Published in final edited form as:
J Am Acad Child Adolesc Psychiatry. 2016 July ; 55(7): 591–601. doi:10.1016/j.jaac.2016.05.002.

Environmental Determinants of Aggression in Adolescents: Role of Urban Neighborhood Greenspace

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Abstract

Objective—Neighborhood greenspace improves mental health of urban-dwelling populations, but its putative neurobehavioral benefits in adolescents remain unclear. We conducted a prospective study on urban-dwelling adolescents to examine the association between greenspace in residential neighborhood and aggressive behaviors.

Method—Participants (n = 1,287) of the Risk Factors for Antisocial Behavior Study, a multi-ethnic cohort of twins and triplets born in 1990–1995 and living in Southern California, were examined in 2000–2012 (aged 9 to 18 years) with repeated assessments of their aggressive

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This article is discussed in an editorial by Dr. Peter Jensen on page xx.

Supplemental material cited in this article is available online.

Preliminary results presented at the Society for Epidemiologic Research Annual Meeting in Denver, Colorado, June 16–19, 2015.

Dr. Berhane served as the statistical expert for this research.

Disclosure: Dr. J. Wu has received grant funding from NIEHS, the Health Effect Institute (HEI), the California Air Resources Board (CARB), and the BP/South Coast Air Quality Management District (AQMD). She has served as a consultant to a project funded by the Susan G. Komen Breast Cancer Foundation (Komen). Dr. Franklin has received grant funding from NIH and the National Aeronautics and Space Administration (NASA). Dr. Berhane has received grant funding from NIH, US Environmental Protection Agency (EPA), the International Development Research Centre (IDRC), the Centers for Disease Control and Prevention (CDC), and the National Institute for Occupational Safety and Health (NIOSH). Dr. McConnell has received grant funding from NIH and US EPA, and research support provided by funds from an air quality violations settlement agreement between the South Coast Air Quality Management District, a California state regulatory agency, and BP. Dr. A. Wu has received grant funding from NIEHS, Komen, the National Cancer Institute (NCI), and the California Breast Cancer Research Program (CBCRP). Dr. Chen has received grant funding from the National Institute on Aging (NIA). Ms. Younan has received grant funding from NIA. Mr. Lurmann has received grant funding from NIH and the US EPA. He is an employee and stockholder of Sonoma Technology, Inc. Drs. Tuvblad, Li, and Baker report no biomedical financial interests or potential conflicts of interest.

behaviors by the parent-reported Child Behavior Checklist. Normalized Difference Vegetation Index (NDVI) derived from satellite imagery was used as a proxy for residential neighborhood greenspace aggregated over various spatiotemporal scales prior to each assessment. Multilevel mixed-effects models were used to estimate the effects of greenspace on aggressive behaviors, adjusting for within-family/within-individual correlations and other potential confounders.

Results—Both short-term (1- to 6-months) and long-term (1- to 3-years) exposures to greenspace within 1,000-meters surrounding residences were associated with reduced aggressive behaviors. The benefit of increasing vegetation over the range (~0.12 in NDVI) commonly seen in urban environments was equivalent to approximately 2 to 2.5 years of behavioral maturation. Sociodemographic factors (e.g., age, gender, race/ethnicity, and socioeconomic status) and neighborhood quality did not confound or modify these associations, and the benefits remained after accounting for temperature.

Conclusion—Our novel findings support the benefits of neighborhood greenspace in reducing aggressive behaviors of urban-dwelling adolescents. Community-based interventions are needed to determine the efficacy of greenspace as a preemptive strategy to reduce aggressive behaviors in urban environments.

Keywords

aggression; greenspace; adolescents; epidemiology; environment

INTRODUCTION

According to the World Health Organization, violence is one of the leading causes of death among 15–44 year olds and is a major global public health issue worldwide. High rates of crime and violence prevail in urban areas, and urban residence is a well-documented risk factor for various mental illnesses. Currently, half of the world's population resides in urban environments, and this proportion is expected to increase by 20% over the next 35 years. Identifying effective measures to reduce violence has become a pressing issue facing societies today, and studying the associated environmental risk factors, especially those modifiable among vulnerable populations, may help inform early intervention strategies.

Aggression during childhood is a strong indicator of developmental processes gone awry and manifests into more serious adverse behaviors such as violence and crime. Aggressive behavior is also a key precursor to many mental illnesses, including antisocial personality disorder. Although genetic factors are important causes of aggressive behaviors, environment also accounts for 50% of its total variance. Previous studies in urban-dwelling populations have primarily focused on social environmental determinants, but whether and how the physical characteristics of urban environments affect aggressive behaviors are not well understood. In search of modifiable physical environmental factors predictive of aggressive behaviors, we only found scant literature suggesting possible adverse effects of air pollution,[–] meteorological factors,[–] and neighborhood noise. The beneficial impacts of greenspace have become increasingly recognized by public health advocates, and clinicians have started prescribing exposure to greenspace as a natural treatment for various physical and mental illnesses. Greenspace has the ability to improve overall wellbeing, decrease stress levels, and reduce symptoms of depression, anxiety, and attention-deficit/hyperactivity disorder.[–] However, no previous studies have examined whether greenspace could reduce aggressive behaviors in urban-dwelling adolescents.

