoning accounted for 57.8% of the association (24.6 to 160.5). The counterfactual model gave a similar proportion of 56.6% (32.0 to 130.2), with an ACME of 0.186 on the logarithmic impressions scale (0.111 to 0.281). Upper confidence limits above 100% arise because the

direct association was imprecise. The data are compatible with zoning accounting for between about a quarter and all of the association.

Table 3. Commercial and industrial zoning and the association between neighborhood disadvantage and panel counts

A. Total and direct associations and proportion mediated

Measure	Disadvantage index, per SD	Designated vs non-designated
Total association, IRR (95% CI)	1.66 (1.22 to 2.27)	1.82 (0.97 to 3.40)
P	0.001	0.062
Direct association net of zoning, IRR (95% CI)	1.24 (0.91 to 1.68)	1.42 (0.77 to 2.61)
P	0.171	0.260
Proportion mediated, difference method, % (95% CI)	57.8 (24.6 to 160.5)	41.4 (−63.2 to 222.4)
ACME (95% CI)	0.186 (0.111 to 0.281)	0.290 (0.164 to 0.432)
Proportion mediated, counterfactual, % (95% CI)	56.6 (32.0 to 130.2)	69.7 (−151.3 to 310.1)
Residual correlation at which ACME = 0	0.28	0.29

B. Zoning classes entered separately and jointly, disadvantage index

Mediator	Direct association, IRR	*P*	Proportion mediated, % (95% CI)
Commercial zoning	1.557	0.006	12.7 (−1.8 to 42.6)
Industrial zoning	1.362	0.045	39.1 (13.9 to 122.2)
Commercial and industrial zoning, jointly	1.256	0.145	55.1 (23.9 to 161.2)

Negative binomial models of panel counts with a log population offset, adjusted for log population density, road length per square mile, log distance to the nearest major road and bus stop density, 782 block groups. The mediator is the percentage of block group area zoned commercial or industrial. Difference method intervals are from 1,000 bootstrap resamples. ACME and counterfactual proportions are from linear models of the mediator and of log(1 + annual impressions per resident) with 1,000 bootstrap simulations. ACME, average causal mediation effect.

With designation as the exposure, the total association was imprecise (IRR 1.82, 0.97 to 3.40, P = 0.062). Its indirect effect through zoning was positive (ACME 0.290, 0.164 to 0.432), but the proportion mediated could not be estimated with useful precision (69.7%, −151.3 to 310.1).

Industrial zoning accounted for more of the association than commercial zoning (Table 3, Fig. 3b). Entered alone, industrial zoning accounted for 39.1% (13.9 to 122.2) and commercial zoning for 12.7% (−1.8 to 42.6). The two together accounted for 55.1% (23.9 to 161.2). For the disadvantage index, the ACME would fall to zero if the residuals of the zoning and impressions models were correlated at 0.28. The corresponding correlation for designation was 0.29.

3.5. Land use from 1995 to 2020

Industrial land use changed little between 1995 and 2020 (Fig. 3c). Block group industrial shares in 1995 correlated with those in 2020 (Spearman correlation 0.82). In 1995 the mean industrial share was 7.35% in designated block groups and 2.34% in non-designated block groups (Wilcoxon $P < 0.001$). Industrial land

use mapped in 1995 accounted for 56.1% of the association between disadvantage and panel counts (95% CI 24.9 to 150.6), compared with 49.7% for land use mapped in 2020 (20.4 to 125.5). Commercial or industrial land use accounted for 79.7% in 1995 (41.3 to 175.6) and 50.8% in 2020 (21.8 to 129.8) (Additional file 1, Table S5).

3.6. Sensitivity analyses

With commercial zoning alone as the mediator, the proportion mediated fell to 12.7% for the disadvantage index and −12.2% for designation (Additional file 1, Table S6). Adding design districts to commercial and industrial zoning gave 56.4%, and the spatial lag model gave 56.0%. Excluding the 63 panels assigned to the nearest zoning polygon gave 45.8%, and the direct association was then statistically significant (IRR 1.41, 95% CI 1.04 to 1.93).

Omitting any one municipality other than Providence gave proportions between 47.0% and 63.4% (Fig. 3d). Providence held 157 of the 507 panels, and omitting it weakened the total association (IRR 1.37, 95% CI 0.95 to 1.97) (Additional file 1, Table S7).

3.7. Clustering, specification and traffic

Resampling municipalities left the estimates for the disadvantage index almost unchanged and widened those for designation (Additional file 1, Table S18). For the index, the total IRR was 1.66 (95% CI 1.12 to 2.26) and the proportion mediated 57.8% (35.1 to 230.2). With designation as the exposure, the interval for the total IRR widened to 0.72 to 4.53. The multilevel model gave 60.2% for the index, with the municipality variance at its lower bound of zero. On the panel count scale, the natural indirect effect ratio was 1.22 (1.14 to 1.31) for the index and 1.37 (1.14 to 1.63) for designation. Neither exposure interacted with zoning (P = 0.79 and P = 0.29).

The proportion mediated depended on how the models were specified. It was 61.7% with population and area entered as covariates and 27.8% (14.1 to 55.1) with panels modeled per unit area. With the per-area denominator, the total association was stronger (IRR 2.08, 1.56 to 3.08) and a direct association remained (1.69, 1.24 to 2.45). The proportion was 47.3% with the index rebuilt without renter occupancy and 38.1% with relative income alone. In each of these models the natural indirect effect ratio was above 1, with an interval that excluded 1.

