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Original Contribution

Does Neighborhood Crime Mediate the Relationship Between Neighborhood Socioeconomic Status and Birth Outcomes? An Application of the Mediational G-Formula

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While the link between living in a low–socioeconomic status (SES) neighborhood and higher risk of adverse birth outcomes has been well established, the underlying mechanisms remain poorly understood. Using the parametric g-formula, we assessed the role of neighborhood crime as a potential mediator of the relationship between neighborhood SES and birth outcomes using data on singleton births occurring in the Netherlands between 2010 and 2017 (n = 1,219,470). We estimated total and mediated effects of neighborhood SES on small-for-gestational-age (SGA) birth, low birth weight (LBW), and preterm birth (PTB) for 3 types of crime (violent crimes, crimes against property, and crimes against public order). The g-formula intervention settings corresponded to a hypothetical improvement in neighborhood SES. A hypothetical improvement in neighborhood SES resulted in a 6.6% (95% CI: 5.6, 7.5) reduction in the proportion of SGA birth, a 9.1% (95% CI: 7.6, 10.6) reduction in LBW, and a 5.8% (95% CI: 5.7, 6.2) decrease in PTB. Neighborhood crime jointly accounted for 28.1% and 8.6% of the total effects on SGA birth and LBW, respectively. For PTB, we found no evidence of mediation. The most relevant pathways were crimes against property and crimes against public order. The results indicate that neighborhood crime mediates a meaningful share of the relationship between neighborhood SES and birth outcomes.

birth outcomes; crime; health inequalities; mediation analysis; neighborhood

Abbreviations: CI, confidence interval; LBW, low birth weight; OR, odds ratio; PTB, preterm birth; SES, socioeconomic status; SGA, small for gestational age; TE, total effect.

Previous studies have consistently found a link between living in a low–socioeconomic status (SES) neighborhood and higher risk of adverse birth outcomes, even after controlling for individual-level SES factors (1–3). Furthermore, in a previous study we observed that changes in neighborhood SES may lead to changes in the risk of adverse health outcomes (4). These health inequalities observed at birth between inhabitants of more and less affluent areas might even prevail throughout the entire life course. Adverse birth outcomes—that is, small-for-gestational-age (SGA) birth, low birth weight (LBW), and preterm birth (PTB)—have been found to increase the risk of subsequent lifelong morbidity (5, 6). To design interventions to reduce sociospatial health inequalities, it is necessary to understand the mechanisms by which neighborhood SES may influence health at birth. However, to date, the study of potential mechanisms remains neglected in the literature.

A reason why low-SES neighborhoods may be detrimental to health is that they expose their residents to disadvantaged social conditions, such as higher crime rates (7, 8). A strong link has been found between neighborhood socioeconomic makeup and local crime rates; neighborhoods with concentrated disadvantage (e.g., a high unemployment rate and low income) tend to have higher crime rates than more advantaged areas (9, 10). At the same time, various studies have found that women living in neighborhoods with high crime rates are more likely to experience adverse birth outcomes (11–13). Area-level crime might influence health either by triggering a chronic stress response in unsafe areas or by promoting avoidance behavior that affects engagement in physical and social activities (14).

There is some evidence that neighborhood violent crime level may mediate the association between neighborhood SES and LBW (7, 15). However, prior evidence has been limited by the analytical approach used, where a change in β coefficients (particularly the statistical significance of the estimates) was taken as evidence of mediation. As has been previously pointed out in the literature, such an approach has severe shortcomings and can result in biased conclusions for models with a binary outcome due to noncollapsibility (16). Furthermore, it relies on overly restrictive assumptions that do not allow for exposure-mediator interactions (17). Given these limitations, researchers studying health inequalities have called for the use of more flexible methods, such as the g-formula (18). Moreover, both of the previous studies (7, 15), conducted in Chicago, Illinois, had relatively limited sample sizes, and their findings may not apply to the European context due to demographic, social, economic, and health-care differences.