Adolescence is a critical period of neural development marked by increased connectivity and interaction between areas of the brain. Many functional and structural changes in the prefrontal lobe occur during this time, which are accompanied by cognitive and behavioral maturation. This phase of rapid change and growth is a crucial time for shaping behavioral trajectories and is a vulnerable period during which developmental processes may be easily disrupted. As a result, adolescents are an important population to target for early intervention of aggressive behavior, and identifying modifiable environmental factors in urban areas should be of interest. This study aims to examine the potential association between residential neighborhood greenspace and aggressive behaviors in adolescents residing in urban areas of Southern California.

METHOD

Study Design

Participants were drawn from the Risk Factors for Antisocial Behavior (RFAB) twin study based at the University of Southern California. RFAB is a prospective study of the interplay of genetic, environmental, social, and biological factors on the development of antisocial behavior from childhood to early adulthood. Participating families were recruited from Los Angeles County and surrounding areas, representative of the ethnic and socioeconomic diversity of the greater Los Angeles area. This ongoing cohort study includes over 780 monozygotic and dizygotic (same-sex and opposite-sex) twin pairs and triplets born between 1990–1995 and aged 9–10 years at study enrollment in 2000. The present study used data collected with up to 4 occasions of longitudinal assessments from childhood to adolescence. Zygosity status was determined using DNA microsatellite analysis. Further details on study protocol and procedures are described elsewhere.[,] The current analyses used data from 1,287 individuals (of 640 families), including 276 monozygotic and 364 dizygotic twin pairs, who had at least two assessments of aggressive behaviors at ages 9–18, provided residential addresses during follow-up, and were part of complete twin or triplet sets (Figure 1)

Behavioral Assessment

Aggressive behaviors over the preceding six months were assessed with the parent-reported version of the widely used Child Behavior Checklist (CBCL/6–18). The high reliability and validity of the CBCL has been reported elsewhere. In clinical settings, the CBCL provides a cost-efficient measure of broad constructs of psychopathology. The Aggressive Behavior subscale consists of 20 items regarding both physical (e.g., gets in many fights, destroys things, physically attacks and threatens others, etc.) and verbal (e.g., argues, teases, screams, etc.) forms of aggression. Each item was coded and scored on a three-point scale (0 = not true; 1 = sometimes true; and 2 = very true/often true),[,] and a continuous raw score was calculated by summing across items. The validity of the aggressive behavior syndrome in predicting or identifying individuals with clinically defined oppositional defiant disorder (with or without conduct disorder) has been documented. In the RFAB study cohort, the

CBCL was administered at each wave with a relatively high internal consistency (average Cronbach's Alpha across waves: $\alpha = 0.873$).

Environmental Exposure Data

Residential Location Data and Geocoding—All residential addresses prospectively collected from the study inception and throughout follow-up were sent to the geocoding services provided by the University of Southern California (USC) Spatial Sciences Institute, which followed standard procedures and returned high-quality geocodes (exact parcel location or specific street segments for 98.6% of our sample). The remaining addresses were geocoded satisfactorily with Google Earth based on visual acceptance. The geographic distribution of RFAB residential locations at baseline in relation to neighborhood greenspace and aggressive behavior scores is presented in Figure S1 (available online). The figure reveals there were no distinctive spatial patterns relating to the two extreme exposure-outcome contrasts.

Residential Neighborhood Greenspace—We assessed neighborhood greenspace surrounding residences using the Normalized Difference Vegetation Index (NDVI) derived from MODerate-resolution Imaging Spectroradiometer (MODIS) at 250-meter resolution. NDVI is calculated as the ratio of visible red and near-infrared reflectance, whereby land surfaces with greener vegetation reflect more near-infrared and absorb more visible red wavelength. We requested a batch download of all 16-day time-series data for the US Southwest region spanning February 2000 to December 2012 from the Global Agriculture Monitoring Project. NDVI values were normalized between 0 and 1, reflecting the range from very sparse to dense vegetation. Neighborhood greenspace was abstracted as the average of NDVI in buffers of 250-, 350-, 500-, and 1000-meters around each residence. Within each defined residential neighborhood, the 16-day time-series NDVI data were then aggregated to represent the time-varying average NDVI estimates of short-term (1-, 3-, and 6-month) and long-term (1-, 2-, and 3-year) exposures preceding each CBCL assessment (for more details see Supplement 1, available online).

Relevant Covariate Data

A directed acyclic graph (DAG) was used to select potential covariates (see Figure S2, available online) known to predict aggressive behavior and likely influence where people lived (and thus their exposure to greenspace), including age, gender, self-reported race/ethnicity (Caucasian, Hispanic, Black, Mixed, or Other), socioeconomic status (SES), and perceived neighborhood quality. Other covariates potentially correlated with greenspace, as evaluated by the DAG, included meteorological factors and neighborhood noise, as well as neighborhood contextual factors and maternal risk factors.

Information on sociodemographic factors and neighborhood quality were collected through structured interviews and questionnaires. Household SES was created from a composite measure of parental education levels, occupational status, family income, and marital status (Hollingshead W. The Hollingshead four-factor index of socioeconomic status [*unpublished manuscript] New Haven, CT: Yale University;* 1979), with higher scores corresponding to higher SES (range: 14–66). Self-perceived neighborhood quality was assessed with parent reports of 17 items regarding criminal and gang-related activities, unemployment, vandalism, and substance use that occurs in the participant's local area. This questionnaire was developed specifically for the RFAB study, resulting in a sum score (with a higher score for a more negative perception of neighborhood quality; range: 2–75) with a high level of internal consistency (average Cronbach's Alpha across waves: $\alpha = 0.945$). For both household SES and neighborhood quality, missing values (8% for household SES; 2% for neighborhood quality) were imputed using median values.

