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ORIGINAL ARTICLE

Relationship Between Neighborhood Poverty and Externalizing Symptoms in Children: Mediation and Moderation by Environmental Factors and Brain Structure

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Abstract
Children living in poverty exhibit worse mental health outcomes, and various environmental and neurological risk factors may contribute to or mitigate this relationship. However, previous research has not examined the interplay of neighborhood SES, mental health, and relevant mechanisms. We examined the extent to which neighborhood poverty uniquely contributes to children's internalizing/externalizing disorder symptoms, as well as identified whether brain measures, toxin levels, and neighborhood threat mediated this relationship and whether socioemotional support moderated it. Data were collected from 8623 9–10 year olds as part of the Adolescent Brain Cognitive Development study. Using a secondary data analysis, we found that neighborhood poverty was positively associated with externalizing symptoms and mediated by reduced intracranial volume and parents/children reporting feeling less safe. Parental support (i.e., Parental Monitoring Survey) attenuated this link, but only for children lower in poverty. Consideration of these risk factors for psychopathology could improve the outcome of holistic interventions.

Keywords Early life adversity · Neighborhood poverty · Children's internalizing · Externalizing disorders · Brain development · Socioemotional support

Introduction

The dynamics of a person's childhood can either promote or impede healthy childhood development. For example, children may experience early life adversity, characterized by negative environmental experiences that represent a deviation from the expectable environment [1]. These negative experiences require significant adaptation by the child and can detrimentally affect the child's cognitive [2], emotional [3], and neural [4] development. These negative environmental experiences can be at the family [5] or neighborhood [6] level and may contribute to the onset of psychopathology. Poverty as a form of socioeconomic adversity has a proximate and direct influence on children's lives and developmental outcomes. Even so, while other studies have examined the association between neighborhood socioeconomic status (SES) and mental health, fewer studies have examined possible mediating mechanisms between the two.

Previous literature has linked the experience of household poverty to poorer physical health [7], structural changes during brain development [8], and hindered educational attainment [9]. These negative implications are widespread, affecting multiple developmental domains. Taking the broader impacts of poverty at the neighborhood level into consideration can reveal negative outcomes not reflected at the individual household level. A recent study found that neighborhood poverty was related to decreased performance on cognitive tests in ways that are dissociable from household income [10] while another study found that neighborhood poverty was associated with increased allostatic load in African American youth [11]. This body of work indicates that facets of a child's larger environment may play a role in determining healthy development across numerous domains.

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Although the neighborhood context is a promising avenue for examining broader influences on children's development, other unmeasured individual characteristics may also lead someone to live in a more impoverished neighborhood than a different person with an identical income would. In particular, the United States' history of racism and discrimination affects minority individuals in many aspects of life, including housing. Factors such as structural inequalities (e.g., redlining) might explain a difference in variance between neighborhood socioeconomic status (SES) and family income. These neighborhood-level factors may impact individuals' ability to choose where to live in ways that may not be fully explained by family income alone. Our interest in examining the contributions of the neighborhood context above and beyond the immediate family situation is motivated by the longstanding and specific U.S. racial climate that contributes to factors that impact the neighborhoods to which families have access, including racial and ethnic identities.

One domain that may be impacted by neighborhood poverty is youth risk for psychopathology—specifically, internalizing and externalizing disorder symptoms. Internalizing and externalizing behaviors involve emotional and behavioral problems such as anxiety, depression, and worry (internalizing) and hyperactivity, aggression, and attention problems (externalizing). Children who exhibit these symptoms in childhood may be more likely to develop severe psychopathology later in life. For example, children who frequently internalize problems in childhood have increased risk for depressive and avoidant personality problems in adulthood. In contrast, children who tended to externalize problems had increased risk for ADHD, antisocial personality, and substance use problems in adulthood [12]. An increased prevalence of these symptoms has also been observed among youth living in more impoverished households, with persistent and recent poverty being linked to children's internalizing/externalizing behaviors [13]. These data suggest that psychopathology is one of many possible outcomes of underprivileged circumstances.

Impaired neural development may, in part, mediate the association between poverty and developmental outcomes. Growing evidence suggests that socioeconomic adversity produces lasting neurobiological changes, as childhood chronic stress exposure affects the structure and function of brain areas that are important for emotion regulation processes [14]. This may be due to correlates of poverty such as chronic stress, tense familial dynamics, or exposure to crime, which may induce unhealthy levels of stress that disrupt emotion regulation and coping. These neurobiological changes may be implicated in the development of psychopathology, as internalizing and externalizing type disorders are most commonly related to reduced amygdala and dorso/ventrolateral prefrontal cortex volumes [15]. Because the amygdala is involved in emotion and fear detection and the prefrontal cortex is largely implicated in executive functioning, inhibitory control, and emotion regulation, alterations of these structures' volumes could manifest in worsened mental health outcomes.

Differences in certain brain white matter tracts such as the uncinate fasciculus and bilateral cingulum may also mediate the relationship between conditions of poverty and psychopathology. Both the uncinate fasciculus and cingulum are tracts connecting pathways of limbic networks; the uncinate fasciculus connects the temporo-amygdala-orbitofrontal network and is involved in emotion regulation/impulsivity while the cingulum connects prefrontal to limbic regions and is involved in emotional processing and goal-directed tasks [15]. Prior research has found that lower family income was associated with lower white matter organization as indicated by fractional anisotropy (FA) values of the uncinate and cingulum bundle [16]. Maladaptive neural outcomes such as these may play a role in determining a child's risk for emotional and behavioral problems. For example, internalizing behaviors have been positively associated with mean diffusivity of the cingulum and externalizing behaviors were negatively associated with FA values of both the left cingulum and uncinate [15]. Proper maturation of these areas is necessary for the ability to engage in healthy emotion functions (e.g., emotion regulation, inhibition); defective maturation of these areas may be relevant to the development of internalizing/externalizing problems.