In this nationwide study, we applied the parametric mediational g-formula to investigate whether neighborhood crime mediates the relationship between neighborhood SES and birth outcomes in the Netherlands. Using data from the Netherlands Perinatal Registry linked to individual-level sociodemographic data and neighborhood-level data, we estimated the share of the total effect of neighborhood SES on birth outcomes explained by neighborhood crime. To our knowledge, this is the first study to have evaluated at a national population level the role of neighborhood crime as an underlying mechanism in the relationship between neighborhood SES and birth outcomes.

METHODS

Approach

We used the parametric mediational g-formula to evaluate the impact of a hypothetical improvement in neighborhood SES on birth outcomes and the role of neighborhood crime as an underlying mechanism. The g-formula is a technique embedded in the potential-outcomes causal inference framework (19) which uses standardization to overcome noncollapsibility problems that arise when comparing nested nonlinear models (20). The g-formula has gained popularity as a flexible approach for mediation analysis to answer mechanistic questions about either contextual or individual-level causes (21). The flexibility of this method comes with the trade-off of being more computationally extensive than other methods.

Study design

This study was based on nationwide individual-level birth records linked to routinely collected neighborhood-level data and population registry data curated by Statistics Netherlands. The cohort comprises singleton births occurring at gestational ages between 24 completed weeks and 41 weeks and 6 days in the Netherlands between January 1, 2010, and December 31, 2017.

Data sources

Birth records were obtained from the Netherlands Perinatal Registry, which provides individual-level information on maternal characteristics and birth outcomes, along with the 4-digit postcode of the mother's place of residency at delivery. The registry covers 97% of all births in the Netherlands (22). Statistics Netherlands performed individual-level linkage of the Netherlands Perinatal Registry records to Statistics Netherlands national registries. Due to stillbirths being nonlinkable, records available for analysis consisted of live births only. Further details on the linkage procedure are available elsewhere (4). Information on ethnicity, educational level, and household income was extracted from Statistics Netherlands registries.

The Netherlands Institute for Social Research status scores are a relative measure of neighborhood SES available for 4-digit postcode areas (which have an average of 4,000 inhabitants) (23). The scores summarize 1) the average neighborhood income, 2) the percentage of inhabitants with a low income, 3) the percentage of inhabitants without a paid job, and 4) the percentage of inhabitants with a low educational level. For this work, we used the scores for the years 2010–2017.

Information on neighborhood characteristics was obtained from the postcode-level data collected yearly by Statistics Netherlands, which is calculated by aggregating the information of all residents from each area (24). Neighborhood-level yearly crime rates (per 1,000 inhabitants) were sourced from the national crime figures data set compiled by Statistics Netherlands (2010–2017) (25). This data set holds information on 3 types of crimes: 1) violent crimes (including sexual crimes), 2) crimes against property, and 3) crimes against public order (including vandalism). Further details are provided in Web Appendix 1 (available at https://doi.org/10.1093/aje/kwad037).

Data variables and measurement

The outcomes analyzed in this study were 1) SGA birth (i.e., birth weight below the 10th percentile adjusted for gestational age and sex, according to national reference curves (26)); 2) LBW (i.e., birth weight below 2,500 g); and 3) PTB (i.e., any livebirth occurring between 24 and 37 completed weeks of gestation).

The Netherlands Institute for Social Research status scores were used as our measure of the exposure, that is, neighborhood SES (23). The Netherlands Institute for Social Research calculates these scores by aggregating yearly information on all neighborhood inhabitants up to January 1 of the reporting year. For example, the scores for reporting year 2017 were based on data collected by Statistics Netherlands between January 2, 2016, and January 1, 2017 (i.e., the preceding year). In the models, we used categories of the status scores corresponding to quintiles (going from lowest to highest). The corresponding measure was assigned to each