Adding highway frontage and peak traffic reduced the total association between disadvantage and panel counts to an IRR of 1.36 (1.01 to 1.97). Disadvantage was correlated with highway frontage (r = 0.42). Zoning accounted for a similar share of the reduced association (54.4%), with wider uncertainty (12.0 to 433.5). Its association with panel counts also remained (IRR 1.66 per SD of zoning, 1.45 to 1.96). Peak traffic was associated with more panels (IRR 1.69 per SD, 1.13 to 2.51), while frontage was not (1.19, 0.85 to 1.69). Before traffic adjustment, an unmeasured confounder would have needed risk ratio associations of 3.17 with both zoning and panel counts to explain away their association.

3.8. Neighborhood characteristics and racial composition

Adjustment for roads and zoning attenuated the associations of individual neighborhood characteristics with panel counts (Additional file 1, Table S4). Adjusted only for population density and bus stops, each

10 percentage points of adults with less than a high school education was associated with more panels (IRR 1.42, 1.12 to 1.80). Relative median household income was associated with fewer panels (IRR 0.253 per unit, 0.128 to 0.498). After adding roads and zoning, these ratios were 1.28 (1.03 to 1.58) and 0.516 (0.268 to 0.992). No characteristic remained associated after correction across the seven characteristics, with every *q* value at or above 0.084.

Net of disadvantage and zoning, neither minority nor Hispanic population share was associated with panel counts (Additional file 1, Table S8). The IRR per 10 percentage points was 1.09 for minority share (0.97 to 1.23) and 1.12 for Hispanic share (0.98 to 1.28).

3.9. Content, format and illumination

Advertising content was similar in designated and non-designated block groups (Table 4, Fig. 4). Service oriented advertising made up 62.9% of panels in designated block groups and 63.5% in non-designated ones, consumer oriented advertising 29.1% and 28.7%, and mission driven advertising 8.0% and 7.7%. Equivalence tests placed the differences within 8.0 percentage points for service oriented, 7.3 for consumer oriented and 4.3 for mission driven advertising. Differences larger than these bounds are unlikely, but smaller ones cannot be excluded.

Table 4. Content of verified billboard advertising by state designation

Content measure	Non-designated, n (%)	Designated, n (%)	Difference, percentage points (90% CI)	Fisher *P*	*q*	Equivalence *P*, 5-point bound	Equivalence *P*, 10-point bound	Smallest equivalence bound, percentage points
Service oriented	115 (63.5)	205 (62.9)	−0.7 (−8.0 to 6.7)	0.924	1.000	0.165	0.018	8.0
Consumer oriented	52 (28.7)	95 (29.1)	0.4 (−6.5 to 7.3)	1.000	1.000	0.137	0.011	7.3
Mission driven	14 (7.7)	26 (8.0)	0.2 (−3.9 to 4.3)	1.000	1.000	0.028	<0.001	4.3
Health related	19 (10.5)	63 (19.3)	8.8 (3.6 to 14.0)	0.011	0.057	0.887	0.355	14.0
Public health messaging	11 (6.1)	37 (11.3)	5.3 (1.2 to 9.4)	0.058	0.144	0.543	0.029	9.4

Percentages are of verified panels within each stratum (non-designated n = 181, designated n = 326). The three industry categories are mutually exclusive. The two health measures are coded independently of industry and overlap for 40 panels. *q* values are Benjamini and Hochberg corrected across the five measures. Equivalence *P* values are from two one-sided tests.

Health related advertising was more common in designated block groups, at 19.3% compared with 10.5% (difference 8.8 percentage points, 90% CI 3.6 to 14.0). The difference did not remain statistically significant after correction (q = 0.057). Public health messaging showed a smaller difference, at 11.3% compared with 6.1% (q = 0.144). Alcohol, cannabis and lottery advertising appeared on 5.2% of panels in designated block groups and 3.9% in non-designated ones (difference 1.3 percentage points, 90% CI −1.8 to 4.5). This difference lay within an equivalence bound of 5 points (P = 0.027) (Additional file 1, Table S19). With food and beverage advertising added, the shares were 14.1% and 12.2%, and equivalence within 5 points was not shown (P = 0.163).

Media type did not differ by designation, with bulletins making up 30.4% of panels in designated block groups and 28.2% in non-designated ones (P = 0.70). Among bulletins, the only format with internal illumination, 12.1% were backlit in designated block groups compared with 56.9% in non-designated block groups (P < 0.001) (Additional file 1, Table S16). Spanish language advertising appeared on 20 panels (3.9%), mostly in smaller formats, with 5.0% on bulletins compared with 30.6% for English language advertising (Fisher P = 0.020) (Additional file 1, Table S17).

3.10. Reach of individual panels

The reach of individual panels did not differ by neighborhood (Additional file 1, Table S10). Block groups accounted for 55.5% of the variance in panel impressions. After adjustment, designation was not associated with the logarithm of annual impressions per panel (difference −0.086, 95% CI −0.358 to 0.186). Media type was the main correlate of reach, and log annual impressions were 1.48 lower for posters than for bulletins (95% CI 1.33 to 1.62).

3.11. Model-based health estimates

Without adjustment, billboard exposure was associated with obesity and with loss of all teeth, a negative control (Additional file 1, Figure S1). After adjustment, the negative controls and three of the four primary outcomes were close to zero. Obesity remained associated (0.45 percentage points per SD of exposure, 95% CI 0.05 to 0.86) but not after correction across the four primary outcomes (q = 0.120) (Additional file 1, Table S9).

4. Discussion

In a census of every billboard the two operators listed in Rhode Island, impressions per resident were nearly ten times higher in the most disadvantaged quintile than in the least. Commercial and industrial zoning accounted for an estimated 58% of the association between disadvantage and panel counts, and for between 28% and 62% across alternative specifications. For state designation, the pre-specified primary exposure, the total association was imprecise, but its indirect effect through zoning was positive. Most of the zoning share ran through industrial zoning, and the industrial land pattern was already in place in 1995. Advertising content differed little between neighborhoods.

