Review

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Exposure to environmental toxicants and young children's cognitive and social development

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Abstract

Background: Understanding the role of environmental toxicant exposure on children's development is an important area of inquiry in order to better understand contextual factors that shape development and ultimately school readiness among young children. There is evidence suggesting negative links between exposure to environmental toxicants and negative physical health outcomes (i.e. asthma, allergies) in children. However, research on children's exposure to environmental toxicants and other developmental outcomes (cognitive, socioemotional) is limited.
Objectives: The goal of the current review was to assess the existing literature on the links between environmental toxicants (excluding heavy metals) and children's cognitive, socioemotional, and behavioral development among young children.
Methods: This literature review highlights research on environmental toxicants (i.e. pesticide exposure, bisphenol A, polycyclic aromatic hydrocarbons, tobacco smoke, polychlorinated biphenyls, flame retardants, phthalates and gas pollutions) and children's development across multiple domains.
Results: The results highlight the potential risk of exposure to multiple environmental toxicants for young children's cognitive and socioemotional development.
Discussion: Discussion will focus on the role of environmental toxicants in the cognitive and socioemotional development of young children, while highlighting gaps in the existing literature.

Keywords: cognitive development; early childhood; environmental toxicants; socioemotional development.

Introduction

To understand the influence of various contexts on children's socioemotional and cognitive outcomes, environmental exposures is an important area of inquiry. Scholars have highlighted the role of several environmental risk factors (e.g. poor neighborhoods, exposure to violence, trauma and stressful life events), and much of this research suggests that such exposures are linked to cognitive deficits, socioemotional, and behavioral maladjustment in children (1–4). Another potential, yet understudied, risk factor is exposure to environmental toxicants. This is a key gap in the literature because emerging evidence suggests that exposure may be detrimental to children's physical health, as well as their cognitive and socioemotional development (5, 6).

The research on exposure to environmental toxicants and children's development has primarily focused on heavy metal exposure, especially lead and mercury. These studies generally suggests that heavy metal exposure can adversely impact children's cognitive and socioemotional outcomes, including problems with attention, cognitive functioning, antisocial and aggressive behaviors, irritability and impulsivity (7–11). However, there is much less research on other environmental toxicants commonly found indoors and in the air, including volatile organic compounds (VOCs). VOCs are chemicals that are emitted into the air from a variety of sources, including household products such as cleaning supplies, pesticides, fuels, cosmetics and furniture products (12).

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Because of the nature of the sources of VOCs and other environmental toxicants, children may be regularly exposed to them in their homes and schools. Limited research suggests that exposure to a selected number of VOCs, is associated with negative physical health outcomes (i.e. asthma, allergies) in children (13). However, the research on effects of children's exposure to environmental toxicants on other developmental outcomes is limited. Of particular interest, is understanding how exposure to specific airborne environmental toxicants is associated with children's academic and socioemotional well-being (e.g. aggression, prosocial behaviors) because socioemotional and cognitive outcomes are known to play fundamental roles in shaping children's health and development. The goal of the current review is to examine the existing research on exposure to environmental toxicants (including VOCs) and children's cognitive and socioemotional development and to highlight important future directions.

Children are particularly susceptible to toxicant exposure for multiple reasons (14). First, children consume more nutrients and breathe more air per pound than adults, and thus can be exposed to higher concentrations of harmful environmental toxicants than adults (15). Second, children's lungs, brains and metabolisms are developing, so exposure during this period can have permanent lifelong impacts. Finally, children have more years left than adults to accumulate the negative effects of toxicant exposure as they continue to develop (14). Because environmental toxicants are released from common products (e.g. cleaning products, toys, furniture), children may be exposed across different environments. Therefore, it is important to understand how exposure to specific environmental toxicants is associated with children's development and health. Additionally, because during early childhood children undergo developmental changes in multiple domains (i.e. cognitive, physical and socioemotional), and they spend considerable amounts of time in various contexts (homes, preschools), it is a critical period to investigate the extent to which exposure to a variety of toxicants impacts children's development.

The current review summarizes research on environmental toxicant (excluding heavy metals) exposure and young children's academic, socioemotional and behavioral development. Based on the extant research, we focus on toxicants that young children may be exposed to from common sources, including cars, cleaning agents, toys, arts and craft supplies, garden supplies and school materials. Such sources can emit toxicants such as pesticides, bisphenol A, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, flame retardants, phthalates and fuel emissions. We review the existing research, identify key gaps in the literature, and provide future directions for research.

Method

We selected the year 2000 as a cutoff date as a way to replicate and extend the review published by Jurewicz and colleagues (14). We included all articles published since the year 2000 that focused on children's infant and early childhood development (birth–age 7) from multiple research databases. We excluded studies focusing on heavy metal exposure, as this was not the focus of the review. We searched Google Scholar, Pubmed and Cab Direct using the following keywords: toxicants, chemicals, toxins, environmental toxicants, environmental toxins and environmental chemicals. In addition, the following keywords and phrases were used to search for child development outcomes of interest: aggression, social behaviors, cognitive development, memory, attention, behaviors, social development. See Table 1 for a summary of all relevant studies on children from birth to age 7. All studies using human subjects were included, and studies focusing on animal models were excluded.