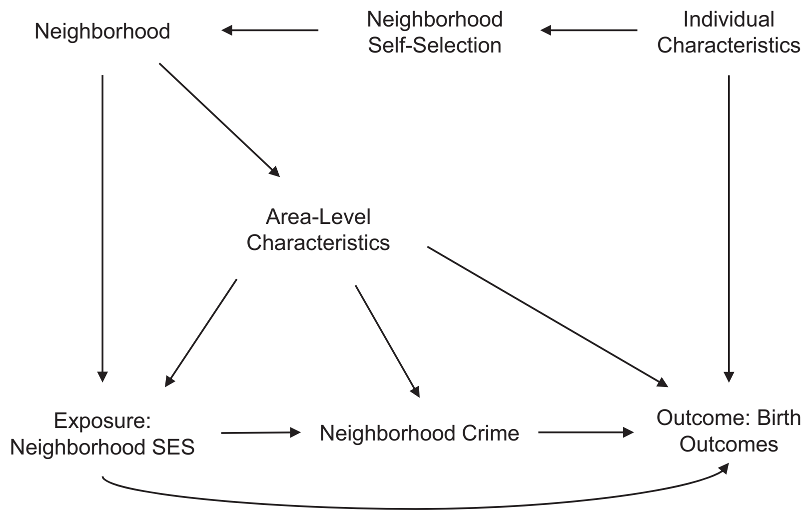

Figure 1. Directed acyclic graph showing the hypothesized relationship between neighborhood socioeconomic status (SES) and birth outcomes, mediated by neighborhood crime, the Netherlands, 2010–2017.

birth record based on residential postcode and birth year; for example, measures for reporting year 2017 were assigned to births that occurred in 2017.

The mediator variables corresponded to neighborhood crime rates (number of crimes per 1,000 inhabitants) for the following 3 types of crime: violent crimes, crimes against property, and crimes against public order (25). The crime rates are calculated using the number of crimes that occurred during each reporting year; for example, the rates for reporting year 2017 included the crimes that occurred between January 1, 2017, and December 31, 2017. In a manner similar to neighborhood SES, we created categories (quintiles) for each type of crime, and these were assigned to the birth records on the basis of postcode and year of birth.

The assessment of mediation involves an aspect of temporality where the exposure should be measured before the mediator, and this in turn is measured before the outcome. Issues like reverse causation and overadjustment may arise if these conditions are not satisfied. If we define year of birth as our main time point (t), neighborhood SES is measured at $t-1$, since for each reporting year the measure is based on data collected in the preceding year. Thus, for all reporting years, the measure of the exposure precedes both neighborhood crime and birth outcomes. Neighborhood crime is measured at t, that is, the same as the year of birth. While the situation is not ideal, we argue that for the mediator-outcome relationship, the direction of the effect is clear (exposure to high neighborhood crime rates would lead to adverse birth outcomes, not the other way around), ruling out potential reverse causation or overadjustment concerns.

The underlying models used in the g-formula adjusted for factors that might confound the exposure-outcome relationship—that is, covariates that are expected to be common precursors of the exposure and the outcome (Figure 1) (27). Additionally, decomposition of the total effect into direct and indirect effects assumes no unmeasured (and uncontrolled) confounding in the mediator-outcome and exposure-mediator relationships (apart from consistency and positivity assumptions) (21). At the individual level, the models included maternal age in categories (≤19, 20–34, or ≥35 years), parity (nulliparous vs. multiparous), maternal country of birth as registered by Statistics Netherlands (Dutch, Turkish, Moroccan, Surinamese, Antillean, other Western, or other non-Western) (28), maternal educational level in categories (as defined by Statistics Netherlands; low, medium, high, or unknown) (29), and equivalized disposable household income (in quintiles; €/year). Household income is often preferred over individual-level income in inequality research, since it might be a more useful indicator of SES, particularly for women, who may not be the main wage-earners in the household (30). At the neighborhood level, the following variables were included (in quintiles): residential address density (number of residential addresses per km^2) as a measure of degree of urbanization, neighborhood average home value, and percentage of non-Western migrants. We also considered other potentially confounding variables, which after further inspection were not included in the final underlying models (Web Appendix 2, Web Tables 1–3). Year of birth (dummy variable) was also included in the models to account for any potential cohort effects.

Missing data

The Netherlands Institute for Social Research does not calculate status scores for areas with fewer than 100 households due to privacy concerns. Therefore, neighborhood SES could not be assigned to births from mothers living in these areas. Values for neighborhood-level variables also could not be assigned to birth records without a postcode available. As a result, neighborhood-level data were missing for 1.5% of the records. Data on at least 1 individual-level characteristic were not available for 1.2% of the cases. Because of this small amount of missing data (2.7%), no data were imputed for the statistical analysis.