Lower quality environmental standards seen in impoverished neighborhoods may confer risk for disruptions in behavior and the brain. Toxins such as particulate matter ($pm_{2.5}$), nitrogen dioxide (NO_2), and lead are present in higher levels in poor compared to more affluent neighborhoods. This is likely because poorer neighborhoods tend to be situated closer to highways (i.e., higher air pollution) and tend to have older lead-based paint. Exposure to higher levels of toxins can have detrimental effects on children's brain development, including decreased adult brain volume in regions responsible for executive functioning and mood regulation, such as the prefrontal cortex and anterior cingulate cortex [17]. This is thought to occur through disrupted dopaminergic functioning that results in necrosis and apostosis, but children's vulnerability to other lead-impaired neurodevelopmental processes may also be explained by its ability to mimic calcium and zinc, cross the blood brain barrier, suppress neurotransmission, reduce astroglial function, and delay synaptic pruning [18]. Moreover, increased levels of lead in maternal and preschool aged children's blood can induce neurological effects that impair children in domains of learning and executive functioning. Lead disrupts neuronal myelination, an important component of gray and white matter development in early childhood. In turn, the decreased efficiency of communication between neurons

invokes poorer impulse control, with the potential for worsened behavioral problems such as increased aggression and delinquency [19]. The detrimental effects of toxins on brain development likely contributes to the association between neighborhood poverty and psychopathology.

Another potential mechanism underlying the association between neighborhood poverty and children's psychopathology may be exposure to crime, which is often more prevalent in impoverished neighborhoods. The presence of crime in one's neighborhood may augment children's feelings of fear and distress, contributing to an increased risk for anxiety and depressive symptoms [20]. Hypervigilance in connection to perception of safety may also lead individuals to respond to threats in a hostile way, resembling externalizing-type behaviors [21]. Therefore, neighborhood threat may also contribute to children's risk for developing internalizing and externalizing disorder symptoms.

The presence of social or emotional support can potentially moderate the otherwise negative impact of neighborhood poverty on children's mental health. At the neighborhood level, children may receive positive encouragement from sources that extend beyond their immediate family dynamic, for instance from peers or school. Previous literature has found that the highest levels of allostatic load occurred for youth who lived in more impoverished neighborhoods, but only in the context of low emotional support [11]. Similarly, high neighborhood cohesion was found to attenuate the association between neighborhood discrimination and adolescents' externalizing symptoms, suggesting that receipt of socioemotional support may improve youth adjustment [22]. Research in this realm has begun to demonstrate the protective effects of receiving socioemotional support from others, and this dimension of resiliency may help buffer maladaptive development in youth.

In this study, we examined the unique associations of neighborhood poverty to children's psychopathology. We sought to identify potential mediator and moderator variables associated with this relationship—including brain structure volumes, the structural integrity of white matter tracts, environmental toxins, neighborhood threat, and receipt of socioemotional support. Combining the individual findings of related studies will allow us to test a more holistic model of the interrelatedness of neighborhood poverty, neural development, environmental risk factors, and psychopathology. This study can help elucidate the broader influences of early life adversity on development and can inform interventions designed to reduce the burden of mental illness.

The current study tests the hypothesis that exposure to neighborhood poverty increases children's risk for psychopathology later in life. We predicted that: (1) living in more impoverished neighborhoods will be associated with increased internalizing and externalizing disorder symptoms, even after accounting for individual household income; (2) increased toxin levels will be associated with reductions in the brain volumes of the amygdala, dorsolateral and ventrolateral prefrontal cortex and decreased diffusivity of the uncinate and cingulum. This, in turn, will plausibly serially mediate the relationship between increased neighborhood poverty and increased internalizing/externalizing symptoms; (3) increased neighborhood threat as reflected by higher crime rates/lower feelings of safety will plausibly mediate the relationship between increased neighborhood poverty and increased internalizing/externalizing disorder symptoms; (4) receipt of socioemotional support will moderate this relationship such that increased neighborhood poverty will be more strongly associated with increased internalizing/externalizing symptoms in the context of low socioemotional support. Figure 1 illustrates the full model that will be tested, including the direct relationship between neighborhood poverty and children's internalizing/externalizing disorder symptoms and the indirect pathways of the various mediator variables and the moderator.

Method

Participants

This study included 8,623 participants, all of whom were children between 9–10 years old at the baseline assessment ($M_{age} = 9.92$ years, $Range_{age} = 2.5$ years). The study featured 4,111 females, 4,509 males, and 3 children who did not report either sex. Of these participants, 53% identified as White, 14% identified as Black, 20% identified as Hispanic, 2% identified as Asian, 11% identified as Other, and eight children did not report any race/ethnicity. This study is a secondary data analysis using data from the Adolescent Brain Cognitive Development (ABCD) study's 2.0.1 release. ABCD is a national collaboration between different universities and research centers, spanning 21 locations across the United States. It is a representative study that reflects the sociodemographic variation of the U.S. population and includes individuals at high risk for the variety of negative outcomes being studied. Additionally, ABCD uses procedures such as a multi-stage probability sample that minimizes issues of systemic sampling biases in recruitment [23]. Participants were selected via school-based recruitment whereby ABCD researchers reached out to several schools within close proximity to each research site. Information packets about the study were provided to 8–10 year old students through the form of school folders, postal mail, or email lists and interested families were then contacted by a researcher to determine eligibility and proceed with enrollment. Compensation for participants was determined per study site based on the cost of living for the area.