Results

Pesticide exposure and developmental outcomes

One important environmental chemical to consider is pesticide use. Children may be exposed to pesticides in their homes, schools or broader communities. Pesticides also travel in the air with other particles, dust and aerosols (74). However, until recently, few scholars have examined the associations between pesticide exposure and children's cognitive and socioemotional outcomes. In one of the few studies conducted in the USA, using a prospective birth cohort of low-income, Mexican-American mothers and children in a low-income, farmworker community in Salinas, California, researchers examined the relation between prenatal exposure to organophosphate (OP) pesticides and children's intelligence and cognitive development, including attention and executive functioning (18). Exposure to pesticides was analyzed in prenatal maternal urine samples and by examining children's urine yearly until 5 years of age. Prenatal exposure to OP pesticides was negatively associated with cognitive scores, verbal comprehension, intelligence and processing speed at 7 years of age (17, 23, 25).

Prenatal exposure to pesticides was also negatively linked to psychomotor and mental development at 6 and

Table 1: Summary of all relevant studies on children from birth to age 7.

Citation	Toxicant and outcome	Sample	Reporter and method	Results
Pesticide exposure				
Andersen et al. (16)	Prenatal pesticide exposure Children's neuropsychological functioning at ages 6–11 years	n = 203 birth cohort children and their mothers	Exposure estimated based on maternal occupation, Children's motor speed, reaction time, attention, memory and language development was assessed at ages 6–11 using a neuropsychological test battery	Prenatal pesticide exposure was negatively linked to neuropsychological functioning in girls but not in boys
Bouchard et al. (17)	Pre and postnatal OPs exposure Children's intelligence at age 7 years	Center for the Health Assessment of Mothers and Children of Salinas (CHAMACOS) n = 329 low-income, Mexican-American mothers and birth cohort children in California	Mothers were interviewed during and after pregnancy and completed the Peabody Picture Vocabulary Test (PPVT) and the Infant-Toddler Home Observation for Measurement of the Environment (HOME) Urine samples were collected twice during pregnancy and from children at 6 months, 1, 2, 3.5 and 5 years. Maternal and child blood and cord blood samples were collected Children's intelligence was assessed at age 7 using the Wechsler Intelligence Scale for Children (WISC)	Pesticides collected in prenatal urine were linked to lower cognitive scores at age 7, most strongly with verbal comprehension and full IQ score
Coker et al. (18)	Prenatal exposure to 15 specific classes of pesticides Children's intelligence at age 7 years	CHAMACOS n = 255 birth cohort children and their mothers in California	Mothers completed the PPVT and the HOME Maternal urine samples were collected twice during pregnancy Children's intelligence was assessed at age 7 using WISC	Pesticide exposure was negatively linked to children's IQ score
de Joode et al. (19)	Pesticide exposure Children's neurodevelopment, including memory, ADHD and oppositional disorders at ages around 6 and 9 years	n = 140 children and their mothers in Talamanca County, Costa Rica	Mothers were interviewed for sociodemographic information, child's medical history and pesticide exposure BMI was assessed, and urine samples were collected from children Test battery includes WISC, behavior problems (Conner's Parent Rating Scale-Revised Short Version (CPRS-R), and a series of measures assessing perception, memory, motor functioning and sensory functioning	Pesticide exposure was negatively linked to children's neurodevelopment, specifically poor working memory in boys, and poor processing speed in girls, and was positively linked to ADHD and behavior problems
Donauer et al. (20)	Prenatal pesticide exposure Children's mental and psychomotor development, intelligence at ages 1–5 years	Health Outcomes and Measures of the Environment Study (HOME Study) n = 327 birth cohort children and their mothers in Cincinnati, Ohio	Maternal urine samples were collected twice during pregnancy Children's mental and motor development was assessed at 1, 2 and 3 years using the Bayley Scales of Infant Development (BSID) Cognitive development was assessed at ages 4 and 5 using the Wechsler Preschool and Primary Scale of Intelligence (WPPSI)	Prenatal pesticide exposure was not significantly linked to children's cognitive functioning

Table 1 (continued)