Table 1. Definitions Used in a Study of Mediation of the Relationship Between Neighborhood Socioeconomic Status and Birth Outcomes by Neighborhood Crime, the Netherlands, 2010–2017

Effect	Abbreviation	Definition[a]
Total effect	TE	$E\left(Y_{\chi} - Y_{\chi*}\right) = E\left(Y_{\chi V_{\chi} P_{\chi} O\chi} - Y_{\chi* V_{\chi} P_{\chi*} O_{\chi*}}\right)$
Natural indirect effect (all mediators)	NIE	$E\left(Y_{\chi* V_{\chi} P_{\chi} O_{\chi}} - Y_{\chi* V_{\chi*} P_{\chi*} O_{\chi*}}\right)$
Total direct effect	TDE	$E\left(Y_{\chi V_{\chi} P_{\chi} O_{\chi}} - Y_{\chi* V_{\chi} P_{\chi} O_{\chi}}\right)$
Indirect effect of neighborhood SES via violent crime	IE violent crime	$E\left(Y_{\chi* V_{\chi} P_{\chi*} O_{\chi*}} - Y_{\chi* V_{\chi*} P_{\chi*} O_{\chi*}}\right)$
Indirect effect of neighborhood SES via crimes against property	IE crime against property	$E\left(Y_{\chi* V_{\chi*} P_{\chi} O_{\chi*}} - Y_{\chi* V_{\chi*} P_{\chi*} O_{\chi*}}\right)$
Indirect effect of neighborhood SES via crimes against public order	IE crime against public order	$E\left(Y_{\chi* V_{\chi*} P_{\chi*} O_{\chi}} - Y_{\chi* V_{\chi*} P_{\chi*} O_{\chi*}}\right)$

Abbreviation: SES, socioeconomic status.

[a] *Y* refers to the outcome(s) and χ to the exposure. Here χ^* represents the lowest-SES scenario, whereas χ represents the highest-SES scenario. *V* refers to violent crime, *P* to crimes against property, and *O* to crimes against public order.

Statistical analysis

The potential-outcomes framework defines effects as the difference between 2 potential outcomes (counterfactuals) (31). A potential outcome refers to the outcome value that would be observed when a person is exposed to a certain exposure value (a hypothetical scenario) (31). Following previous literature (32, 33), we used hypothetical scenarios corresponding to the most and least disadvantaged neighborhood SES categories—that is, 1) setting the exposure values for all mothers to the lowest SES category and 2) setting the exposure values for all mothers to the highest SES category. Thus, the total effect (TE) of the exposure is interpreted as the effect of changing the exposure value from the most disadvantaged to the least disadvantaged (Table 1). In the remainder of this article, we will refer to this change as a hypothetical intervention where neighborhood SES is improved from the lowest category to the highest.

The g-formula approach facilitates the simultaneous inclusion of multiple mediators (i.e., 3 types of crime) in the models. The procedure allows for the estimation of mediation effects via all mediators jointly and then via each mediator individually to determine the most important pathways (see Table 1). Figure 1 represents the hypothesized relationship between neighborhood SES and birth outcomes, mediated by neighborhood crime.

The mediation effects defined in Table 1 were estimated following the g-formula steps described in Web Appendix 3, which have also been extensively addressed elsewhere (32, 34). Two steps are of special interest: an estimation step and a simulation step. In the estimation step, we fitted suitable models for mediators and outcomes (underlying models), which included all measured confounders. The models for the outcomes additionally included all of the mediator variables. Models allowing for exposure-mediator interactions were considered. Given that the point estimates from models with and without the interaction terms were equivalent, the most parsimonious models (without the interaction terms) were chosen as final models. The 3 outcomes were modeled using logistic regression.

Then, following the steps in Web Appendix 3, we simulated a natural course scenario (no intervention scenario) and the 2 hypothetical scenarios described above. The simulation step requires drawing values of the mediators and outcomes from suitable probability distributions, and the exact values assigned to individuals can change across multiple draws. This between-draws variability is known as Monte Carlo error (35). To reduce this error, the simulations (and calculations of average values) are repeated multiple times, each time drawing a new set of mediator and outcome values (36). The number of iterations needed is based on the stability of the outcome and mediator averages, which can be checked by plotting the cumulative averages as shown in Web Figure 1. Based on this information, 30 Monte Carlo iterations were considered sufficient to produce stable estimates. For each mediator and outcome, the mean values over the simulated scenarios were saved. The mean values represented the proportion of births with a given outcome (or mediator) in each scenario. The average of the Monte Carlo iterations was then used as the estimate in effect calculations. The comparison between the observed means (for the outcome and mediators) and the means derived under the natural course scenario was used as a check against gross model misspecification (32).