Maternal smoking during pregnancy[–] and maternal depression were used as indicators of maternal risk factors. To assess smoking during pregnancy, mothers were administered a maternal health questionnaire designed for the RFAB study, asking mothers if they had smoked cigarettes during their pregnancy with the twins (yes/no). Maternal depression was assessed with self-reports of 6-items from the Brief Symptom Inventory administered at baseline. Each item was coded and scored on a five-point scale, and a mean score was calculated, with higher scores indicating more symptoms of depression.

Meteorological data was obtained from the California Air Resources Board (CARB) Air Quality and Meteorological Information System. Meteorological conditions recorded at the closest site were assigned to each geocoded residence to construct monthly time-series of average ambient temperature (ºC) and relative humidity (%) from 1990 to 2012. Temperature and relative humidity were averaged for the periods 1-, 3-, and 6-months and 1-, 2-, and 3-years preceding CBCL assessment (for more details see Supplement 2, available online).

Proximity to freeways and other roads and traffic density were used as indicators for neighborhood noise. Using roadway geometry from ESRI's Streetmap Premium database (ArcGIS 10.1, Environmental Systems Research Institute Inc., Redlands, CA) and geographic information systems (GIS) tools, we computed the distances from each residence to the nearest road of four Feature Class Code road classes: freeway or limited-access highway; major collector; minor collector; and arterial road. Annual average daily traffic volumes, obtained from the California Department of Transportation and TeleAtlas/GDT, were assigned to the roadways and used in GIS to map traffic density within 150- and 300-m radius buffers. Annual traffic density was assigned using 2002, 2005, 2008, and 2010 roadways and average traffic volumes for waves 1–4, respectively.

We used the socioeconomic data from the 2000 US Census to objectively define the neighborhood contextual factors, as several studies have shown that the resulting neighborhood socioeconomic characteristics (nSES) are a strong predictor of neighborhood violence and crime,[,] with higher rates of crime found in disadvantaged neighborhoods. We followed the reported procedures to determine the nSES index that had been used in social epidemiologic studies. Briefly, an index at the census tract level was constructed using the following six variables obtained from the 2000 Census: 1) the percentage of adults 25 years old with less than a high school education; 2) the percentage of unemployed males; 3) median household income; 4) the percentage of households with income below the poverty line; 5) the percentage of households receiving public assistance; and 6) the percentage of households with children that are headed by a female. Items were summed and standardized (mean = 0; SD = 1), with the resulting index scores greater than 0 indicating tracts above the average nSES characteristics (range: −1.50–4.06).

Statistical Analysis

Descriptive Statistics Analysis—

We calculated the population characteristics by quartile of NDVI and by level of aggressive behaviors at the study baseline (i.e., the first valid CBCL assessment). Differences in population characteristics in relation to exposure/outcome were examined according to analysis of variance (ANOVA) tests for continuous variables and Pearson Chi-square tests for categorical variables. We also calculated the intraclass correlation coefficient (ICC) for both exposure and outcome to determine the correlation among twins/triplets within the same family.

Multilevel Mixed Effects Modeling—

Three-level mixed effects models regressing repeated measures of aggressive behavior scores on NDVI, accounting for within-family (random intercept and slope [age])/within-individual (random intercept) correlations and potential confounding by multiple covariates. Random effects terms were included to account for the correlation between participants within a family, as well as the correlation across time within a participant (for more details see Supplement 3, available online). These models were constructed using the restricted maximum likelihood approach, and an unstructured covariance structure was specified. Time-varying covariates included age, meteorological variables, and other spatial covariates (e.g., traffic density, proximity to freeways and roads).

Based on our DAG, age, gender, ethnicity, household SES, self-perceived neighborhood quality, and ambient temperature were considered as confounders and included in the fully adjusted models. Relative humidity was not selected because it was not significantly associated with aggressive behavior in our sample and did not confound the NDVI–aggressive behavior relationship. Our empirical data suggested a significant linear effect of short-term (6-month average) temperature and a non-linear effect of long-term (1- to 3-year average) temperature. The corresponding temperature effects were included in our adjusted analyses when looking at short-term (1- to 6-month average) vs long-term (1- to 3-year average) effects of NDVI, respectively.

Sensitivity analyses were conducted to evaluate possible confounding by other covariates, such as traffic noise, other neighborhood contextual characteristics, and maternal risk factors that were not included in our main models. Therefore, we carried out additional analyses further adjusting for traffic density and proximity to freeways and roads (proxies for traffic noise), nSES index (a strong predictor of neighborhood crime rate), and maternal depression and maternal smoking during pregnancy (proxies for maternal risk factors). Lastly, we investigated potential modification of effects of neighborhood greenspace by sociodemographic factors and neighborhood quality.

All analyses were performed using the Statistical Analysis System (SAS 9.4), and figures were created using the R software (version 2.15.2).

RESULTS

Distributions of Estimated NDVI and Aggressive Behavior Scores

Table 1 shows our comparison of population characteristics of the 1,287 RFAB participants in relation to the quartile distribution of NDVI in a 1,000-m buffer averaged over the 6-month period prior to baseline. In our study sample, Caucasians, those from households with higher SES, those perceiving better neighborhood quality, and those born to nonsmoking mothers were more likely to reside in locations with higher levels of NDVI (e.g., in the highest-exposure quartile), as compared to their counterparts. Furthermore, neighborhoods with denser vegetation (high NDVI) were more likely to be in locations further from freeways and roads, with less traffic density, cooler temperatures, and less relative humidity. Across all spatiotemporal scales, NDVI estimates were highly correlated with one another (range of Spearman's R: 0.77–0.99; range of means: 0.32–0.33; all standard deviations = 0.08). Based on ICCs, we found 81–88% of the total variance in NDVI across spatiotemporal scales occurred between families, suggesting that most of the NDVI variabilities were attributed to the geographic distribution of our study participants. For this urban-dwelling population, an interquartile range (~0.12 NDVI) difference in NDVI estimate was equivalent to the difference between living in a residence surrounded by other housing complexes, shopping centers, or freeways compared to living within close proximity to a park, golf course, or school field.