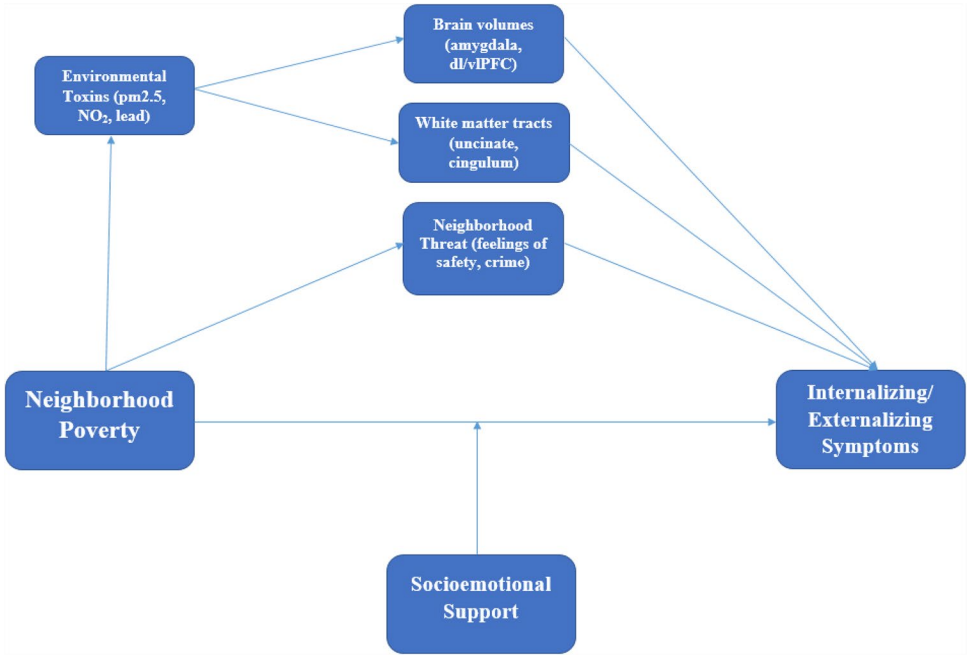

Fig. 1 Model for mediations and moderation on the link between neighborhood poverty and children's psychopathology. Model illustrating the mediation pathways between neighborhood poverty, the various mediator variables (environmental toxins, brain volumes, white matter tracts, neighborhood threat), and internalizing/externalizing disorder symptoms. Includes the moderation of socioemotional support on the link between neighborhood poverty and psychopathology

Approximately 11,878 children take part in ABCD, but, for the purposes of the current study, 3,255 children were excluded given missing data for neighborhood poverty, parent income, and/or internalizing/externalizing behaviors. In terms of non-responders differing from those included in the analyses, we observed that slightly more Black youth had missing data for neighborhood poverty and family income, while slightly more White youth were not missing data for either of these variables. However, these effect sizes are relatively small and modestly significant even with a large sample size. See Supplemental Tables 1–7 for information on missingness.

Design

The goal of ABCD is to study trajectories of change throughout adolescence. More specifically, ABCD aims to understand how "childhood experiences (e.g., sports, video games, social media, unhealthy sleep patterns, and smoking) interact with each other and with a child's changing biology to affect brain development and social, behavioral, academic, health, and other outcomes [24]." ABCD is intended to last 10 years and follows participants according to a longitudinal design; full assessments—including questionnaires, brain imaging, cognitive tests, etc.—occur every two years while briefer assessments occur in the intermediate years. Every three to six months, brief follow-ups are conducted online or by phone. The current study examines data collected at the baseline assessment. Although ABCD is an ongoing longitudinal study, the current study only utilized baseline data due to practical constraints on the availability of data. In order to conduct a full causal mediation, we would ideally have three time points of complete brain measure and internalizing/externalizing behavior data. At the time of analyses, a second time point with a complete wave of imaging data coincident with psychiatric outcomes was not yet available and a third time point of imaging data will not be available for one to two more years.

Measures

Neighborhood Poverty

Neighborhood poverty is a composite measure consisting of nine census-tract variables from the Area Deprivation Index (ADI), which were assessed through residential history questionnaires administered through ABCD [25]. The nine variables included percent of labor force > 16 years unemployed, percentage of families below the poverty level, percentage of population below 138% of the poverty threshold, percent of single parent households, percentage of occupied housing units without a motor vehicle, percentage of population aged > / = 25 with at least a high school diploma, percentage of homeowners, median family income, and income disparity. All nine variables had been included in an exploratory factor analysis using the factoanal() function in R to determine how correlated each variable was with the overarching construct of neighborhood poverty. Using participants' home addresses, 17 ADI values were factor analyzed; our final measure of neighborhood poverty consisted of 9 of the 17 ADI values with the strongest factor loadings (> 0.70)

[10]. Full factor analysis results are reported in Supplemental Table 8.

Individual Household Income

Household income was calculated using combined income of the primary caretaker and any additional household members.

Internalizing/Externalizing Disorder Symptoms

The validated Child Behavior Checklist (CBCL) was administered to each participant to gauge internalizing/externalizing disorder symptoms and was parent-reported. This report is intended to assess potential emotional and behavioral problems in children and is part of the Achenbach System of Empirically Based Assessment (ASEBA) [26]. The CBCL yields eight subscales, namely anxiety, depression, somatic complaints, social problems, thought problems, attention problems, rule-breaking behavior, and aggressive behavior. For the purposes of the current study, multiple subscales were combined to form a "broad" composite measure of internalizing and externalizing symptoms; internalizing behaviors consisted of anxiety, depression, and worry subscales whereas externalizing behaviors were grouped by the hyperactivity, non-compliance, and attention problem subscales.

Brain Imaging Procedures

The volumes of brain structures of interest and the structural integrity of white matter tracts were obtained through magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI), respectively. This study looked at amygdala, dorso- and ventrolateral prefrontal cortex (dl/vlPFC), and intracranial volume; for each brain region, the two hemispheres' volumes were correlated to determine whether they should be combined or kept separate due to potential evidence of lateralization. Only the dlPFC was combined into a composite volume ($r = 0.75$). Additionally, FA values were obtained to assess the structural integrity of the uncinate and cingulum white matter tracts. Imaging procedures were harmonized across the 21 ABCD study sites and used three 3 T scanner platforms with a standard adult size coil—Siemens Prisma, General Electric 750, and Philips. During structural imaging scans, children either viewed a movie or looked in the direction of a fixation crosshair. 3D T1-weighted gradient echo scans were obtained for the brain structures of interest and high angular resolution diffusion imaging scans were obtained for measuring the structural integrity of white matter tracts. Motion detection and correction technologies were used to account for potential concerns with imaging children [27].