These results agree with earlier evidence linking land use to where outdoor advertising stands, including the New York City finding that vacant lot area predicted panel density [1]. Communities in Los

Angeles with identical zoning still differed in the share of harmful content [2]. That contrast suggests that zoning sets where advertising can go while other factors affect what it carries. Our results are consistent with Maantay's account of industrial zoning accumulating in poorer neighborhoods [17], extended here to outdoor advertising. In Providence, measured sound levels were also higher near industrial land [56], so the same land use is linked to more than one environmental exposure.

Industrial zoning accounted for about three times the share that commercial zoning did. We did not test why. One possibility is that industrial land in the state lies along interstate corridors, where operators place large bulletins. Adding highway frontage and traffic volume left the share accounted for by commercial and industrial zoning similar, so the pattern does not appear to reflect proximity to major highways alone.

Federal law offers one route by which zoning could shape where billboards stand. Along interstate and federal-aid primary highways, the Highway Beautification Act permits billboards mainly in areas zoned commercial or industrial, or in unzoned commercial or industrial areas [44]. Frontage on these corridors was not associated with panel counts once traffic volume and zoning were included. Municipal sign ordinances were not modeled, so we cannot say which rule governed the placement of any panel.

The similar composition of content agrees with a city-wide study in Northern England [8]. That study found socioeconomic differences in the area of food advertising but little difference in the type or nutritional content of the foods advertised. Studies that found content differences compared selected communities [2, 9] or examined one product group such as sugary drinks [6]. Our equivalence bounds exclude differences in the three industry categories larger than about 8 percentage points, but not smaller ones. The higher share of health related advertising in designated block groups did not survive correction. Most of that difference came from health insurance advertising, which appeared on 19 of the 326 panels in designated block groups and 1 of the 181 in non-designated ones.

Racial and Hispanic composition were not associated with panel counts after accounting for disadvantage and zoning, although the intervals include small positive associations. This result agrees with findings in San Francisco and Oakland, where income but not racial composition was associated with unhealthy branded advertising, with a borderline association for Hispanic composition [5]. It also agrees with a statewide panel of Rhode Island businesses, in which unhealthy retail outlets followed income and not racial composition once income was included [57]. Our result differs from findings in New York City, where sugary drink advertising was associated with the share of Black residents [6]. It also differs from a four-city study in which advertising density was highest in African American areas [3]. The difference may reflect the setting or the products studied. In our data, the median minority share rose from 9.0% in the least disadvantaged quintile to 66.8% in the most, which limits how well any model can separate racial composition from disadvantage.

Model-based health estimates could not test whether billboards affect health. Adjustment removed the association with a negative control along with most primary associations, the pattern expected when confounding produces the unadjusted associations [51]. A test of health effects would need individual measures of exposure, such as the GPS tracking used to measure children's exposure to advertising in Scotland [10], linked to individual outcomes.

Backlit bulletins were concentrated outside designated block groups and frontlit panels within them, so the share of illuminated panels was similar while the type of lighting differed. Artificial light at night has been linked to circadian disruption [58, 59], and night-time illuminance has been measured directly across Rhode Island communities [60]. We did not measure light reaching homes, so whether this difference changes residents' exposure to light at night is unknown.

4.1. Strengths and limitations

Complete enumeration with field verification is the main strength of the study. Field visits showed that operator inventories overstated the panel count by 14.8%, an error that studies relying on inventory records alone would carry into their exposure estimates. Statewide zoning, and land use maps from 1995 onward, allowed the zoning hypothesis to be tested and checked against recent rezoning.

The decomposition assumes that no unmeasured factor affects both zoning and billboard placement. Adjustment for highway frontage and traffic volume left the zoning share similar, though less precise. An unmeasured confounder would need risk ratio associations of 3.17 with both zoning and panel counts to explain away their association [42]. Factors at the parcel level, such as sightlines and the willingness of landowners to lease, remain unmeasured.

Our design cannot establish the order of disadvantage and land use. Industrial uses may have been sited in poorer neighborhoods, or residents with fewer options may have moved near industry [18, 19]. The decomposition describes how much of the association runs through zoning under either order but cannot say which came first.

How much zoning accounted for also depended on the denominator. With panels modeled per unit area, zoning accounted for 27.8%, and a direct association between disadvantage and panel counts remained. Per resident, the measure that corresponds to residents' exposure, the share was close to three fifths.

Assigning the 63 panels in gaps between zoning polygons to the nearest polygon also mattered. Excluding them lowered the proportion mediated to 45.8% and left a direct association (IRR 1.41, 95% CI 1.04 to 1.93), so in that analysis zoning did not account for the whole association. Our conclusion also depends on including industrial zoning. Commercial zoning alone accounted for 12.7% of the association, so a definition limited to commercial districts would have led to a different conclusion. It also depends on Providence, which held 157 of the 507 panels. Without Providence the total association between disadvantage and panel counts was weaker and imprecise.

Exposure is measured where panels stand rather than where residents travel. Commuters see billboards outside their home block group, and the direction of the resulting bias is uncertain. Impression estimates were supplied by the operators and were not validated, and they differed between panels mainly by media type. The main decomposition used panel counts, which do not depend on these estimates.

Content was coded without double coding. Codes were consistent for the same advertiser across panels, at 98.7% for industry, and misclassification that did not differ by designation would bias content comparisons toward no difference. We applied the state criteria at block group level, so our designated

areas differ from those RIDEM designates by tract. Billboards held by other operators, if any, were not included, which would understate exposure wherever such billboards stand. Small format signage was excluded, and all findings come from one small state. A study in a state where minority and low-income populations are less geographically concentrated could test whether industrial zoning accounts for a similar share elsewhere.