To determine the indirect effect of the hypothetical intervention via each individual mediating pathway, we simulated additional scenarios (Table 1) following the steps described in Web Appendix 3 (21). While the mediation effects are not additive because of the nonlinear nature of the models, the procedure gives insight into the specific pathways through which neighborhood SES is related to birth outcomes (34).

As a sensitivity analysis, we assessed the impact of women moving to another neighborhood during (or shortly prior to) their pregnancy, by restricting the underlying models used in the g-formula to women who had been living at the same residential address for at least 2 years at the time of delivery.

For interpretability, we report the mediation parameters in relative terms, that is, percentage change in the proportion of births with a given outcome. Absolute values for the

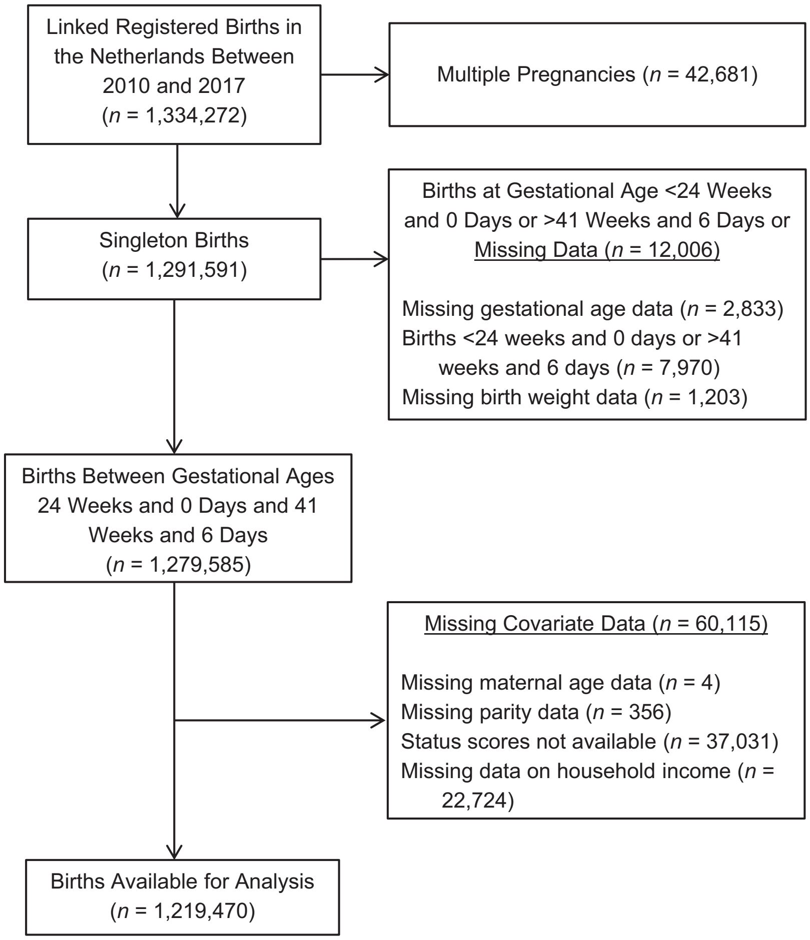

Figure 2. Selection of participants for a study of mediation of the relationship between neighborhood socioeconomic status and birth outcomes by neighborhood crime, the Netherlands, 2010–2017.

mediation parameters are available in Web Table 4. The 95% confidence intervals (CIs) for the mediation parameters were obtained from 250 clustered bootstrapped iterations of the g-formula. This method accounts for clustering of individuals within neighborhoods (37). The cumulative averages of the outcomes and mediators were plotted to assess the bootstrap and Monte Carlo stability of the estimates. All of the analyses were conducted in R, version 4.0.5 (38). The R package *cfdecomp* (R Foundation for Statistical Computing, Vienna, Austria) was used to perform the clustered bootstrap analysis and to produce Monte Carlo and bootstrap stability plots (39).