Environmental Toxins

Toxin level estimates for particulate matter, nitrogen dioxide, and lead risk were calculated using participants' home addresses [28]. Particulate matter indexes air pollution from a variety of sources (e.g., factory emissions) and refers to the finest grain particles (2.5 μm) that are inhalable. An annual average of daily particulate matter 2.5 was assessed at 1 km^2 spatial resolution. Nitrogen dioxide levels are primarily assessed from the burning of fuel, particularly car emissions, and were obtained from the NASA Socioeconomic Data and Applications Center (SEDAC) based on satellite reports with a resolution of 100 km^2. Finally, lead exposure risk is derived from lead-based paint and is a more liberal measure that includes families below 125% of the poverty threshold. Participant addresses were geocoded at the census-tract level and then lead risk scores ranging from 1 to 10 (10 being the most severe) were calculated based on data from vox.com (https://www.vox.com/a/lead-exposure-risk-map). Correlations between each of the toxin variables were similarly moderate; nitrogen dioxide and particulate matter were correlated at $r = 0.39$, nitrogen dioxide and lead risk were correlated at $r = 0.38$, and particulate matter and lead risk were correlated at $r = 0.26$. The three toxin variables were aggregated into a composite toxins measure.

Neighborhood Threat

Neighborhood threat was created as a construct that encompassed perception of crime and objective crime rates. Perception of crime involved parent- and child-reported answers to the ABCD Parent (or Youth) Neighborhood Safety/Crime Survey that assessed feelings of safety. The parent-reported version featured three questions to which responses were made on a 1–5 Likert scale of agreement: "I feel safe walking in my neighborhood, day or night," "Violence is not a problem in my neighborhood," and "My neighborhood is safe from crime [29]." On the other hand, the child-reported version featured only the single question of "My neighborhood is safe from crime" on the same response scale. Feelings of safety constituted both the parent- and child-reported measures.

Additionally, objective crime rates were measured by the Uniform Crime Reports database. Participants' zip codes were used to generate crime rates at their specific county level that included total adult offenses such as drug sale and possession, adult violent crimes (burglary, murder, rape), and DUI's. Correlations among the three neighborhood threat variables indicated that none of the variables were strongly related enough ($r = 0.29$) to justify aggregating them into a composite measure for analyses.

Receipt of Socioemotional Support

Socioemotional support sought to capture sources of support beyond the nuclear family household—namely from parents, peers, and school—and was assessed through ABCD questionnaires administered to child participants [29]. Parent support is assessed by both the 18-item Family Environment Scale (youth and parent reported) [30] and the 5-item Parental Monitoring Survey (youth reported) [31] that asks questions such as "We fight a lot in our family" and "How often do your parents know where you are?," respectively. The Family Environment Scale uses true/false options in which the number of "true" responses are summed while the Parental Monitoring Survey uses the 5-point Likert scale ranging from 1 ("Never") to 5 ("Always or Almost Always"). Peer support is assessed by two questions from the Resilience Questionnaire [29], specifically "How many close friends do you have that are girls?" and likewise for close friends that are boys. Lastly, school support is assessed by the 12-item School Risk and Protective Factors Survey [32] that features questions such as "My teacher notices when I do a good job and lets me know about it" on a 4-point Likert scale ranging from 1 ("Definitely not true") to 4 ("Definitely true"). None of the socioemotional support variables were correlated more than 0.30 and thus were not aggregated into a composite measure.

Statistical Analyses

Generalized Linear Models

Generalized linear models tested for significant associations between all of the individual variables using the lmer function within the lme4 package version 1.1–26 in R; analyses are nested by site ID to only include one child per family and all variables are standardized prior to computing analyses. Direct relationships between the predictors of neighborhood poverty and household income and the outcome variables of internalizing and externalizing disorder symptoms were first established. We then determined whether neighborhood poverty was significantly related to internalizing and externalizing behaviors after accounting for household income in the model. Covariates included sex and age in months.

Individual relationships between neighborhood poverty and each of the mediator variables (brain volumes, white matter tracts, toxins, neighborhood threat) and between the mediator variables and internalizing/externalizing behaviors were examined using generalized linear models. We determined whether environmental toxins and the brain variables (volumes, white matter tracts) were associated such that they could plausibly serially mediate the relationship between neighborhood poverty and children's psychopathology. All analyses involving specific brain regions and white matter tracts controlled for intracranial volume to ensure that any observed effects are independent of a uniform increase in brain volume. We also corrected for multiple comparisons using a false discovery rate (FDR) test that adjusted the significance threshold for the associations between neighborhood poverty and each group of mediator variables separately (brain measures and neighborhood threat). Based on which variables were still significantly associated with neighborhood poverty, we then implemented FDR corrections for the associations between toxin levels and brain measures and brain measures/neighborhood threat to externalizing symptoms. Finally, FDR corrections were used for each of the interactions between neighborhood poverty and the various socioemotional support moderator variables.

Structural Equation Modeling

If evidence for a potential mediation was supported, structural equation models (SEM) following a Baron and Kenny approach [33] were then used to more explicitly examine indirect pathways acting on the relationship between neighborhood poverty and internalizing/externalizing disorder symptoms. This was accomplished using the lavaan package version 0.6–7 within R including the aforementioned covariates, in addition to intracranial volume for relevant brain measures.