5. Conclusions

In Rhode Island, billboards stood mostly on commercial and industrial land, and that land was concentrated in disadvantaged neighborhoods. Commercial and industrial zoning accounted for between about a quarter and three fifths of the association between neighborhood disadvantage and panel counts, depending on specification. Advertising content differed little between neighborhoods.

Abbreviations

ACME: average causal mediation effect; CI: confidence interval; IRR: incidence rate ratio; RIDEM: Rhode Island Department of Environmental Management; RIGIS: Rhode Island Geographic Information System; SD: standard deviation.

Declarations

Ethics approval and consent to participate

Not applicable. The study used publicly observable commercial signage in public rights of way and publicly available census, zoning and health estimates. It involved no human participants, human data or human tissue.

Consent for publication

Not applicable.

Clinical trial number

Clinical trial number: not applicable.

Availability of data and materials

Billboard inventories are publicly available from Lamar Advertising Company and Clear Channel Outdoor. The analysis code and the datasets generated and analyzed during this study are available from the corresponding author on reasonable request. Census data are available from the US Census Bureau and zoning and land use data from RIGIS. Bus stop locations are available from the Rhode Island Public Transit Authority and PLACES estimates from the Centers for Disease Control and Prevention. Traffic volume and road classification data are available from the Highway Performance Monitoring System of the Federal Highway Administration.

Competing interests

The authors declare that they have no competing interests. Billboard location and specification data were obtained from the publicly available inventories of Lamar Advertising Company and Clear Channel Outdoor. No author has any financial or personal relationship with either company.

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Authors' contributions

E.D.W. and S.V.M. conceived the study and developed the methodology. E.D.W., S.V.M., S.L., J.Y., A.R. and H.N. collected the data, and E.D.W., S.L., J.Y., A.R. and H.N. curated it. S.V.M. and M.L. performed the formal analysis and validated the results. E.D.W. and S.V.M. developed the software, and S.V.M. prepared the figures. S.V.M. wrote the original draft of the manuscript. E.D.W. acquired the funding, provided resources, administered the project and supervised the work. All authors reviewed and edited the manuscript and approved the final version.

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References

[1] Kwate NO, Lee TH. Ghettoizing outdoor advertising: disadvantage and ad panel density in black neighborhoods. J Urban Health. 2007;84(1):21-31. doi:10.1007/s11524-006-9127-5.

[2] Lowery BC, Sloane DC. The prevalence of harmful content on outdoor advertising in Los Angeles: land use, community characteristics, and the spatial inequality of a public health nuisance. Am J Public Health. 2014;104(4):658-64. doi:10.2105/AJPH.2013.301694.

[3] Yancey AK, Cole BL, Brown R, Williams JD, Hillier A, Kline RS, et al. A cross-sectional prevalence study of ethnically targeted and general audience outdoor obesity-related advertising. Milbank Q. 2009;87(1):155-84. doi:10.1111/j.1468-0009.2009.00551.x.

[4] Cassady DL, Liaw K, Miller LM. Disparities in obesity-related outdoor advertising by neighborhood income and race. J Urban Health. 2015;92(5):835-42. doi:10.1007/s11524-015-9980-1.

[5] Zahid N, Pulvera R, Madsen KA, Lee MM, Ibarra-Castro A, Falbe J. Socioeconomic disparities in outdoor branded advertising in San Francisco and Oakland, California. Prev Med Rep. 2022;27:101796. doi:10.1016/j.pmedr.2022.101796.

[6] Dowling EA, Roberts C, Adjoian T, Farley SM, Dannefer R. Disparities in sugary drink advertising on New York City streets. Am J Prev Med. 2020;58(3):e87-95. doi:10.1016/j.amepre.2019.09.025.

[7] Lucan SC, Maroko AR, Sanon OC, Schechter CB. Unhealthful food-and-beverage advertising in subway stations: targeted marketing, vulnerable groups, dietary intake, and poor health. J Urban Health. 2017;94(2):220-32. doi:10.1007/s11524-016-0127-9.

[8] Adams J, Ganiti E, White M. Socio-economic differences in outdoor food advertising in a city in Northern England. Public Health Nutr. 2011;14(6):945-50. doi:10.1017/S1368980010003332.

[9] Settle PJ, Cameron AJ, Thornton LE. Socioeconomic differences in outdoor food advertising at public transit stops across Melbourne suburbs. Aust N Z J Public Health. 2014;38(5):414-8. doi:10.1111/1753-6405.12257.

[10] Olsen JR, Patterson C, Caryl FM, Robertson T, Mooney SJ, Rundle AG, et al. Exposure to unhealthy product advertising: spatial proximity analysis to schools and socio-economic inequalities in daily exposure measured

using Scottish children's individual-level GPS data. Health Place. 2021;68:102535. doi:10.1016/j.healthplace.2021.102535.

[11] Boyland EJ, Nolan S, Kelly B, Tudur-Smith C, Jones A, Halford JC, et al. Advertising as a cue to consume: a systematic review and meta-analysis of the effects of acute exposure to unhealthy food and nonalcoholic beverage advertising on intake in children and adults. Am J Clin Nutr. 2016;103(2):519-33. doi:10.3945/ajcn.115.120022.

[12] Backholer K, Gupta A, Zorbas C, Bennett R, Huse O, Chung A, et al. Differential exposure to, and potential impact of, unhealthy advertising to children by socio-economic and ethnic groups: a systematic review of the evidence. Obes Rev. 2021;22(3):e13144. doi:10.1111/obr.13144.