RESULTS

Between 2010 and 2017, there were 1,334,272 linked registered births in the Netherlands. After exclusion of multiple births, births with a gestational age below 24 weeks or above 41 weeks and 6 days, and cases with missing information, there were 1,219,470 births available for the analysis (Figure 2). Web Figures 2–6 illustrate the geographic distribution of area-level SES, crime rates, and adverse birth outcomes in the Netherlands. It can be observed that lower SES, higher crime rates, and higher prevalences of adverse outcomes are concentrated in the largest cities.

Table 2 presents individual-level demographic and health characteristics along with area-level attributes by neighborhood SES (lowest category vs. highest). Compared with the highest SES category, prevalences of the 3 outcomes were higher in the lowest category. Moreover, crime rates for the 3 types of crime were higher for the lowest SES category than for the highest category. The results for the models including all mediators and confounders showed higher odds of SGA birth (odds ratio (OR) = 1.06 (95% CI: 1.03, 1.08)), LBW (OR = 1.11 (95% CI: 1.07, 1.14)), and PTB (OR = 1.07 (95% CI: 1.04, 1.10)) for women in the lowest neighborhood SES category than for women from the most advantaged areas (Web Appendix 2, Web Tables 1–3). The strongest associations between mediators and outcomes were observed for the highest quintile of each type of crime.

Simulated outcome and mediator mean values under the natural course scenario were comparable to the observed outcome and mediator values, which is an indication that gross

Table 2. Demographic Characteristics and Birth Outcomes of Study Participants According to Neighborhood Socioeconomic Status Category (Lowest vs. Highest), the Netherlands, 2010–2017

Characteristic	Total (*n* = 1,219,470)[a]			Neighborhood SES Category: Lowest (*n* = 336,213)			Neighborhood SES Category: Highest (*n* = 237,600)		
	No.	%	Mean (SD)	No.	%	Mean (SD)	No.	%	Mean (SD)
Individual Characteristics									
Primiparity	546,765	44.8		155,405	46.2		102,114	43.0	
Maternal age, years			30.6 (4.8)			30.0 (5.1)			31.4 (4.6)
Maternal country of birth									
Moroccan	30,773	2.5		18,918	6.5		2,902	1.2	
Turkish	20,900	1.7		13,493	4.6		1,760	0.7	
Surinamese	11,575	0.9		6,390	2.2		2,000	0.8	
Antillean	9,553	0.8		5,516	1.9		1,046	0.4	
Other non-Western	76,480	6.3		31,835	10.3		12,681	5.4	
Other Western	73,975	6.1		24,728	7.6		14,630	6.2	
Dutch	996,214	80.1		225,262	67.0		202,581	85.2	
Educational level									
Low (primary education)	106,213	8.7		49,880	14.8		10,693	4.5	
Medium (secondary education)	498,116	40.8		143,174	42.6		82,287	34.6	
High (higher education)	457,102	37.5		104,117	31.0		113,193	47.6	
Unknown	158,039	12.9		39,042	11.6		31,427	13.2	
Equivalized disposable household income, €/year[b]	26,255 (21,388–37,127)			22,193 (19,316–35,009)			29,910 (25,033–41,012)		
Pregnancy outcome									
Low birth weight	54,038	4.4		17,690	5.2		9,022	3.8	
Preterm birth	66,783	5.4		19,788	5.9		12,195	5.1	
SGA birth	131,493	10.8		43,310	12.9		22,830	9.6	
Area-Level Characteristics									
Residential address density, no. of residential addresses per km^2			1,777 (1,555)			2,408 (2,312)			1,281 (1,263)
Percentage of non-Western migrants			13.7 (15.0)			27.8 (19.9)			9.0 (7.2)
Average home value, 1,000 €			242 (83)			179 (52)			296 (96)
Neighborhood crime[c]									
Violent crimes			9.4 (12.6)			15.1 (15.5)			6.7 (11.9)
Crimes against property			60.2 (86.7)			87.3 (95.0)			51.5 (98.7)
Crimes against public order			12.8 (13.8)			17.3 (16.3)			10.9 (13.7)

Abbreviations: IQR, interquartile range; SD, standard deviation; SES, socioeconomic status; SGA, small for gestational age.
[a] All births available for analysis.
[b] Values are expressed as median (IQR).
[c] Yearly neighborhood crime rate (number of crimes per 1,000 inhabitants).

model misspecification is unlikely to have been present in our models (Web Table 5).