In this sample, younger participants, boys, those from lower-SES households, those perceiving poorer neighborhood quality, and those born to smoking mothers were more likely to engage in aggressive behaviors as compared to their counterparts (Table 2). According to the ICC, 42% of the variability in aggressive behavior scores was attributable to between-family differences, with the remaining 58% contributed by within-family differences including changes over time. A statistically significant age effect on aggressive behaviors was consistent across all models, with decreasing scores by 0.16 to 0.19 (all p-values < .0001) per year, reflecting age-related behavioral maturation during adolescence (*data not shown*).

Associations Between Neighborhood Greenspace and Aggressive Behaviors

In Figure 2, we present the results of the multilevel mixed-effects models, with the regression coefficient β (95% CI) expressed as the difference in aggression score across the interquartile range (IQR) of each exposure (IQR = 0.12 for 1-month to 3-year average NDVI in a 250-m buffer; IQR = 0.11 for 1-month to 3-year average NDVI in 350-, 500-, and 1000-m buffers). Our crude analyses showed that aggressive behaviors decreased with increasing exposure to short-term (1-, 3-, and 6-months) and 3-year average NDVI in a 1000-m before CBCL assessment (all p-values < .05). Adjustment for sociodemographic factors, neighborhood quality, and 6-month average temperature (linear term) resulted in an increase in the strength of the short-term effect estimates for NDVI averaged in a 1000-m buffer, while the other buffer sizes remained nonsignificant. For each interquartile increment of 1-month average NDVI in a 1000-m buffer around residences, aggressive behavior scores decreased by 0.43 (95% CI: −0.75, −0.11), with slightly lower effect estimates for 3-month (β = −0.42; 95% CI: −0.75, −0.09) and 6-month (β = −0.36; 95% CI: −0.71, −0.02) average

NDVI. Additionally, the long-term effect of NDVI averaged in a 1000-m buffer became significant across all exposure durations after adjustment for sociodemographic factors, neighborhood quality, and temperature (linear and quadratic terms) for the same temporal scale as NDVI estimates (e.g., 1- 2- and 3-year temperature effects respectively for 1, 2, 3-year NDVI estimates). For each interquartile increment of 1-year average NDVI, aggressive behavior scores decreased by 0.36 (95% CI: −0.69, −0.02), with slightly greater effects for 2-year ($\beta = -0.41$; 95% CI: −0.79, −0.04) and 3-year ($\beta = -0.40$; 95% CI: −0.75, −0.05) averages. The results of our adjusted analyses suggest a consistent pattern of decreased aggression associated with increasing residential greenspace within a 1000-m buffer, with both short-term and long-term beneficial effects equivalent to 1.9–2.2 and 2.1–2.5 years of age-related behavioral maturation, respectively. Additionally, ethnicity, household SES, neighborhood quality, and temperature accounted for the observed positive confounding when the results of crude and adjusted analyses were compared.

Sensitivity analyses were further carried out for the short- and long-term NDVI estimates averaged in the 1000-m buffer, as this appeared to produce consistent significant results. Effect estimates were not sensitive to further adjustment for proximity to freeways or roads, traffic density in a 150- or 300-m area, or maternal smoking during pregnancy (Table 3; Sensitivity Analyses I–V). Participants from neighborhoods with better contextual socioeconomic characteristics had significantly ($p<.001$) higher levels of estimated NDVI and were less likely to have aggressive behaviors (Spearman $r = -0.08$; $p = .004$). However, after we accounted for this objective measure of neighborhood SES characteristics in our adjusted analyses (VI), there were very few changes to the estimated longitudinal effects of neighborhood greenspace on aggressive behaviors. Mothers with less depressive symptoms at baseline were more likely to have resided in neighborhoods with higher levels of NDVI for an extended period of time (e.g., Spearman $r = -0.10$ between depressive score and 3-year average NDVI within a 1000-m of residential buffer; $p = .002$), and children of mothers with less depression were reported to have less aggressive behaviors during the follow-up ($p = .02$). However, after we further adjusted for the maternal depressive symptoms (VII), the observed beneficial effects of neighborhood greenspace remained statistically significant.

Lastly, there were no statistically significant modifications of the observed neighborhood greenspace effects by age (dichotomized at median: ≥14 years vs. <14 years; dichotomized at 75th percentile: ≥16 years vs. <16 years), gender (boys vs. girls), race/ethnicity (Hispanic vs. Caucasian; Black vs. Caucasian; mixed vs. Caucasian; other vs. Caucasian), SES (dichotomized at median: ≥43.5 vs. <43.5; dichotomized at 75th percentile: ≥51.5 vs. <51.5), or perceived neighborhood quality (dichotomized at median: ≥24.0 vs. <24.0; dichotomized at 75th percentile: ≥31.0 vs. <31.0) (*data not shown*).