[13] Finlay A, Robinson E, Jones A, Maden M, Cerny C, Muc M, et al. A scoping review of outdoor food marketing: exposure, power and impacts on eating behaviour and health. BMC Public Health. 2022;22(1):1431. doi:10.1186/s12889-022-13784-8.

[14] Grier SA, Kumanyika S. Targeted marketing and public health. Annu Rev Public Health. 2010;31:349-69. doi:10.1146/annurev.publhealth.012809.103607.

[15] Gilmore AB, Fabbri A, Baum F, Bertscher A, Bondy K, Chang HJ, et al. Defining and conceptualising the commercial determinants of health. Lancet. 2023;401(10383):1194-213. doi:10.1016/S0140-6736(23)00013-2.

[16] Lacy-Nichols J, Nandi S, Mialon M, McCambridge J, Lee K, Jones A, et al. Conceptualising commercial entities in public health: beyond unhealthy commodities and transnational corporations. Lancet. 2023;401(10383):1214-28. doi:10.1016/S0140-6736(23)00012-0.

[17] Maantay J. Zoning, equity, and public health. Am J Public Health. 2001;91(7):1033-41. doi:10.2105/ajph.91.7.1033.

[18] Been V. Locally undesirable land uses in minority neighborhoods: disproportionate siting or market dynamics? Yale Law J. 1994;103(6):1383-422.

[19] Mohai *P*, Saha R. Which came first, people or pollution? Assessing the disparate siting and post-siting demographic change hypotheses of environmental injustice. Environ Res Lett. 2015;10(11):115008. doi:10.1088/1748-9326/10/11/115008.

[20] US Census Bureau. American Community Survey 2019-2023 5-year estimates. Washington (DC): US Census Bureau; 2024.

[21] Lamar Advertising Company. Billboard inventory, Rhode Island. https://lamar.com/

[22] Clear Channel Outdoor. Billboard inventory, Rhode Island. https://clearchanneloutdoor.com/

[23] US Census Bureau. TIGER/Line shapefiles: block groups and primary and secondary roads, Rhode Island, 2023. Washington (DC): US Census Bureau; 2023.

[24] Rhode Island Department of Environmental Management. Environmental Justice Policy, Version 1.3. Providence (RI): RIDEM; 2023. https://dem.ri.gov/sites/g/files/xkgbur861/files/2023-09/ridem-environmental-justice-policy.pdf

[25] Rhode Island Geographic Information System. Rhode Island zoning and overlay zones: municipal zoning classifications. Kingston (RI): RIGIS; 2026. https://rigis-edc.opendata.arcgis.com/

[26] Rhode Island Geographic Information System. Land use and land cover, 1995, 2003-2004, 2011 and 2020. Kingston (RI): RIGIS. https://rigis-edc.opendata.arcgis.com/

[27] Walker K. tigris: load census TIGER/Line shapefiles. R package version 2.2.1. 2025. doi:10.32614/CRAN.package.tigris.

[28] Rhode Island Public Transit Authority. General Transit Feed Specification (GTFS) static feed: bus stop locations. Providence (RI): Rhode Island Public Transit Authority. https://ripta.com/RIPTA-GTFS.zip

[29] Messer LC, Laraia BA, Kaufman JS, Eyster J, Holzman C, Culhane J, et al. The development of a standardized neighborhood deprivation index. J Urban Health. 2006;83(6):1041-62. doi:10.1007/s11524-006-9094-x.

[30] Wagstaff A, Paci *P*, van Doorslaer E. On the measurement of inequalities in health. Soc Sci Med. 1991;33(5):545-57. doi:10.1016/0277-9536(91)90212-u.

[31] Canty A, Ripley B. boot: bootstrap functions. R package version 1.3-32. 2025. doi:10.32614/CRAN.package.boot.

[32] Davison AC, Hinkley DV. Bootstrap methods and their application. Cambridge: Cambridge University Press; 1997. doi:10.1017/CBO9780511802843.

[33] Cameron AC, Trivedi PK. Regression analysis of count data. 2nd ed. Cambridge: Cambridge University Press; 2013. doi:10.1017/CBO9781139013567.

[34] Venables WN, Ripley BD. Modern applied statistics with S. 4th ed. New York: Springer; 2002. doi:10.1007/978-0-387-21706-2.

[35] Imai K, Keele L, Tingley D. A general approach to causal mediation analysis. Psychol Methods. 2010;15(4):309-34. doi:10.1037/a0020761.

[36] Tingley D, Yamamoto T, Hirose K, Keele L, Imai K. mediation: R package for causal mediation analysis. J Stat Softw. 2014;59(5):1-38. doi:10.18637/jss.v059.i05.

[37] Zhao X, Lynch JG, Chen Q. Reconsidering Baron and Kenny: myths and truths about mediation analysis. J Consum Res. 2010;37(2):197-206. doi:10.1086/651257.

[38] Anselin L. Spatial econometrics: methods and models. Dordrecht: Kluwer Academic; 1988. doi:10.1007/978-94-015-7799-1.

[39] Bivand RS, Wong DWS. Comparing implementations of global and local indicators of spatial association. TEST. 2018;27(3):716-48. doi:10.1007/s11749-018-0599-x.

[40] Field CA, Welsh AH. Bootstrapping clustered data. J R Stat Soc Series B Stat Methodol. 2007;69(3):369-390. doi:10.1111/j.1467-9868.2007.00593.x

[41] Guo Z, Small DS, Gansky SA, Cheng J. Mediation analysis for count and zero-inflated count data without sequential ignorability and its application in dental studies. J R Stat Soc Ser C Appl Stat. 2018;67(2):371-394. doi:10.1111/rssc.12233

[42] VanderWeele TJ, Ding P. Sensitivity analysis in observational research: introducing the E-value. Ann Intern Med. 2017;167(4):268-274. doi:10.7326/M16-2607

[43] Federal Highway Administration. Highway Performance Monitoring System (HPMS) 2024. Washington (DC): US Department of Transportation, Bureau of Transportation Statistics, National Transportation Atlas Database; 2025. doi:10.21949/91q8-zb78

[44] Control of outdoor advertising. 23 U.S.C. § 131. United States Code, 2014 edition. https://www.govinfo.gov/content/pkg/USCODE-2014-title23/html/USCODE-2014-title23-chap1-sec131.htm

[45] Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J R Stat Soc Series B. 1995;57(1):289-300. doi:10.1111/j.2517-6161.1995.tb02031.x.