Table 3 presents the mediation effect estimates obtained from the g-formula. The TE of neighborhood SES on birth outcomes represents the combined effect of all direct and indirect pathways. At the population level, we found that a hypothetical improvement in neighborhood SES from the lowest category to the highest would be associated with a

Table 3. G-Formula Mediation Effects of Neighborhood Socioeconomic Status Improvement (From the Lowest Category to the Highest) on Adverse Birth Outcomes, the Netherlands, 2010–2017

Pregnancy Outcome	Reduction in Adverse Birth Outcome, %					
	Total Effect	95% CI	Total Direct Effect	95% CI	Natural Indirect Effect	95% CI
SGA birth	6.6	5.6, 7.5	4.8	4.0, 5.4	1.8	1.6, 2.1
Preterm birth	5.8	5.7, 6.2	5.7	5.2, 6.1	0.1	−0.2, 0.4
Low birth weight	9.1	7.6, 10.6	8.3	7.1, 9.6	0.8	0.5, 0.9

Abbreviations: CI, confidence interval; SGA, small for gestational age.

6.6% (95% CI: 5.6, 7.5) decrease in the proportion of SGA births, a 9.1% (CI: 7.6, 10.6) reduction in births with LBW, and a 5.8% (CI: 5.7, 6.2) reduction in PTB. Absolute effect values are shown in Web Table 4.

The TE was further decomposed into the total direct effect and the natural indirect effect. The natural indirect effect accounted for 28.1% (95% CI: 24.1, 32.4) of the TE of neighborhood SES on SGA birth and for 8.6% (CI: 5.4, 11.5) of the TE on LBW. For PTB, we found no evidence of mediation by neighborhood crime (1.6%, 95% CI: −3.0, 7.2). When evaluating the intervention effect operating via each of the mediators individually, we observed that crime against property and crime against public order were the most relevant pathways (Web Appendix 4, Web Table 6).

The estimates from the underlying models used in the g-formula remained unchanged when we restricted the underlying models to women who had been living at the same residential address for at least 2 years at the time of delivery (Web Appendix 2).

DISCUSSION

In this nationwide population-based study in the Netherlands, we found that neighborhood crime mediated the relationship between neighborhood SES and key adverse birth outcomes. Neighborhood crime accounted for 28.1% of the total effect of neighborhood SES on SGA birth and 8.6% of the effect for LBW. However, no evidence of mediation was found for PTB. To our knowledge, this is the first study to have examined at a national level the role of neighborhood crime as a potential underlying mechanism for the relationship between neighborhood SES and birth outcomes.

This study added to the literature by using the parametric mediational g-formula approach to decompose the total effect of neighborhood SES on birth outcomes into direct and indirect effects via neighborhood crime. We found that a moderate portion of the total effect of neighborhood SES on birth outcomes was accounted for by the mediators. Regarding the magnitude of the mediation, a direct comparison between our findings and previous literature was unfortunately not feasible, since neither of the 2 prior studies had carried out the decomposition to be able to calculate this figure (e.g., percentage mediated). However, the overall finding that neighborhood crime mediated the relationship between neighborhood socioeconomic disadvantage and LBW is consistent with what was previously observed (7, 15). Our work progressed from the previous literature by simultaneously including 3 types of crime as mediators in the models to determine the most relevant pathways. The finding that crimes against property and public order (including vandalism) were the most important pathways suggests that more visible and frequent types of crime might be most relevant for birth outcomes. Research has found that vandalism and crime against property show stronger associations with health outcomes than certain types of violent crime (11, 40). This could be partly explained by these types of crime occurring on a more day-to-day basis than violent crime (41). Moreover, prior studies in the Dutch population observed that, particularly for women, objective measures of crimes against property translate into stronger feelings of unsafety (42).