DISCUSSION

In this large and likely the first study on urban-dwelling children and adolescents (aged 9–18) with prospectively collected longitudinal data on residential histories and behavioral assessments, we found strong evidence supporting the benefits of neighborhood greenspace in reducing aggressive behaviors. The benefits of increasing vegetation over the range (~0.12 in NDVI) commonly seen in urban environments were equivalent to approximately 2 to 2.5

years of age-related behavioral maturation. The observed associations could not be explained by sociodemographic factors or neighborhood quality, remained statistically significant even after accounting for the observed temperature effects, and were not sensitive to the further adjustment of traffic density, proximity to freeways and roads, neighborhood socioeconomic characteristics, maternal smoking during pregnancy, or maternal depression. Furthermore, we found no evidence of effect modification by sociodemographic factors or neighborhood quality, suggesting the universal benefits of neighborhood greenspace.

Our study findings, if replicated by others, will have important public health and clinical implications. Our analyses reveal the first observational evidence for the NDVI-reduced aggressive behavior in adolescents, and provide a rationale for studies of interventions to improving greenspace in residential neighborhoods. In our sample, living within close proximity to a park, golf course, or field, in comparison to residing in a location surrounded by other housing, shopping centers, or freeways, was equivalent to having an increased NDVI associated with a 0.36 to 0.41 reduction in aggressive behavior scores. Although considered a small change at the individual level, this observed decrease of aggressive behaviors associated with increasing neighborhood greenspace can translate to a significant public health impact when viewed at the population level. There are an estimated 3.5 million adolescents in California, and approximately 95% of California residents are located within urban areas. According to Achenbach and Rescorla, a CBCL raw score 2 standard deviations above the mean represents a clinically significant level of aggressive behavior. In our sample, mean raw scores were 4.86 (SD = 5.03), similar to what was found in previous studies. Assuming this mean score for urban-dwelling adolescents in California (n = 3.3 million), an estimated 74,036 would present aggressive behavior scores above the clinical range; however, a 0.4-point drop in scores would shift this mean to 4.46, and the number of clinically significant individuals would decrease by approximately 9,000 (12%) in California adolescents alone. Furthermore, these results may even have implications on adult behavior, as one study found that CBCL-measured raw aggressive behavior scores above the clinical/deviant cut-off at ages 12–16 strongly predicted externalizing behavior (aggressive and delinquent behaviors) at a follow-up assessment 14 years later (odds ratio = 2.3; 95% CI: 1.5, 3.7). Collectively, these findings underscore the societal impact of increasing neighborhood greenspace even by the range of vegetation (~0.12 of NDVI) commonly seen in urban environments.

Although the underlying mechanism is not fully understood, we propose several possible pathways that may explain the relationship between greenspace and aggressive behaviors. First, many studies suggest maternal stress and depression increase externalizing behavioral problems in children, and exposure to greenspace can improve mental health by reducing stress levels and lowering depression. Second, low self-esteem is related to aggressive behavior in children and adolescents, and intervention studies have found that greenspace improvements encourage participation in physical activity and that increased physical activity improves self-esteem. Third, recent epidemiological studies suggest that ambient air pollution and ambient noise could possibly increase aggressive behavior, and greenspace may reduce air pollution levels and act as a buffer for ambient noise. Fourth, many organisms important for immunoregulatory mechanisms and brain development are almost completely eliminated from urban environments, but greenspace in urban areas preserves the microbial biodiversity needed to drive immunoregulation and optimize brain health. Because there are likely many possible pathways involved, mediation analyses are needed to identify the exact mechanism by which greenspace may reduce aggressive behavior.

Our study findings also have important implications for future research on environmental epidemiology of aggressive behavior in urban-dwelling populations. As mentioned earlier, previous studies primarily focused on studying social environments, and our literature search (see Table S1, available online) revealed 19 peer-reviewed publications (with 7 observational studies, all cross-sectional) investigating physical characteristics of ambient environments (e.g., meteorological factors, ambient air pollution, and ambient noise) and aggressive behaviors. Previous experimental studies have produced inconsistent results on the relationship between aggressive behavior and short-term temperature, and no studies have investigated the long-term effects of temperature. Only one cross-sectional study examined the association between self-reported noise exposure and aggression, and investigators found that low-frequency, high-intensity, and continuous noises were associated with higher displaced aggression scores. However, their results might be biased due to unmeasured confounding by SES or residential greenspace. Lastly, three epidemiologic studies with cross-sectional analyses reported provocative findings suggesting the adverse effects of ambient air pollution on aggressive behavior.– However, it was unclear if the reported associations were confounded by neighborhood greenspace. The scant literature likely reflects one major methodological challenge in differentiating the isolated effect of these potential environmental determinants of aggressive behaviors, as unfavorable characteristics of ambient environments are inter-correlated with each other (e.g., highest traffic density and nearest to major roads in locations with the lowest NDVI as shown in Table 1). In this study we were able to adjust for indicators of neighborhood noise and ambient temperature, and our sensitivity analyses showed that the relationship between neighborhood greenspace and aggressive behaviors could not be explained by these other environmental factors, which strengthened our findings. Environmental epidemiology studies investigating the neurotoxic effect of air pollution on aggressive behaviors will need to address the potential confounding by neighborhood greenspace and temperature, which correlate with ambient air pollution levels.