[46] Lakens D. Equivalence tests: a practical primer for t tests, correlations, and meta-analyses. Soc Psychol Personal Sci. 2017;8(4):355-62. doi:10.1177/1948550617697177.

[47] Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. J Stat Softw. 2015;67(1):1-48. doi:10.18637/jss.v067.i01.

[48] Kuznetsova A, Brockhoff PB, Christensen RHB. lmerTest package: tests in linear mixed effects models. J Stat Softw. 2017;82(13):1-26. doi:10.18637/jss.v082.i13.

[49] Centers for Disease Control and Prevention. PLACES: census tract data (GIS friendly format), 2025 release. Atlanta (GA): CDC; 2025. https://data.cdc.gov/d/yjkw-uj5s

[50] Zhang X, Holt JB, Lu H, Wheaton AG, Ford ES, Greenlund KJ, et al. Multilevel regression and poststratification for small-area estimation of population health outcomes: a case study of chronic obstructive pulmonary disease prevalence using the behavioral risk factor surveillance system. Am J Epidemiol. 2014;179(8):1025-33. doi:10.1093/aje/kwu018.

[51] Lipsitch M, Tchetgen Tchetgen E, Cohen T. Negative controls: a tool for detecting confounding and bias in observational studies. Epidemiology. 2010;21(3):383-8. doi:10.1097/EDE.0b013e3181d61eeb.

[52] R Core Team. R: a language and environment for statistical computing. Version 4.6.0. Vienna: R Foundation for Statistical Computing; 2026.

[53] Pebesma E. Simple features for R: standardized support for spatial vector data. R J. 2018;10(1):439-46. doi:10.32614/RJ-2018-009.

[54] Wickham H. ggplot2: elegant graphics for data analysis. New York: Springer-Verlag; 2016. ISBN 978-3-319-24277-4.

[55] Pedersen T. patchwork: the composer of plots. R package version 1.3.2. 2025. doi:10.32614/CRAN.package.patchwork.

[56] Walker ED, Mandalapu SV, Lefebvre S. The acoustic environment is a property of place and fine particulate matter a property of time: co-located measurements across Providence, Rhode Island. Research Square [Preprint]. 2026. doi:10.21203/rs.3.rs-10385808/v1.

[57] Mandalapu SV, Lefebvre S, Walker ED. How new openings sustain the income gradient in unhealthy retail: evidence from a statewide establishment panel, Rhode Island, 2016-2025. medRxiv [Preprint]. 2026. doi:10.64898/2026.08.20.26360917.

[58] Pauley SM. Lighting for the human circadian clock: recent research indicates that lighting has become a public health issue. Med Hypotheses. 2004;63(4):588-96. doi:10.1016/j.mehy.2004.03.020.

[59] Chepesiuk R. Missing the dark: health effects of light pollution. Environ Health Perspect. 2009;117(1):A20-7. doi:10.1289/ehp.117-a20.

[60] Walker ED, Mandalapu SV, Lefebvre S. Divergent social patterning of directly measured environmental exposures across Rhode Island communities. medRxiv [Preprint]. 2026. doi:10.64898/2026.08.20.26360933.

Figure legends

Fig. 1. Neighborhood disadvantage, commercial and industrial zoning and billboard locations in Rhode Island. a, Disadvantage index by population-weighted quintile, with darker shading indicating more disadvantage. b, Land zoned commercial (blue) or industrial (red). c, The 507 verified panels, colored by the zoning class of their location: commercial (blue), industrial (red) or other (gray). Gray lines show interstate highways and the dashed box marks the area shown in d and e. d, The Providence metropolitan core, with commercial and industrial zoning shaded and panels shown as open circles. e, The same area shaded by disadvantage quintile. Block Island is excluded from the maps but included in all analyses. Zoning is from RIGIS [25] and boundaries from 2023 TIGER/Line files [23].

Fig. 2. Distribution of billboard exposure and zoning across neighborhood disadvantage. a, Cumulative share of annual impressions (solid line) and panels (dashed line) against cumulative share of residents, with block groups ranked from most to least disadvantaged. The dotted diagonal marks an equal distribution, and the marker shows the share received by the most disadvantaged 20% of residents. b, Annual impressions per resident by population-weighted quintile of the disadvantage index, with 95% CI from 1,000 bootstrap resamples of block groups. c, Mean percentage of block group area zoned commercial (circles) and industrial (triangles) by quintile, with 95% CI. Analysis of 782 block groups.

Fig. 3. Commercial and industrial zoning and the association between disadvantage and panel counts. a, Incidence rate ratio for panel counts per SD of the disadvantage index, without zoning and with commercial zoning, industrial zoning or both added, on a log scale with 95% CI. Models are negative binomial with a log population offset, adjusted for population density, road length per square mile, distance to the nearest major road and bus stop density. b, Proportion of the association accounted for by commercial zoning, industrial zoning and both combined, by the difference method and by counterfactual mediation, with 95% CI. Dashed lines mark 0% and 100%. c, Proportion accounted for by industrial land use (triangles) and commercial or industrial land use (circles) mapped in 1995, 2003 to 2004, 2011 and 2020, and by current zoning. d, Proportion accounted for with each municipality omitted

in turn. Filled markers indicate a total association with $P < 0.05$, and the dashed line marks the full-sample estimate of 57.8%.