Main Effects and Interaction

Main effects for the relationships of neighborhood poverty and each of the socioemotional support variables (family environment scale—parent and youth, parental monitoring, peer, and school support) to internalizing/externalizing disorders were tested for using linear mixed models. Interaction analyses with the same covariates were then performed to determine whether any of the socioemotional support variables significantly moderated the association between neighborhood poverty and children's internalizing and externalizing symptoms.

Results

Linear Regressions

Neighborhood poverty and household income were strongly negatively correlated ($r = -0.59$, $p < 0.001$), such that lower neighborhood poverty was associated with higher household income.

Neighborhood Poverty and Household Income Predicting Internalizing/Externalizing Disorder Symptoms

Increased neighborhood poverty was a significant predictor of increased externalizing disorder symptoms [*Std.* $b = 0.03$, $t(8100) = 2.03$, $p = 0.04$] after accounting for household income in the model. In contrast, increased neighborhood poverty was significantly associated with decreased internalizing disorder symptoms [*Std.* $b = -0.03$, $t(8067) = -2.07$, $p = 0.04$] after accounting for household income. Because the direction of this relationship contradicted our prediction that higher neighborhood poverty would be related to higher internalizing behaviors, we only examined evidence of a mediation(s) for the relationship between neighborhood poverty and externalizing behaviors.

Neighborhood Poverty and Household Income Predicting Brain Measures

Amygdala Volume Left and right amygdala hemispheres were examined separately. As shown in Table 1, neighborhood poverty independently predicted left, but not right, hemisphere amygdala volume after accounting for household income such that higher neighborhood poverty was related to lower left hemisphere amygdala volume. This result survived FDR correction.

Cortical Volumes Neighborhood poverty was not significantly related to either left or right hemisphere dlPFC and vlPFC volumes (Table 1).

White Matter Neighborhood poverty was significantly and positively related to right hemisphere cingulum structural integrity after accounting for household income, a result that survived FDR correction. However, neighborhood poverty was not significantly related to right or left hemisphere uncinate nor left cingulum FA (Table 1).

Intracranial Volume We also examined whether neighborhood poverty was more broadly related to intracranial volume. Greater neighborhood poverty was significantly related to decreased intracranial volume, a result which survived FDR correction (Table 1).

Neighborhood Poverty and Household Income Predicting Toxin Levels

Toxin levels included particulate matter, nitrogen dioxide, and lead and were aggregated into a composite measure after individual correlation coefficients between the three variables were calculated. Higher neighborhood poverty was significantly related to increased toxin levels after accounting for household income, a result which survived FDR correction (Table 1).

Table 1 Neighborhood poverty predicting potential mediator variables

	Estimate	SE	T	P	FDR-adjusted Q
Brain measures					
RH Amygdala	− .02	0.01	− 1.77	0.08	0.22
LH Amygdala	− .05	0.01	− 3.65	< 0.001***	< 0.001***
RH vlPFC	− 0.00	0.01	− 0.20	0.85	0.85
LH vlPFC	− .01	0.01	− 0.69	0.49	0.67
RH dlPFC	− 0.01	0.01	− 0.63	0.53	0.67
LH dlPFC	− 0.01	0.01	− 0.60	0.55	0.67
RH cingulum	0.05	0.02	2.83	< 0.001***	< 0.001***
LH cingulum	0.03	0.02	1.59	0.11	0.24
RH uncinate	0.02	0.01	1.32	0.19	0.35
LH uncinate	0.00	0.01	0.33	0.74	0.81
Intracranial volume	− 0.11	0.01	− 8.07	< 0.001***	< 0.001***
Toxin levels					
Toxins	0.52	.01	60.64	< 0.001***	N/A
Neighborhood threat					
Parent feelings of safety	− 0.51	0.01	− 36.50	< 0.001***	< 0.001***
Child feelings of safety	− 0.28	0.02	− 18.12	< 0.001***	< 0.001***
Crime rates	0.01	0.00	2.31	0.02*	0.02*

Results for neighborhood poverty predicting each of the brain measures, toxins, and neighborhood threat variables after accounting for household income. Includes false discovery rate (FDR)-adjusted Q values for multiple comparisons

Neighborhood Poverty and Household Income Predicting Neighborhood Threat Variables

Neighborhood threat consisted of parent- and child-reported feelings of safety and objective crime rates. However, the three variables were not aggregated into a composite measure of neighborhood threat because none of the correlations between each of the variables exceeded a value of $r > 0.30$. Higher neighborhood poverty was significantly associated with parents feeling less safe (Table 1). Neighborhood poverty was significantly related to child-reported feelings of safety, with higher neighborhood poverty being associated with children feeling less safe (Table 1). Finally, higher neighborhood poverty was significantly related to higher objective crime rates after accounting for population density (Table 1). All of the aforementioned analyses also accounted for household income in the model and survived FDR correction.

Toxin Levels Predicting Brain Structure Volumes

As part of our model, we examined the relationships between our initial mediator of toxin levels and our subsequent mediators of brain structure volume and white matter tract integrity, but only those that were related to neighborhood poverty. Toxins were not related to left amygdala volume, but were significantly related to FA of the right hemisphere cingulum as well as to intracranial volume, both of which survived FDR correction (Table S9).

Brain Measures Predicting Externalizing Disorder Symptoms

Neither left amygdala volume nor left/right hemisphere cingulum FA were significantly related to externalizing symptoms. However, higher intracranial volume was significantly associated with decreased externalizing behaviors, which survived FDR correction (Table S10).

Toxin Levels Predicting Externalizing Disorder Symptoms

Toxins were not significantly related to externalizing behaviors (Table S10).

Neighborhood Threat Predicting Externalizing Disorder Symptoms

Both parents and children feeling less safe were significantly related to higher externalizing disorder symptoms, which survived FDR correction. Objective crime rates were not significantly related to externalizing symptoms (Table S10).