Citation	Toxicant and outcome	Sample	Reporter and method	Results
Eskenazi et al. (21)	Prenatal DDT and DDE exposure Children's mental and psychomotor development at 6, 12 and 24 months	CHAMACOS n = 360 birth cohort children and their mothers in California	Prenatal blood samples were collected from mothers Children's mental and psychomotor development were assessed at 6, 12 and 24 months using Bayley Scales of Mental Development (BSMD)	Prenatal DDT exposure was negatively linked to children's psychomotor development at 6 and 12 months (but not 24 months) and DDE exposure only at 6 months DDT exposure was negatively linked to children's mental development at 12 and 24 months, but not at 6 months
Eskenazi et al. (22)	Prenatal insecticide exposure Children's neurodevelopment at 1 and 2 years	Birth cohort n = 752 mother-child pairs in South Africa	Maternal exposure to DDT and its breakdown product, DDE, in maternal serum, and pyrethroid metabolites in maternal urine Bayley Scales of Infant Development at 1 and 2 years	Maternal exposure to insecticides was negatively associated with socioemotional scores at 1 year, language composition and expressive communication at 2 years The link between pyrethroid exposure and motor functioning at 2 years was stronger for boys than girls
Gaspar et al. (23)	Prenatal DDT and DDE exposure Children's cognitive functioning at age 7 and 10.5 years	CHAMACOS n = 619 birth cohort children and their mothers in California	Prenatal blood samples were collected from mothers Children's cognitive functioning was assessed at ages 7 and 10.5 years using the WISC. Full-scale IQ score, working memory, perceptual reasoning, verbal comprehension and processing speed subscale scores were calculated	Prenatal DDT and DDE exposure were not significantly linked to Full-Scale IQ and other WISC subscales DDT exposure was negatively linked to processing speed at age 7 years among girls
González-Alzaga et al. (24)	Prenatal, postnatal, and current pesticide exposure Children's intelligence and cognitive functioning at ages 6–11 years	n = 305 children in South-Eastern Spain	Prenatal and postnatal exposure assessed using GIS mapping. Current exposure assessed via children's urine samples Children's cognitive functioning was assessed at ages 6–11 years using the WISC. Full-scale IQ score, working memory, perceptual reasoning, verbal comprehension, and processing speed were assessed	Prenatal exposure was negatively linked to processing speed and postnatal exposure was negatively linked to IQ, processing speed, and verbal comprehension. In general, pesticide exposure was negatively linked to IQ and verbal comprehension (stronger for boys than girls)
Gunier et al. (25)	Prenatal pesticide exposure Children's intelligence and cognitive functioning at age 7 years	CHAMACOS n = 283 birth cohort children and their mothers in California	Exposure assessed using GIS mapping Mothers were interviewed during and after pregnancy and completed the PPVT and the HOME Children's cognitive functioning was assessed at age 7 years using the WISC. Full-Scale IQ score, Working Memory, Perceptual Reasoning, Verbal Comprehension, and Processing Speed subscale scores were calculated	Prenatal pesticide exposure was negatively linked to children's IQ and verbal comprehension

Table 1 (continued)

Citation	Toxicant and outcome	Sample	Reporter and method	Results
Rauh et al. (2011)	Prenatal pesticide (CPF) exposure Children's neurodevelopment at age 7 years	Columbia Center for Children's Environmental Health (CCCEH NYC) n = 256 low-income birth cohort children and their African- American and Dominican mothers in New York City	Mothers were interviewed and completed Test of Nonverbal Intelligence (TONI), the HOME and the Child Behavior Checklist (CBCL) Maternal blood at postpartum and cord blood samples were collected Children's cognitive functioning was assessed at age 7 years using the WISC. Full-scale IQ score, working memory, perceptual reasoning, verbal comprehension and processing speed were examined	Prenatal CPF exposure was negatively linked to children's working memory and IQ
Ribas-Fitó et al. (26)	Prenatal HCB (agricultural and industrial chemical) exposure Children's ADHD and social competence at age 4 years	Ribera d'Ebre and Menorca n = 475 birth cohort children in Spain	Cord blood samples were collected Teachers using the California Preschool Social Competence Scale and the ADHD scales assessed children's social competence and ADHD at age 4 years	Higher levels of prenatal HCB exposure were negatively linked to children's social competence and positively linked to ADHD symptoms at age 4 years
Ribas-Fito et al. (27)	Cord serum level of DDT and DDE Children's cognitive functioning at age 4 years	Ribera d'Ebre and Menorca n = 475 birth cohort children in Spain	Cord blood samples were collected Children's cognitive development was assessed at age 4 years using the McCarthy Scales of Children's Abilities (MCSA)	DDT was negatively linked to verbal, memory, quantitative and perceptual performance scores (stronger among girls)
Stein et al. (28)	Prenatal organophosphate exposure Children's cognitive ability at age 7 years	CHAMACOS n = 329 birth cohort children and their mothers in California	Mothers were interviewed and completed the HOME for adversity. Maternal urine samples were collected Children's cognitive abilities were assessed at age 7 years using WISC. Full-scale IQ score, working memory, perceptual reasoning, verbal comprehension and processing speed subscale scores were calculated	Adversity was negatively linked to children's cognitive ability. Adversity also exacerbated the link between exposure and cognitive ability
Viel et al. (29)	Prenatal and childhood pesticide and BPA exposure Children's verbal comprehension and working memory at age 6 years	n = 287 children and their mothers in France	Mothers were interviewed for demographic information and completed the Wechsler Adult Intelligence Scale (WAIS). Maternal urine samples were collected during pregnancy and children's urine sample was collected at age 6 years Children's verbal comprehension and working memory were assessed at age 6 years using WISC	Childhood pesticide and BPA exposure (but not prenatal exposure) were negatively linked to children's verbal comprehension and working memory
Bisphenol A				
Braun et al. (30)	Prenatal and childhood BPA exposure Children's aggression, attention, hyperactivity, depression, anxiety and somatization and executive functions at age 3 years	HOME Study n = 244 birth cohort children and their mothers in Cincinnati, Ohio	Urine samples from mother were collected twice during pregnancy and children at ages 1, 2 and 3 years Children's behavior and executive function were assessed at age 3 years using Behavior Assessment System for Children (BASC-2) and the Behavior Rating Inventory of Executive Function-Preschool (BRIEF-P)	Prenatal BPA exposure (not childhood exposure) was positively linked to children's anxiety, hyperactivity, and depression, and negatively linked to emotional control and inhibition (stronger among girls)