Similar to Masi et al. (15), we observed that neighborhood crime mediated the association between neighborhood SES and SGA birth (along with LBW), but this was not the case for PTB. The literature outlines 2 main pathways through which neighborhood crime may influence birth outcomes. One way is by neighborhood crime's being an ecological stressor, which leads to an activated stress response that translates into higher levels of cortisol (11). A second explanation might be that unsafe areas may pressure women into adopting avoidance behaviors that affect their engagement in physical (and social) activities (43, 44). Both PTB and SGA birth have been associated with maternal stress and health behaviors; however, in previous literature, authors have argued that PTB is closely linked to maternal stress and that SGA birth is primarily influenced by health behaviors (45, 46). It could then be hypothesized that crime might be mainly influencing health at birth via avoidance behaviors. Nevertheless, these hypotheses would need to be further investigated.

A main strength of this study is its focus on disentangling one of the mechanisms by which neighborhood SES may influence health at birth. Furthermore, application of the g-formula allowed us to overcome potential noncollapsibility issues with nonlinear outcomes. Additionally, it facilitated the simultaneous inclusion of multiple mediators (3 types of crime), which provided more precise information about the most relevant pathways. The use of routinely collected high-quality, national-level data corresponding to an extended time period (2010–2017) led to over 1.2 million individual records being available for analysis, which resulted in estimates that are applicable to a nationwide context instead of single cities only. Given that conclusions similar to ours have been drawn in studies conducted in the United States (7, 15), it is plausible that our findings are also applicable to contexts outside of the Netherlands, particularly to other European countries with similar social and economic conditions. However, more nationwide studies are essential to confirm our main results and to build evidence regarding the magnitude of the mediation. Our findings could be valuable when designing neighborhood-level targeted interventions. Particularly, programs targeted at reducing vandalism and crimes against property might be a promising approach to improving birth outcomes and reducing early-life health inequalities.

A limitation of this study is that some births (including stillbirths) could not be linked. However, the impact is likely to have been small, since only 3% of the cases could not be linked. Related to the previous point, collider bias can arise due to selection on live births (47). A conventional strategy for reducing some of this bias is to adjust the model's results for common causes of the outcome that also influence fetal death. The underlying model used for the g-formula adjusts for known common causes of stillbirth and SGA birth, PTB, and LBW—that is, maternal age, primiparity, education, and income (48). Moreover, in sensitivity analyses, the models accounted for additional potential confounders that are known common causes of stillbirth and other adverse birth outcomes (diabetes, hypertension, smoking, and alcohol and drug use), leading to similar results.

The validity of the g-formula estimation was dependent on the validity of the underlying models used to create the simulated data. Misspecification of these models, either through omitted confounders or misspecification of functional form, would have led to bias (21). Reassuringly, the check against gross model misspecification did not show signs of this being the case. The underlying models accounted for relevant individual and area-level characteristics, which have been found to be the most important confounders in neighborhood-level research and drivers of neighborhood self-selection (49). Moreover, we explored the relevance of various other potential confounders, including potential mediator-outcome confounders that are exposure-dependent. However, our study was based on registry data, which did not allow us to observe and control for all possible confounders. For example, there could have been unobserved maternal beliefs or preferences that might have influenced not only exposure to certain neighborhood environments but also birth outcomes. At the neighborhood level, unobserved physical neighborhood characteristics (that could be exposure-dependent), like walkability, might influence crime rates and birth outcomes. These scenarios would bias our results upwards. Thus, causal interpretation of our results needs to be done with caution.

In future research, investigators might consider using individual-level measures of perceived neighborhood safety. These measures, which unfortunately were not available, have been found to have a stronger link to health outcomes than objective measures (50). More research is still needed to shed light on other potential pathways through which neighborhood may affect birth outcomes—for example, social capital, disorder, air pollution, walkability, etc. Because of the previously described advantages of the g-formula, we encourage the application of this approach in further research attempting to disentangle the mechanisms through which neighborhood SES may affect birth outcomes.

In conclusion, our results indicate that neighborhood crime mediates a meaningful share of the association between neighborhood SES and adverse birth outcomes in the Netherlands. Crimes against property and crimes against public order were the most relevant pathways.

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