Mediation Analyses

The Baron and Kenny approach we followed specifies that each individual pathway between the predictor, mediator(s), and outcome variables must be significant in order to proceed with a mediation. To be conservative, we focused on separate mediation analyses of potential mediators that were related to both neighborhood poverty and externalizing symptoms as described above. Based on the linear regression results, we conducted mediation analyses for our brain measures—specifically global intracranial volume, and for neighborhood threat—including both parent- and child-reported feelings of safety, all of which were associated with both neighborhood poverty and externalizing symptoms. In the first mediation analysis, we found evidence for a plausible mediation such that intracranial volume significantly mediated the link between neighborhood poverty and children's externalizing behaviors (Fig. 2). These results support the idea that socioeconomic adversity in childhood may be related to psychopathology through broader alterations in

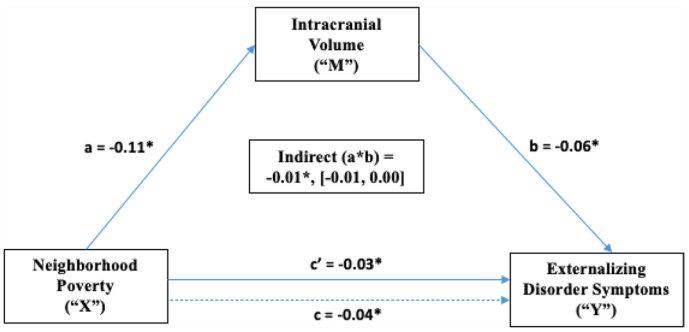

Fig. 2 Mediation for reduced intracranial volume on the relationship between neighborhood poverty and externalizing symptoms. Mediation model depicting estimates for the direct relationships between neighborhood poverty and intracranial volume (path a), intracranial volume and externalizing symptoms (path b), and neighborhood poverty and externalizing symptoms (path c'). Includes the estimate for the total effect (path c) and for the significant indirect effect (a*b) of intracranial volume as a mediator

brain volume rather than being tied to alterations of specific structures.

In the second mediation analysis, parent-reported feelings of safety were significantly associated with neighborhood poverty and with externalizing disorder symptoms; when the indirect effect of parent-reported feelings of safety was considered, the direct effect of neighborhood poverty on externalizing behaviors was no longer significant (Fig. 3; Table S11). Finally, the third mediation analysis indicated that child-reported feelings of safety were significantly associated with neighborhood poverty and with externalizing disorder symptoms; when the indirect effect of child-reported feelings of safety was considered, the direct effect of neighborhood poverty on externalizing behaviors was no longer significant (Fig. 4; Table S11). It may be that an individual's *perception* of safety, as opposed to an objective index of crime rates, comprises a potential mechanism by which neighborhood poverty is associated with externalizing outcomes in children.

There were a number of interesting associations with neighborhood poverty and/or toxin levels that we did not examine further because they did not also relate to clinical outcomes. For example, neighborhood poverty was significantly related to left hemisphere amygdala volume, structural integrity of the right hemisphere cingulum, and toxins, while toxin levels were also significantly related to structural integrity of the right hemisphere cingulum. We chose to focus on analyses that involved a more clinically significant association with externalizing symptoms; nevertheless, there may be other interesting outcomes we did not focus on such as cognition that could be significantly related to neighborhood poverty, toxins, white matter structural integrity, etc.

Moderation Analyses

We examined socioemotional support as a potential moderator of the relationship between neighborhood poverty and children's externalizing problems; socioemotional support included sources at the parent, peer, and school level. Each of the variables comprising socioemotional support were analyzed separately given that the highest correlation between any two of the variables had an *r*-value of

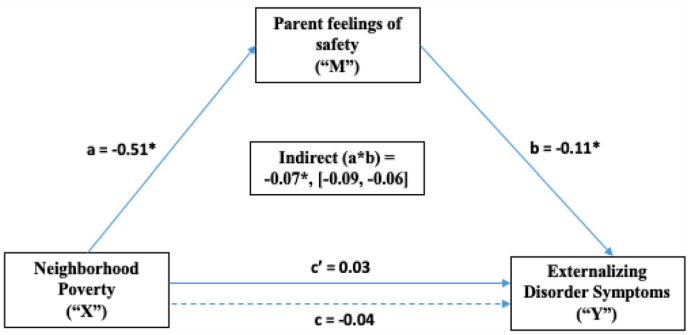

Fig. 3 Mediation for parent-reported feelings of safety on the relationship between neighborhood poverty and externalizing symptoms. Mediation model depicting estimates for the direct relationships between neighborhood poverty and parent feelings of safety (path a), parent feelings of safety and externalizing symptoms (path b), and neighborhood poverty and externalizing symptoms (path c'). Includes the estimate for the total effect (path c) and for the significant indirect effect (a*b) of parent-reported feelings of safety as a mediator

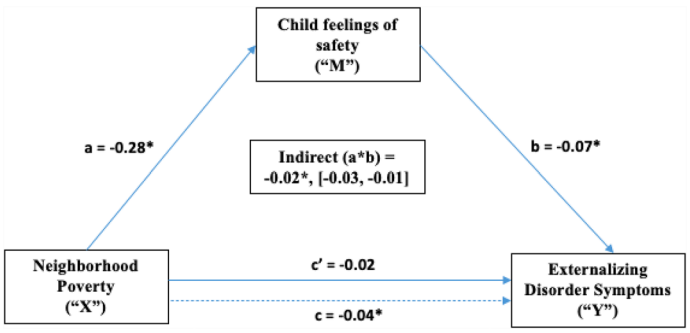

Fig. 4 Mediation for child-reported feelings of safety on the relationship between neighborhood poverty and externalizing symptoms. Mediation model depicting estimates for the direct relationships between neighborhood poverty and child feelings of safety (path a), child feelings of safety and externalizing symptoms (path b), and neighborhood poverty and externalizing symptoms (path c'). Includes the estimate for the total effect (path c) and for the significant indirect effect (a*b) of child-reported feelings of safety as a mediator

0.19. Main effects for each of the socioemotional support variables are reported in Table S12.

Interactions

Out of the various sources of socioemotional support considered, the Parental Monitoring Survey was the only variable that significantly interacted with neighborhood poverty to predict externalizing disorder symptoms after FDR correction. For all levels of neighborhood poverty but especially for lower levels (i.e., higher SES), children exhibited fewer externalizing problems in the context of greater parental support as indicated by higher scores on the Parental Monitoring Survey (Fig. 5; Table S13). These data indicate that the presence of parental support in particular may be more effective at preventing children from developing worse mental health outcomes when SES is not already a source of hardship.