Table 1 (continued)

Citation	Toxicant and outcome	Sample	Reporter and method	Results
Braun et al. (31)	Prenatal BPA exposure Children's cognitive functioning, internalizing and somatic symptoms at age 3 years	n = 812 children and their mothers in Canada	Maternal urine samples were collected during pregnancy Children's cognitive abilities were assessed at age 3 years using the WPPSI, and internalizing and somatic symptoms were assessed using the BASC-2	Prenatal BPA exposure was not significantly linked to children's IQ. BPA was negatively linked to working memory in boys, but the link was positive for girls. BPA was also positively linked to somatic and internalizing symptoms for boys but not girls
Casas et al. (32)	Prenatal BPA exposure Children's psychomotor skills, ADHD, behavior problems, cognitive development at age 1, 4 and 7 years	n = 438 children and their mothers in Sabadell, Catalonia, Spain	Maternal urine samples were collected twice during pregnancy Children's cognitive and psychomotor development were assessed at age 1 using BSID and at age 4 using MSCA, and ADHD and other behavior problems were assessed at age 4 by teachers using ADHD-DSM-IV form and at age 7 by parents using the CPRS	Prenatal BPA exposure was not significantly linked to children's cognitive development at age 1 and 4, but it was negatively linked to psychomotor development at age 1 BPA was positively linked to ADHD symptoms at age 4 (stronger in boys)
Perera et al. (33)	Prenatal and current BPA exposure Children's behaviors at the age between 3 and 5 years	CCCEH NYC n = 198 low-income birth cohort children and their African-American and Dominican mothers in New York City	Maternal urine samples were collected during pregnancy. Children's urine samples were collected between 3 and 4 years. Children's behaviors at the age between 3 and 5 years were assessed using the CBCL	Prenatal BPA exposure was positively linked to emotional reactivity and aggressive behaviors in boys, but it was negatively linked to anxious/depressed and aggressive behaviors in girls
Roen et al. (34)	Prenatal and early childhood BPA exposure Children's behaviors at the age between 7 and 9 years	CCCEH NYC n = 198 low-income birth cohort children and their African-American and Dominican mothers in New York City	Maternal urine samples were collected during pregnancy. Children's urine samples were collected between 3 and 5 years Children's behaviors were assessed using CBCL	Prenatal BPA exposure was negatively linked to withdrawn/ depressed symptoms and internalizing problems in girls, but it was positively linked to anxious/depressed symptoms, somatic complaints, thought problems, rule-breaking behavior, aggressive behavior and total externalizing and internalizing behaviors in boys
Viel et al. (29)	Prenatal and childhood pesticide and BPA exposure Children's verbal comprehension and working memory at age 6 years	n = 287 children and their mothers in France	Mothers were interviewed for demographic information and completed the WAIS. Maternal urine samples were collected during pregnancy and children's urine sample was collected at age 6 years Children's verbal comprehension and working memory were assessed at age 6 years using WISC	Childhood pesticide and BPA exposure (but not prenatal exposure) were negatively linked to children's verbal comprehension and working memory

Table 1 (continued)