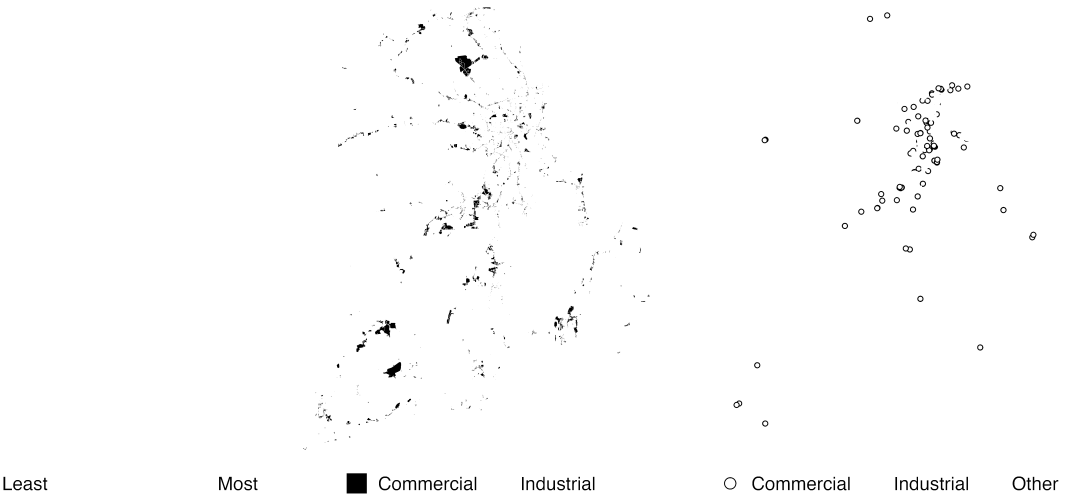
Fig. 4. Content of verified billboard advertising by state designation. a, Share of verified panels in each content category in non-designated (circles) and designated (triangles) block groups. b, Difference in share, designated minus non-designated, in percentage points with 90% CI. Shaded bands mark equivalence bounds of 5 and 10 percentage points. The two health measures are coded independently of the three industry categories and overlap for 40 panels.