Discussion

The primary objective of this study was to investigate the unique contribution of neighborhood poverty to children's psychopathology, as well as identify potential mediator and moderator variables implicated in this link. Our data support the hypothesis that greater neighborhood poverty relates to increased externalizing disorder symptoms in children above and beyond individual household income. Decreased parent- and child-reported feelings of safety and reduced intracranial volume significantly mediated this relationship while parental monitoring attenuated the relationship between neighborhood poverty and externalizing symptoms for children lower

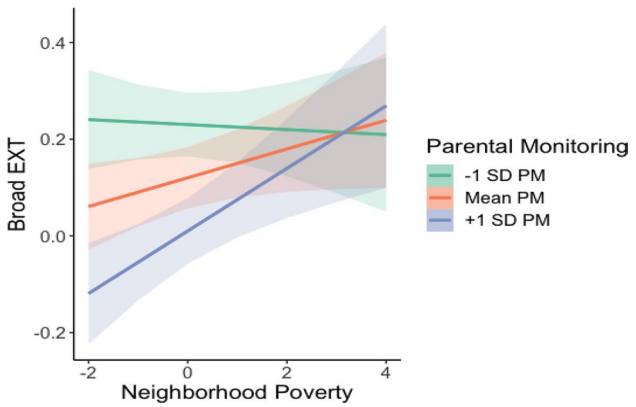

Fig. 5 Moderation of broad externalizing symptoms by neighborhood poverty and parental monitoring. Interaction graph depicting the impact of parental monitoring on the relationship between neighborhood poverty and broad externalizing disorder symptoms. Parental Monitoring Survey scores were standardized and then categorized into scores at (orange), above (blue), and below (green) the mean

in poverty. These findings support the idea that the broader neighborhood context uniquely contributes to children's mental health outcomes in ways that are dissociable from household income. Considering neighborhood poverty and the broader environment as a risk factor can help researchers and clinicians develop ways of helping children cope more effectively.

Higher levels of neighborhood poverty were significantly related to increased externalizing problems before and after accounting for household income. This corroborates our predictions based on previous research indicating that early life adversity in the form of deprivation is associated with a host of poorer developmental outcomes, including mental health [6, 11, 13]. However, we were surprised to find that neighborhood poverty was positively correlated with internalizing disorder symptoms before accounting for household income, but negatively associated with internalizing problems after accounting for household income. This may be because neighborhood poverty and household income are closely related, and household income is accounting for the majority of the variance in the relationship. Further, it is also possible that there is a contrast effect, whereby the experience of impact of the neighborhood varies as a function of one's individual family situation. Given the study's setting in the U.S., we believe that external social factors such as race and racism may help explain dissociations between neighborhood SES and family income. Racial segregation—an experience shared by many minorities—likely contributes to the separable effects of neighborhood poverty and family income that we have found.

We predicted that neighborhood poverty would be related to a range of brain structure volumes and white matter tracts. However, the results indicate that neighborhood poverty is only significantly related to left hemisphere amygdala volume and the structural integrity of the right cingulum, and neither of these variables are significantly related to externalizing disorder symptoms. The significant associations between intracranial volume and both neighborhood poverty and externalizing behaviors prompted us to investigate whether total intracranial volume mediates the association between neighborhood poverty and externalizing symptoms. We found that intracranial volume significantly mediated the relationship between neighborhood poverty and children's externalizing behaviors. This finding is consistent with research showing that alterations in global brain structure are implicated in impoverished circumstances [14, 16] and confer risk for certain unfavorable mental health outcomes [15].

Although our effect sizes are smaller compared to other studies, there are only a few population based studies of neurodevelopment and the environment. Further, incorporating a host of factors to obtain a more generalizable sample inevitably reduces the effect size of any one factor. Nevertheless,

our observed statistical differences are similarly consistent with other clinically relevant findings from previous studies. For example, family income-to-needs is positively correlated with left and right amygdala volume (Std. $\beta = 0.20$, 0.13 respectively) [34] while both greater income and better education was related to greater intracranial volume in a childhood sample (Std. $\beta = 0.15$, 0.16 respectively) [35]. While effect sizes of this magnitude may not be useful for identifying an individual child for treatment, these associations can reveal pathways and mechanisms that might more generally be avenues for prevention or treatment. Our results ultimately suggest that neighborhood poverty is related to externalizing problems by way of differences in brain structure, but not at the level of specificity that we had predicted. Instead, it may be that an overall reduction in intracranial volume better explains the association between neighborhood poverty and externalizing behaviors. Alternatively, there may be other structures/pathways in the brain and/or metrics not examined in this study that underlie this association, such as cortical thickness or brain activation patterns.

As predicted, toxins were related to neighborhood poverty. However, contrary to our hypotheses, toxin levels were not significantly related to externalizing symptoms when analyzed using generalized linear models. While our findings support the interrelatedness of impoverished neighborhoods and increased toxin levels, they do not support the possibility of a serial mediation whereby exposure to toxins reduces brain volume, potentially mediating the relationship between neighborhood poverty and children's externalizing disorder symptoms. This may be attributed to a weak measure of toxin levels. Specifically, neighborhood toxin levels were assessed using participants' home addresses; this indirect measure can over- or under-estimate particulate matter, NO_2, and lead risk levels. Other mitigating factors, such as having a home filtration system installed, may modify the extent to which the ambient accurately reflects children's exposure. In the future, direct assessments such as blood samples are needed to examine the role of toxins.