Citation	Toxicant and outcome	Sample	Reporter and method	Results
Polycyclic aromatic hydrocarbons				
Abid et al. (35)	Childhood PAH exposure Children's ADHD, learning disabilities (LD), and enrollment in Special Education (SE) at ages 6–15 years	National Health and Nutrition Examination Survey (NHANES) n = 1257 children and their parents	Children's urine samples were collected at age 6 years Parents' reported on children's diagnoses related to ADHD, LD, and enrollment in SE	Childhood PAH exposure was positively linked to enrolment in SE (stronger for boys)
Cowell et al. (36, 37)	Prenatal black carbon exposure and stress Children's memory and learning at age 6 years	n = 258 children and their mothers in Massachusetts, Boston	Prenatal exposure was estimated using land-use regression model Parents' stress was assessed using Crisis in Family Systems-Revised form Children's memory and learning was assessed at age 6 years using Wide Range Assessment of Memory and Learning (WRAML2)	Prenatal black carbon exposure was not significantly linked to children's memory and learning. But, for boys, prenatal stress interacted with exposure such that boys with higher levels of exposure and parents' reporting higher prenatal stress had lower attention concentration scores
Edwards et al. (38)	Prenatal indoor and outdoor air pollution (PAH) exposure Children's nonverbal reasoning ability at age 5 years	n = 214 children and their mothers in Krakow, Poland	Mothers were interviewed about demographic information and toxin risk Maternal blood and cord blood samples were collected Air samples were collected during pregnancy Children's nonverbal reasoning ability was assessed at age 5 years using Raven Colored Progressive Matrices (RCPM)	Prenatal air pollution exposure was negatively linked to children's nonverbal reasoning ability
Guxens et al. (39)	Prenatal air pollution exposure Children's cognitive and psychomotor development at ages 1–6 years	n = 9482 children and their mothers from The Netherlands, Germany, France, Italy, Greece, and Spain	Air pollution exposure was estimated using land-use regression model. Children's cognitive and psychomotor development were assessed at ages 1–6 years using Ages and Stages Questionnaire (ASQ), BSID, Denver Developmental Screening Test (DDST), and MCDI	Air pollution was negatively linked to psychomotor development but was not linked to cognitive development
Jedrychowski et al. (40)	Prenatal PAH exposure Children's cognitive functioning at age 7 years	n = 170 children and their mothers in Krakow, Poland	Cord blood samples were collected Children's cognitive functioning was assessed at age 7 years using the WISC-R	Prenatal PAH exposure was negatively linked to children's depressed verbal IQ
Lovasi et al. (41)	Prenatal PAH exposure Children's intelligence at age 5 years	CCCEH NYC n = 326 low-income birth cohort children and their African-American and Dominican mothers in New York City	Mothers were interviewed and completed Test of Nonverbal Intelligence (TONI) and the HOME. Mothers wore air monitors for 2 consecutive days during the third trimester of pregnancy to assess PAH exposure Children's intelligence was assessed at age 5 years using WPPSI-R	Prenatal PAH exposure was negatively linked to children's IQ

Table 1 (continued)

Citation	Toxicant and outcome	Sample	Reporter and method	Results
Perera et al. (42)	Prenatal and childhood PAH exposure Children's ADHD symptoms at age 9 years	CCCEH NYC n = 250 low-income birth cohort children and their African- American and Dominican mothers in New York City	Maternal and cord blood samples were collected Children's urine samples were collected at age 3 or 5 years Children's ADHD symptoms were assessed at age 9 using CBCL and CPRS-R	Prenatal PAH exposure was positively linked to children's ADHD symptoms
Perera et al. (43)	Prenatal PAH exposure Children's behavioral, mental and psychomotor development at age 3 years	CCCEH NYC n = 183 low-income birth cohort children and their African- American and Dominican mothers in New York City	Mothers were interviewed about demographic information and risks and completed TONI Air samples and cord blood samples were collected. Children's behavioral, mental, and psychomotor development were assessed at age 3 using BSID and CBCL	Parental PAH exposure was negatively linked to mental development scores at age 3 years, but not behavioral and psychomotor development
Perera et al. (44)	Prenatal PAH, lead and DNA exposure Children's behavior and attention problems at ages 4 and 7	CCCEH NYC n = 271 low-income birth cohort children and their African-American and Dominican mothers in New York City	Mothers were interviewed and completed the HOME, TONI and Psychiatric Epidemiology Research Instrument Demoralization Scale (PERIDS). Cord blood samples were collected Children's behavior and attention problems were assessed at ages 4 and 7 using CBCL	Without controls, children with higher exposure had increased anxiety/ depression symptoms and attention problems at ages 4 and 7 years After controls were added, association with attention became even more significant and remained significant with internalizing symptoms
Perera et al. (45)	Prenatal PAH exposure Prenatal/childhood material hardship Children's ADHD and behavior problems at age 9 years	CCCEH NYC n = 351 low-income birth cohort children and their African-American and Dominican mothers in New York City	Maternal blood samples were collected at delivery Prenatal/childhood material hardship was assessed during pregnancy and through 9 years of age using mother's self-report Children's ADHD and behavior problems were assessed at age 9 years using CPRS-R	Prenatal PAH exposure was positively linked to children's ADHD and behavior problems and the effect was strong with greater hardship from pregnancy through childhood
Porta et al. (46)	Prenatal traffic related air pollution exposure Children's IQ at age 7 years	n = 474 children and their mothers in Rome	Air pollution exposure was estimated using land-use regression model Children's IQ was assessed at age 7 years using the WISC	Prenatal traffic-related air pollution exposure was negatively linked to children's IQ
Sunyer et al. (47)	Children's traffic-related air pollution exposure at school buildings Children's cognitive development at age 7–10 years	n = 2715 children and their mothers in Barcelona, Spain	Traffic pollution was measured inside classrooms and outside the school buildings using air sampling Children's working memory and attention were assessed at age 7–10 years using computerized tests and Attentional Network Test (ANT)	Children attending highly traffic-related air polluted schools experienced significantly slower growth in cognitive development across both attention and working memory