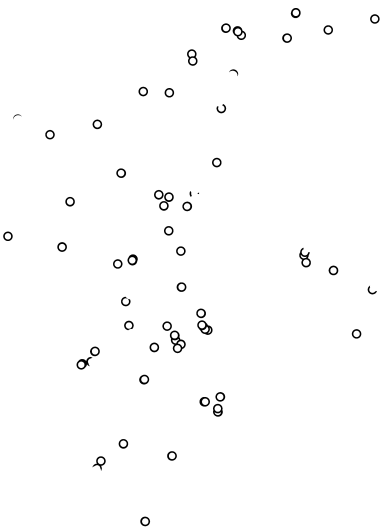
Supplementary information

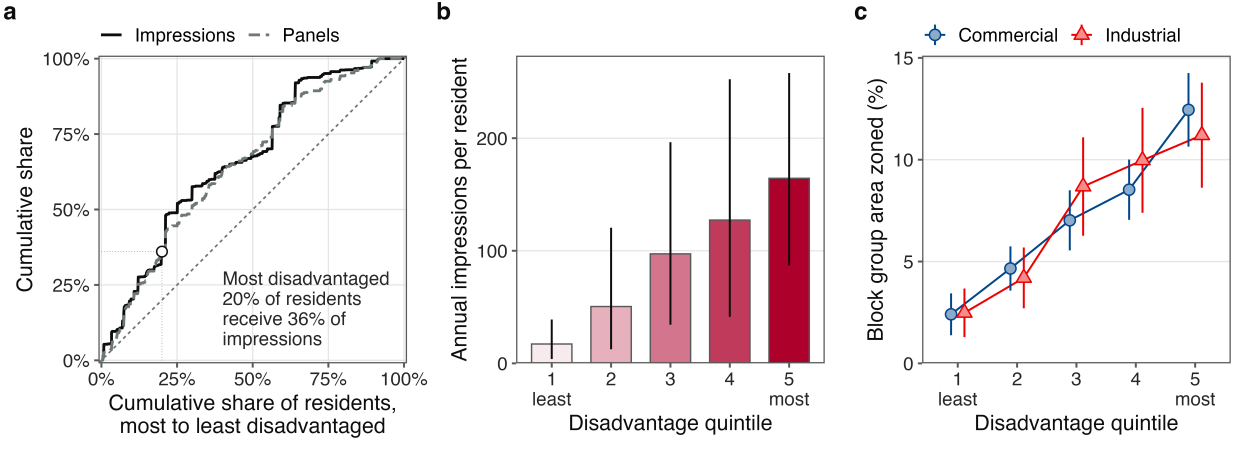
Additional file 1

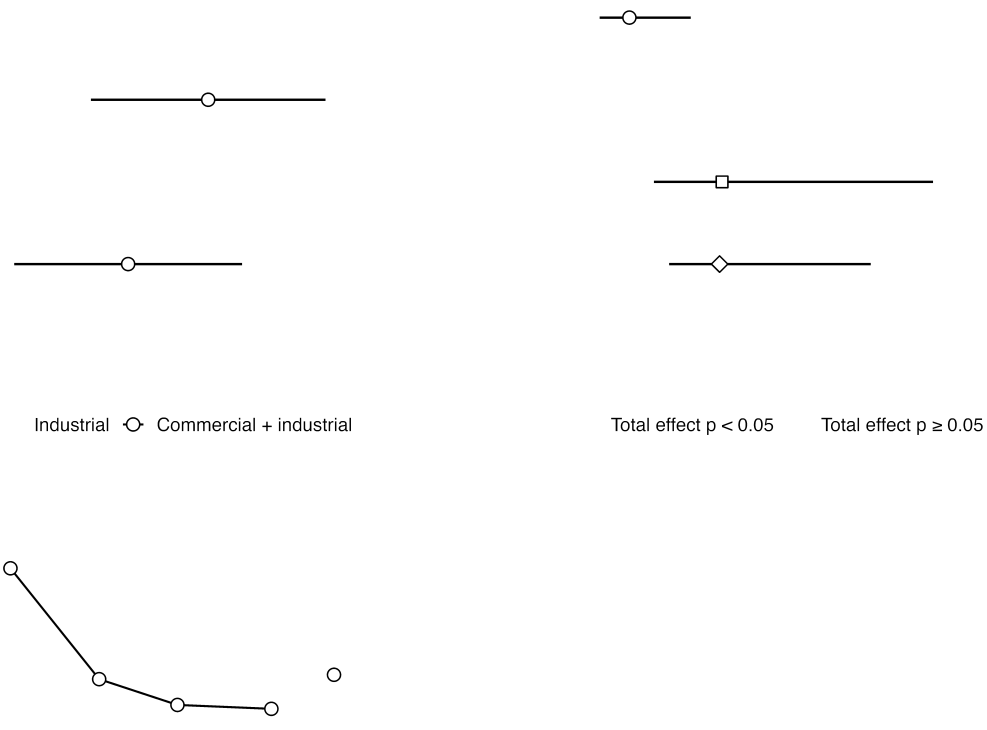
File name: Additional_file_1.docx. File format: Microsoft Word document (.docx). Title: Supplementary tables and figure. Description:

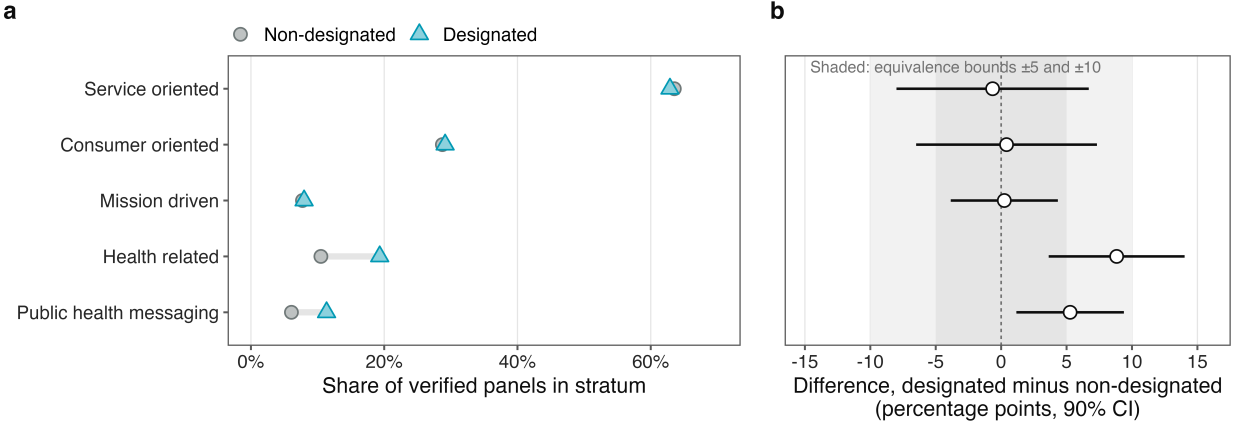
Table S1. Content coding definitions.
Table S2. Construction of the disadvantage index.
Table S3. Disadvantage and designation in relation to commercial and industrial zoning.
Table S4. Neighborhood characteristics and panel counts with sequential adjustment for roads and zoning.
Table S5. Industrial and commercial land use from 1995 to 2020.
Table S6. Sensitivity analyses.
Table S7. Municipalities omitted in turn.
Table S8. Racial and Hispanic composition, net of the disadvantage index and zoning.
Table S9. PLACES health outcomes with negative control outcomes.
Table S10. Linear mixed model of panel reach.
Table S11. Attrition and inventory overstatement.
Table S12. Coding consistency within advertiser.
Table S13. Field visit dates.
Table S14. All 31 sponsoring industries by designation.
Table S15. Health measures by sponsoring industry.
Table S16. Media type, illumination and condition by designation.
Table S17. Language of advertising.
Table S18. Robustness of the zoning decomposition to clustering, specification and traffic.
Table S19. Health-harming product group by designation.
Figure S1. Billboard exposure and model-based tract health estimates, with negative control outcomes.


Least
Most
Commercial
Industrial
Commercial
Industrial
Other




a
Impressions
Panels
100%
75%
50%
25%
0%
Cumulative share
Most disadvantaged 20% of residents receive 36% of impressions
0%
25%
50%
75%
100%
Cumulative share of residents, most to least disadvantaged
b
Annual impressions per resident
200
100
0
1
least
2
3
4
5
most
Disadvantage quintile
c
Commercial
Industrial
Block group area zoned (%)
15
10
5
0
1
least
2
3
4
5
most
Disadvantage quintile


Industrial
Commercial + industrial
Total effect p < 0.05
Total effect p ≥ 0.05


a
Non-designated
Designated
Service oriented
Consumer oriented
Mission driven
Health related
Public health messaging
0%
20%
40%
60%
Share of verified panels in stratum
b
Shaded: equivalence bounds ±5 and ±10
-15
-10
-5
0
5
10
15
Difference, designated minus non-designated
(percentage points, 90% CI)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Additionalfile1.docx