Decreased parent- and child-reported feelings of safety also mediated the relationship between neighborhood poverty and children's externalizing problems. Neighborhood crime can worsen children's emotional and behavioral problems, thereby increasing their risk for related psychopathology [19, 20]. Our findings suggest that perception of neighborhood safety—not objective crime—may be a better indicator of neighborhood threat. This may be explained by the scope of the Uniform Crime Reports measure, as this database generates a crime index for participants' county based on their home addresses. Because county level crime estimates do not directly align at the neighborhood level, these values may not accurately reflect the perceived neighborhood threat children experienced in their own neighborhood context.

An additional aim of this study was to explore sources of social and/or emotional support as a potential mitigating factor. We found that parental support, as captured by the Parental Monitoring Survey, significantly moderated the link between neighborhood poverty and externalizing behaviors. Prior studies have confirmed the beneficial role of socioemotional support in the context of early life adversity and developmental outcomes [11, 21], but our results did not confirm the idea that socioemotional support can act as a protective factor for children living in poverty that improves their adjustment to adverse circumstances. Rather, our results indicate that children from less impoverished neighborhoods with supporting environments exhibited fewer externalizing behaviors, but the level of support did not impact children in more impoverished neighborhoods to the same extent. The presence of a positive familial environment only acted as a buffer when there was a lack of additional stressors (i.e., low SES), and our measures of parental support did not convey a protective effect such that the effects of neighborhood poverty still impinged on children. The lack of significance for the peer and school sources of socioemotional support may be explained by the age at which the children in this study were sampled. Because children were relatively young at the baseline assessment, the reliability of some measures may be less robust; for example, pertaining to the Resilience Questionnaire, children tended to over-inflate their responses when asked about the number of close friends they had, sometimes responding with estimates such as "100." Peer and school support may not be as influential to children earlier in life, or they may not yet understand the importance of peer and school support in their lives.

One potential limitation of the current study is its cross-sectional design because it only allows us to look at associations between the variables and does not establish causality. Given our cross-sectional mediation analyses, it is not feasible to empirically discern the directionality of the relationship between neighborhood poverty and children's mental health outcomes. As such, these analyses should be considered as assessing the plausibility of mediation, with future analyses using multiple time points needed to test causality. We do not feel a discussion of measurement error and/or ecological fallacy is necessary; neighborhood-level effects are estimated according to the Area Deprivation Index, which is not a direct measure of the family's experience of the environment. Secondly, we examined other variables such as perception of crime/feelings of safety that are assumed to be valid at the individual level.

Further, it may be the case that structural inequities limit the neighborhoods to which people have access, leading families to live in a more disadvantaged neighborhood in part because of barriers that preclude them from moving elsewhere. These same families may also be experiencing increased stressors due to factors other than the

neighborhood's in which they are living (e.g., inequalities in their school or work environments, poor health care, etc.,). Consequently, our observed effect of worse psychopathological outcomes cannot be definitively attributed to neighborhood-level influences. Ideally, a longitudinal study can be carried out in the future once ABCD gathers data across multiple time point assessments. Doing so would allow us to more confidently make predictions about increased neighborhood poverty potentially contributing to risk for poor mental health outcomes and the mechanisms by which this may occur.

Of note, while robust, some of the effect sizes were relatively small, which is consistent with the multi factorial nature of causes for most behavioral outcomes in children. With a larger sample size such as ours, we do not expect to see large effect sizes due to the increased likelihood of variability from a multitude of factors. However, the significance of the association—albeit small—still indicates that the neighborhood context uniquely relates to children's development. This finding suggests a measurable association and may also be more generalizable due to the representativeness of the sample. There may also be additional predictor, mediator or moderator variables not accounted for that play a role in determining children's psychological development. We were not able to consider other information on the household in our analyses because we did not have data on these types of constructs, such as family chaos, parenting style, etc. This lack of family-level information limits our understanding of the multifactorial nature of child development and is an important direction to consider. Additional variables such as parenting style or cognitive stimulation may also help explain the role of the household in impacting children's risk for psychopathology. Future research is needed to examine the impacts of such variables in the consideration of early life adversity and children's developmental outcomes.

Whereas the majority of previous research has looked at environmental influences within the immediate nuclear family in conjunction with mental health, our novel approach examined the impact of the broader neighborhood context in order to potentially reveal impactful correlates of low SES not captured at the familial level alone. The implications of this study can inform more holistic interventions designed to reduce the burden of mental illness.

Summary

In summary, we examined the extent to which neighborhood poverty relates to children's mental health outcomes independent of household income. We also asked if neighborhood threat, toxin levels, brain volume, and the structural integrity of white matter tracts mediated this relationship and whether socioemotional support moderated it. Our sample was comprised of 8,623 9–10 year old children; using a secondary data analysis from the Adolescent Brain Cognitive Development (ABCD) study, we found that increased neighborhood poverty uniquely contributed to increased externalizing symptoms in children after accounting for household income, and parent/child reported feelings of safety and intracranial volume mediated this relationship. On the other hand, parental support as assessed by the Parental Monitoring Survey attenuated this link but only among children in less impoverished neighborhoods. These results highlight the importance of identifying environmental and neurological markers that may increase risk for later psychopathology in order to better inform holistic interventions designed to reduce the burden of mental illness.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors. IRB Approval: The Washington University IRB approval for this secondary data analysis of publicly available data is 201708123.

Informed Consent Informed consent and assent was obtained from all individual parent and child participants included in the study. All procedures in this study were conducted with full IRB approval.

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