Table 1 (continued)

Citation	Toxicant and outcome	Sample	Reporter and method	Results
Tobacco smoke				
Chastang et al. (48)	Pre and postnatal ETS exposure at home School-age children's behavioral problems, emotional symptoms and conduct problems	n = 5221 children and their mothers in six cities, France	Pre and postnatal ETS exposure at home were assessed using parents' self-report questionnaire School-age children's behavioral problems were assessed using Strengths and Difficulties Questionnaire (SDQ)	Pre and postnatal ETS exposure were positively linked to children's behavioral problems, emotional symptoms and conduct problems
Davis et al. (49)	Passive smoke exposure among overweight children Children's cognitive performance at ages 7–11 years	n = 222 overweight or obese children in Augusta, Georgia	Children's plasma samples were collected to measure smoke exposure Children's BMI information was collected, and cognitive performance was assessed using the Cognitive Assessment System (CAS)	Passive smoke exposure was negatively linked to children's cognitive performance
Hopson et al. (50)	Prenatal tobacco smoke exposure at home Children's externalizing behaviors at age 7 years	CCCEH NYC n = 417 low-income birth cohort children and their African-American and Dominican mothers in New York City	Children's prenatal tobacco exposure was assessed at age 3 using mother report HOME inventory and externalizing behaviors were assessed at age 7 using CBCL	Prenatal tobacco smoke exposure was positively linked to children's externalizing behaviors only for children living in adverse home environments (not for children from positive home environments)
Melchior et al. (51)	Maternal tobacco smoke during pregnancy Children's emotional symptoms, conduct problems, hyperactivity/inattention, peer relationships and prosocial behaviors at age 5	n = 1113 birth cohort children and their mothers in France	Maternal tobacco smoke during pregnancy was assessed using self-report questionnaire Children's emotional symptoms, conduct problems, hyperactivity/inattention, peer relationships and prosocial behaviors were assessed at age 5 using SDQ	Maternal tobacco smoke during pregnancy was positively linked to children's hyperactivity but no other behavioral outcomes
Leung et al. (52)	Pre and postnatal second-hand smoke exposure Children's emotional and behavior problems at age 7 years, self-esteem at age 11 years and depressive symptoms at age 13 years	n = 6937 birth cohort children in Hong Kong	Pre and postnatal second-hand smoke exposure was assessed using primary caregiver's self-report questionnaire Children's emotional and behavior problems were assessed using the Revised Parent's Rutter Scales, self-esteem was assessed using the Culture-Free Self Esteem Inventories, and depressive symptoms were assessed using the Patient Health Questionnaire	Prenatal second-hand smoke exposure was positively linked to behavior problems Parental smoking was positively linked to behavior problems, depressive symptoms, and negatively linked to self-esteem
Polanska et al. (53)	Prenatal passive smoke exposure Children's neurodevelopment at age 1 and 2 years	n = 461 children and their non-smoking mothers	Maternal saliva samples were collected during pregnancy for passive smoke exposure and mothers completed questionnaire about smoking Children's neurodevelopment was assessed at age 1 and 2 years using the BSID	Prenatal passive smoke exposure was negatively linked to children's language functions at age 1 and 2 years, cognitive and psychomotor development at age 2 years

Table 1 (continued)