We recognized a few limitations in our study. First, aggressive behaviors were assessed using the parent-reported version of the CBCL. Parents are aware of their child’s behavior primarily in home environments and may not be as familiar with their child’s behaviors in other social settings. Although a self-reported version of the CBCL (the Youth Self Report) was available, it is not validated for ages 10 and under and was only administered after wave 3 (ages 14–15 years old), making it unsuitable for the present study focused on longitudinal analyses from ages 9–18. Second, neighborhood greenspace exposures were assigned using NDVI as a proxy. Although NDVI has been validated as a useful measure of neighborhood greenspace for epidemiologic research, our study is still subject to exposure measurement errors. However, the expected non-differential measurement errors in using NDVI to assess neighborhood greenspace would likely have attenuated the observed associations. Third, we had conducted several sensitivity analyses to further adjust for other correlated spatial covariates, but we could not rule out the possibility of unmeasured or residual confounding contributed by other environmental determinants of aggressive behaviors. For instance, although our reported association was not confounded by nSES, which is a strong predictor of neighborhood violence and crime,[,] our analyses could not adjust for neighborhood crime rates; as such, uniform data were not available across the Southern California communities. Fourth, the plausible mediating role of physical activities could not be explored in this study because such data were not available. Lastly, our analyses only include the Aggressive Behavior subscale as a global measure. Built on the novel association we discovered, future studies should explore the possible influences on the subtypes of aggression that are relevant to child psychiatry.[,] The major strengths of this study are the longitudinal study design, the extended follow-up from late childhood through adolescence, the large sample size, and the detailed investigation of the effects of neighborhood greenspace by testing various spatiotemporal scales of NDVI exposure.

In summary, this study provided the first epidemiological evidence supporting the hypothesized beneficial impact of neighborhood greenspace on aggressive behaviors in urban-dwelling adolescents, with consistent effects observed for both short- and long-term exposures. Future studies are needed to replicate our findings in other population settings and to identify mechanisms by which greenspaces may reduce aggressive behavior. If substantiated in other studies, these results should motivate community-based interventions to determine the effectiveness of greenspace as a preemptive strategy to reduce aggressive behavior in urban environments.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work was supported by the National Institute of Environmental Health Sciences (NIEHS; R21 ES022369 and F31 ES025080) and the Southern California Environmental Health Sciences Center (5P30ES007048). The USC Twin Cohort Study is funded by the National Institute of Mental Health (NIMH; R01 MH058354). The contents of this manuscript are solely the responsibility of the authors and do not necessarily represent the official views of the National Institutes of Health (NIH).

The authors thank the staff and participants of the USC Twin Cohort Study for their time and effort, as well as Xinhui Wang, PhD, of Kaiser Permanente Southern California, for her helpful advice on developing the figures.

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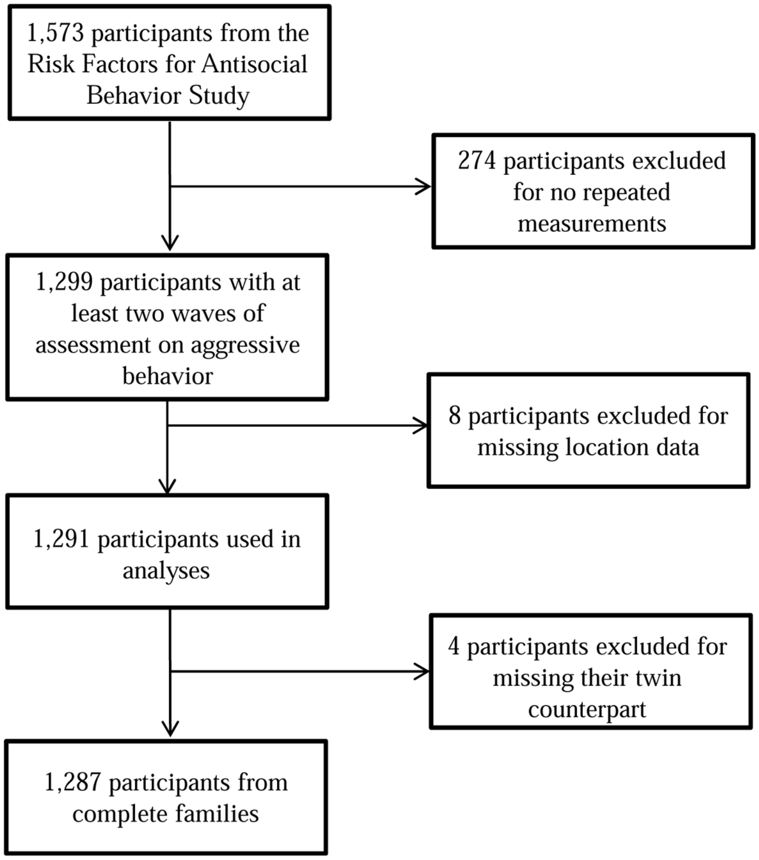

Figure 1.

Study flow chart.

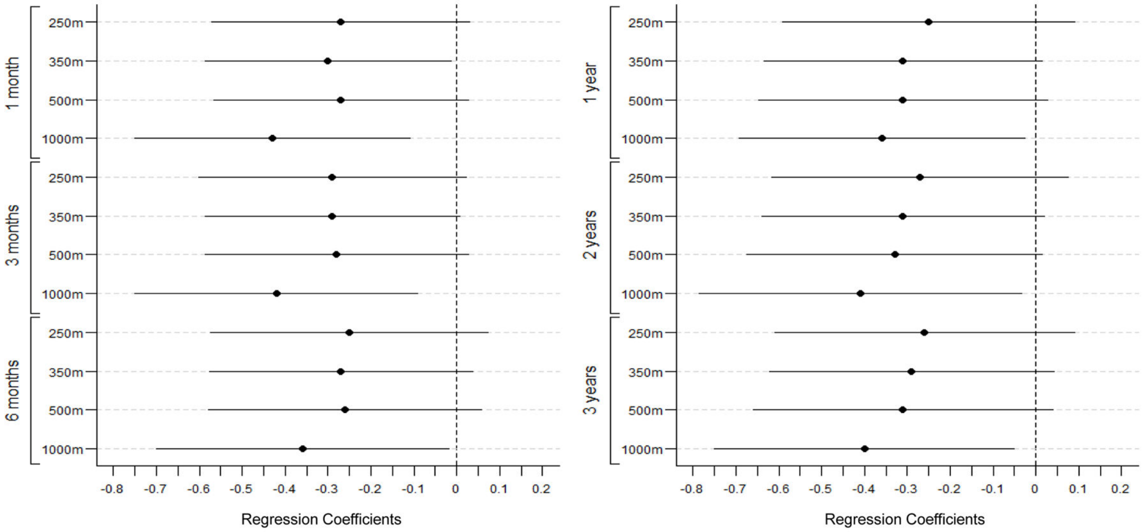

Figure 2.

Estimated effects on aggressive behaviors associated with short-term (1–6 months) and long-term (1–3 years) Normalized Difference Vegetation Index within residential neighborhood of different buffer sizes (250-, 350-, 500-, 1000-m). Note: All models were conditioned on age, gender, ethnicity, household socioeconomic status, neighborhood quality, and temperature (linear term for short-term; quadratic terms for long-term). Symbols (bars) represent regression coefficients (95% CIs) given by multilevel mixed-effects models adjusting for both within-family and within-individual correlations.

Table 1

Population Characteristics in Relation to Average Normalized Difference Vegetation Index in a 1000-Meter Buffer Surrounding Residences 6 Months Prior to Baseline (n = 1,287[a])

Population Characteristics	**Quartile of NDVI**								
	0.15–0.27 Median = 0.24 (n = 321)		**0.27–0.31 Median = 0.29 (n = 322)**		**0.31–0.37 Median = 0.34 (n = 323)**		**0.37–0.62 Median = 0.42 (n = 321)**		
	n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**p-value[b]**
Gender									.081
Male	141	22.4	174	27.7	155	24.6	159	25.3	
Female	180	27.4	148	22.5	168	25.5	162	24.6	
Ethnicity									<.001
Caucasian	36	9.0	65	16.3	115	28.8	184	46.0	
Hispanic	178	39.9	127	28.5	90	20.2	51	11.4	
Black	60	38.0	62	39.2	26	16.5	10	6.3	
Mixed	41	18.2	62	27.6	64	28.4	58	25.8	
Other or missing	6	10.3	6	10.3	28	48.3	18	31.0	
Maternal smoking during pregnancy									<.001
No	276	23.8	286	24.9	297	25.7	295	25.5	
Yes	24	35.3	26	38.2	4	5.9	14	20.6	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**p-value[c]**
Age	10.61	2.14	10.64	2.13	10.85	2.15	10.44	1.91	.103
Household socioeconomic status	36.57	10.95	39.84	11.38	44.60	9.84	49.07	9.77	<.001
Neighborhood quality	31.35	11.68	28.25	10.75	25.33	8.38	23.83	5.63	<.001
Proximity to freeways (meters)	1562.88	1472.04	1817.81	1367.03	1797.74	1509.73	2365.44	2299.42	<.001
Proximity to roads (meters)	3807.74	2960.79	4084.46	3128.72	4609.49	3821.96	4745.55	3034.30	<.001
Traffic density in 150 meter area	98.42	213.59	66.50	128.35	65.12	132.87	44.92	98.29	<.001
Traffic density in 300 meter area	119.42	195.86	79.26	113.11	72.18	114.30	49.22	84.96	<.001
Temperature 6-months prior (°C)	17.24	2.42	17.02	2.26	17.84	2.30	16.76	2.70	<.001
Relative humidity 6-months prior (%)	62.48	8.92	63.85	8.43	63.50	9.04	60.33	8.03	<.001

Note: NDVI = Normalized Difference Vegetation Index; SD = standard deviation

[a] Total number of subjects decreases slightly due to missing values

[b] P-value for Pearson χ^2 test comparing the distribution of NDVI across population characteristics

[c] P-value for analysis of variance test comparing means of population characteristics for quartile of NDVI

Table 2

Population Characteristics in Relation to Raw Aggressive Behavior Scores at Baseline (n = 1,287[a])

Population Characteristics	**Levels of Raw Aggressive Behavior Scores**								
	0.00–1.00 Median = 0.00 (n = 310)		**2.00–4.00 Median = 3.00 (n = 383)**		**4.21–7.37 Median = 6.00 (n = 265)**		**8.00–39.00 Median = 11.00 (n = 329)**		
	n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**p-value[b]**
Gender									.002
Male	126	20.0	183	29.1	141	22.4	179	28.5	
Female	184	28.0	200	30.4	124	18.8	150	22.8	
Ethnicity									.273
Caucasian	102	25.5	111	27.8	82	20.5	105	26.3	
Hispanic	103	23.1	133	29.8	92	20.6	118	26.5	
Black	28	17.7	55	34.8	36	22.8	39	24.7	
Mixed	61	27.1	69	30.7	37	16.4	58	25.8	
Other or missing	16	27.6	15	25.9	18	31.0	9	15.5	
Maternal smoking during pregnancy									<.001
No	278	24.1	352	30.5	243	21.0	283	24.5	
Yes	7	10.3	13	19.1	15	22.1	33	48.5	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**p-value[c]**
Age	11.10	2.31	10.55	2.03	10.57	2.06	10.35	1.87	<.001
Household socioeconomic status	43.93	11.32	42.74	11.52	41.72	12.00	41.58	11.18	.041
Neighborhood Quality	25.27	8.49	27.43	10.41	28.09	10.24	27.99	9.75	.001
Proximity to freeways (meters)	1913.88	1791.49	1850.44	1820.47	1959.68	1683.31	1840.92	1582.95	.814
Proximity to roads (meters)	4302.15	3361.64	4410.80	3161.94	4306.15	3372.88	4211.35	3249.28	.882
Traffic density in 150 meter area	66.29	114.38	67.12	150.07	63.78	158.17	76.91	173.31	.710
Traffic density in 300 meter area	74.20	113.58	79.87	143.23	73.83	129.24	90.61	150.54	.374
Temperature 6-months prior (°C)	17.10	2.55	17.24	2.44	17.09	2.40	17.40	2.43	.354
Relative humidity 6 months prior (%)	61.81	8.34	62.81	8.44	63.18	8.72	62.41	9.34	.259