Citation	Toxicant and outcome	Sample	Reporter and method	Results
Polychlorinated biphenyls				
Caspersen et al. (54)	Prenatal dietary PCB and dioxins exposure Children's language development at age 3 years	Norwegian Mother and Child Cohort Study (MoBa) n = 44092 children and their mothers	Prenatal dietary PCB and dioxins exposure were assessed using a food frequency questionnaire Children's language development was assessed at age 3 years using the Ages and Stages Questionnaire (ASQ)	High prenatal dietary PCB and dioxins exposure was positively linked to children's moderate language delay and negatively linked to communication scores in girls
Plusquellec et al. (11)	Prenatal and childhood PCB exposure Children's behavioral functioning at age 5 years	Cord Blood Monitoring Program n = 110 Inuit children and their mothers in Quebec, Canada	Cord blood samples and child blood samples were collected at age 5 years Children's behavioral functioning was assessed at age 5 years using BSID and observation	Prenatal PCBs exposure was linked to emotional tone, anxiety and affect rate
Saint-Amour et al. (9)	Prenatal and childhood PCB exposure from seafood Children's visual brain processing at age 5–6 years	Cord Blood Monitoring Program n = 110 Inuit children and their mothers in Quebec, Canada	Cord blood samples, and child blood and hair samples were collected at age 5–6 years Children's visual processing was assessed at age 5–6 years using VEPs	Childhood mercury exposure was linked to VEP latency and PCB exposure was linked to reduced VEP amplitude
Stewart et al. (55)	Prenatal PCB and mercury exposure Children's cognitive development at age 38 months and 54 months	Oswego Newborn and Infant Development Project n = 212 children and their mothers	Breast milk, cord blood, maternal hair samples were collected Children's cognitive development was assessed at age 38 months and 54 months using the MSCA	Prenatal PCB exposure was negatively linked to children's cognition at age 38 months. PCB exacerbated the effects of mercury on child cognition. Both additive and interactive effects were examined. The interaction was significant at 38 months of age
Tatsuta et al. (56)	Prenatal PCB, mercury, and lead exposure Children's intellectual abilities at age 42 months	n = 387 children and their mothers in Japan	Cord blood samples were collected Children's intellectual abilities were assessed at age 42 months using the Kaufman Assessment Battery for Children (K-ABC)	Prenatal PCB exposure was negatively linked to sequential and mental processing scores (stronger in boys)
Flame retardants				
Agent et al. (57)	PBDE's in flame retardants Children's behavior and cognitive skills at age 36 months	n = 304 children and their mothers	Breast milk samples were collected for PBDE exposure Children's behaviors were assessed using the Behavioral Assessment System for Children 2 (BASC-2) and cognitive skills were assessed using the Mullen Scales of Early Learning at age 36 months	PBDE exposure was positively linked to children's anxious and withdrawn behavior and cognitive performance

Table 1 (continued)

Citation	Toxicant and outcome	Sample	Reporter and method	Results
Castorina et al. (58)	Prenatal flame retardants exposure Children's cognition and behavior at age 7 years	CHAMACOS n = 310 birth cohort children and their mothers	Maternal urine samples were collected Children's cognition was assessed using WISC and behaviors were assessed using BASC-2 and Conners' ADHD/DSM-IV Scales (CADS) at age 7 years Full-Scale IQ score, Working Memory, Perceptual Reasoning, Verbal Comprehension, and Processing Speed subscale scores were calculated	Prenatal flame retardants exposure was negatively linked to full-scale IQ and working memory Exposure was also positively linked to hyperactivity
Cowell et al. (36, 37)	Prenatal flame retardants exposure Children's attention and social behaviors at ages 3–7 years	n = 210 children and their mothers	Mothers were interviewed and completed TONI-2 Cord blood samples were collected Children's attention and social behaviors were assessed at ages 3–7 using CBCL	Prenatal flame retardants exposure was positively linked to children's attention problems except at ages 5 and 6 years
Herbstman et al. (59)	Prenatal PBDE flame retardant exposure Children's neurodevelopment at age 12, 24 and 36 months	n = 210 children and their mothers	Mothers were interviewed and completed TONI-2 Medical records were examined. Cord blood and maternal blood samples were collected Children's neurodevelopment was assessed at age 12, 24 and 36 months using BSID and WPPSI-R	Prenatal PBDE flame retardant exposure was negatively linked to children's mental and physical development at every time point
Lipscomb et al. (60)	Childhood flame retardant exposure Children's social behaviors at ages 3–5 years	n = 72 preschool children	Children wore silicone passive wristband air sampler 7 consecutive days Children's social behaviors were assessed at ages 3–5 years by the teacher using the Social Skills Improvement System Rating Scale (SSIS-RS)	Childhood flame retardant exposure was negatively linked to assertiveness and responsible behaviors and positively linked to externalizing behaviors
Roze et al. (61)	Prenatal organohalogens (OHCs) flame retardants exposure Children's motor skills, cognitive skills (intelligence, visual perception, visuomotor integration, inhibitory control, verbal memory, and attention and behavior at age 5–6 years	Comparison of Exposure-Effect Pathways to Improve the Assessment of Human Health Risks of Complex Environmental Mixtures of Organohalogens (COMPARE) n = 62 children and their mothers in Groningen	Maternal blood and cord blood samples were collected Children's motor skills were assessed using Movement ABC, Developmental Coordination Disorder Questionnaire (DCD-Q); cognitive skills were assessed using WPPSI-R and NEPSY-II, the Rey's Auditory Verbal Learning Test (AVLT), and Test of Everyday Attention for Children and behavioral outcomes were assessed using CBCL, ADHD questionnaire at age 5–6 years	Prenatal flame-retardant exposure was positively linked to children's internalizing and externalizing behaviors and negatively linked to fine motor skills, attention and perception OHCs were negatively linked to associated with selective attention The wood protective agent was negatively linked to coordination, sensory and visuomotor integration and attention
Vuong et al. (62)	Pre and postnatal flame retardants exposure Children's attention and impulse control at age 8 years	HOME Study n = 214 birth cohort children and their mothers in Cincinnati, Ohio	Maternal blood samples during pregnancy and children's blood samples at age 1, 2, 3, 5 and 8 years were collected Children's attention and impulse control were assessed at age 8 using Conners' Continuous Performance Test-Second Edition (CPT-II)	Flame retardants exposure was negatively linked to children's attention and impulse control (stronger in boys). The associations also weakened by 8 years old