[a] Total number of participants decreases slightly due to missing values

[b] P-value for Pearson χ^2 test comparing the distribution of aggressive behavior scores across population characteristics

[c] P-value for analysis of variance test comparing means of population characteristics for quartile of aggressive behavior scores

Table 3

Associations[a] of Reduced Aggressive Behaviors and Residential Neighborhood Green Space in a 1000-Meter Buffer

	Short-Term						Long-Term					
	1 Month Prior		3 Months Prior		6 Months Prior		1 Year Prior		2 Years Prior		3 Years Prior	
Models[b]	**β**	**95% CI**	**β**	**95% CI**	**β**	**95% CI**	**β**	**95% CI**	**β**	**95% CI**	**β**	**95% CI**
Crude	−0.36[l]	−0.64, −0.08	−0.37[l]	−0.66, −0.09	−0.32[l]	−0.62, −0.03	−0.26	−0.55, 0.03	−0.26	−0.59, 0.07	−0.32[l]	−0.62, −0.01
Adjusted I[c]	−0.51[l]	−0.83, −0.20	−0.52[l]	−0.84, −0.20	−0.46[l]	−0.79, −0.12	−0.35[l]	−0.68, −0.02	−0.39[l]	−0.77, −0.01	−0.37[l]	−0.72, −0.02
Adjusted II[d]	−0.43[l]	−0.75, −0.11	−0.42[l]	−0.75, −0.09	−0.36[l]	−0.71, −0.02	−0.36[l]	−0.69, −0.02	−0.41[l]	−0.79, −0.04	−0.40[l]	−0.75, −0.05
Sensitivity Analyses												
I[e]	−0.45[l]	−0.77, −0.13	−0.43[l]	−0.76, −0.10	−0.37[l]	−0.71, −0.03	−0.36[l]	−0.69, −0.03	−0.41[l]	−0.79, −0.03	−0.39[l]	−0.74, −0.04
II[f]	−0.43[l]	−0.75, −0.11	−0.42[l]	−0.75, −0.09	−0.36[l]	−0.70, −0.02	−0.35[l]	−0.69, −0.01	−0.40[l]	−0.78, −0.03	−0.39[l]	−0.75, −0.04
III[g]	−0.42[l]	−0.74, −0.10	−0.41[l]	−0.74, −0.08	−0.36[l]	−0.70, −0.02	−0.35[l]	−0.68, −0.02	−0.41[l]	−0.79, −0.03	−0.39[l]	−0.74, −0.04
IV[h]	−0.42[l]	−0.74, −0.10	−0.41[l]	−0.74, −0.08	−0.35[l]	−0.69, −0.01	−0.34[l]	−0.67, −0.01	−0.40[l]	−0.77, −0.02	−0.38[l]	−0.73, −0.03
V[i]	−0.42[l]	−0.74, −0.09	−0.43[l]	−0.76, −0.09	−0.38[l]	−0.73, −0.03	−0.37[l]	−0.71, −0.03	−0.45[l]	−0.93, −0.07	−0.44[l]	−0.80, −0.09
VI[j]	−0.46[l]	−0.79, −0.12	−0.45[l]	−0.79, −0.10	−0.39[l]	−0.75, −0.03	−0.38[l]	−0.74, −0.03	−0.43[l]	−0.83, −0.03	−0.39[l]	−0.77, −0.02
VII[k]	−0.44[l]	−0.76, −0.12	−0.42[l]	−0.75, −0.09	−0.37[l]	−0.71, −0.03	−0.36[l]	−0.70, −0.03	−0.42[l]	−0.80, −0.04	−0.40[l]	−0.75, −0.05

[a] expressed as the regression coefficient (β) and 95% CI per interquartile-range increase in Normalized Difference Vegetation Index

[b] n = 1,287 from 640 families included in mixed-modeling analyses except for sensitivity analyses V (n = 1,224 from 609 families) and VII (n = 1,253 from 623 families)

[c] Model was adjusted for age, gender, ethnicity, household socioeconomic status, and perceived neighborhood quality

[d] Adjusted I + temperature (linear term for short-term; quadratic terms for long-term)

[e] Adjusted II + proximity to freeways

[f] Adjusted II + proximity to roads

[g] Adjusted II + traffic density in 150-m area

[h] Adjusted II + traffic density in 300-m area

[i] Adjusted II + maternal smoking during pregnancy

[j] Adjusted II + neighborhood socioeconomic characteristics

[k] Adjusted II + maternal depression

[l] $p<.05$ for Normalized Difference Vegetation Index effect by the Wald test