Table 1 (continued)

Citation	Toxicant and outcome	Sample	Reporter and method	Results
Phthalates				
Doherty et al. (63)	Prenatal phthalate exposure Children's mental and psychomotor development at age 24 months	The Mount Sinai Children's Environmental Health Study n = 276 children and their mothers in New York City	Maternal urine samples were collected during pregnancy Children's mental and psychomotor development was assessed at age 24 months using BSID-II	Prenatal phthalate exposure was negatively linked to children's mental and psychomotor development in girls but it was weakly and positively linked to mental and psychomotor development in boys
Engel et al. (64)	Prenatal phthalate exposure Children's problem behaviors and executive functioning ages 4–9 years	The Mount Sinai Children's Environmental Health Study n = 404 children and their mothers in New York City	Maternal urine samples were collected during pregnancy Children's problem behaviors and executive functions were assessed at age 4–9 years using BRIEF and BASC-PRS	Higher prenatal phthalate exposure was linked to poor aggressive behaviors, conduct problems, attention problems, depressive symptoms, externalizing behaviors and poor executive functioning and emotional control
Engel et al. (65)	Prenatal phthalate exposure Infants' behavior within 5 days of delivery	The Mount Sinai Children's Environmental Health Study n = 295 children and their mothers in New York City	Maternal urine samples were collected twice during pregnancy Infants' behaviors were assessed within 5 days of delivery using Brazelton Neonatal Behavioral Assessment Scale (BNBAS)	Prenatal phthalate exposure was negatively linked to orientation and quality of alertness scores and motor performance in girls But it was positively linked to motor performance in boys
Factor-Litvak et al. (66)	Prenatal phthalate exposure Children's mental and motor development (IQ) at age 7 years	n = 328 children and their mothers	Maternal urine samples were collected during pregnancy Children's mental and motor development were assessed at age 7 years using WISC. Full-Scale IQ score, Working Memory, Perceptual Reasoning, Verbal Comprehension, and Processing Speed subscale scores were calculated	Prenatal phthalate exposure was negatively linked to children's full-scale IQ score, processing speed, perceptual reasoning, verbal comprehension and working memory
Gascon et al. (67)	Prenatal phthalate exposure Children's cognitive, behavioral, and psychomotor development at ages 1–7 years	INMA-Sabadell Study n = 367 children and their mothers in Catalonia, Spain	Maternal urine samples were collected twice during pregnancy Children's cognitive and psychomotor development were assessed at age 1 and 4 years using BSID and MSCA; social competence, ADHD symptoms, and other behavioral problems were assessed at 4 years using teacher report California Preschool Social Competence Scale (CPSCS) and ADHD-DSM-IV, and age 7 years using parent report SDQ and CSRS	Prenatal phthalate exposure was not significantly linked to cognitive and psychomotor development, except the link between MBzP and lower psychomotor scores Overall, links were weak and mixed, suggesting prenatal phthalate exposure was not negatively linked to children's cognitive, behavioral, and psychomotor development
Huang et al. (68)	Pre and postnatal phthalate exposure Children's cognitive functioning at age 2–12 years	n = 110 children and their mothers in Taichung, Taiwan	Maternal urine samples were collected during pregnancy. Children urine samples were collected at ages 2, 5, 8 and 11 years Children's cognitive functioning was assessed at ages 2, 5, 8 and 11 years using BSID and WISC	Postnatal phthalate exposure was negatively linked to children's IQ, but not prenatal exposure

Table 1 (continued)

Citation	Toxicant and outcome	Sample	Reporter and method	Results
Kim et al. (69)	Prenatal phthalate exposure Infants' mental and psychomotor development at age 6 months	Mothers and Children's Environmental Health Study n = 460 infants and their mothers in Seoul, Cheonan, and Ulsan, Korea	Maternal urine samples were collected during pregnancy Infants' cognitive development was assessed at age 6 months using BSID	Prenatal phthalate exposure was negatively linked to infants' mental and psychomotor development for boys but not girls
Polanska et al. (70)	Pre and early postnatal phthalate exposure Children's cognitive development at 24 months	Polish Mother and Child Cohort Study (REPRO PL) n = 165 children and mothers	Maternal urine samples were collected in pregnancy. Children's urine samples were collected at age 24 months Children's cognitive development was assessed at age 2 years using BSID	Prenatal phthalate exposure was negatively linked to children's cognitive development. Postnatal phthalate exposure was not significantly linked
Swan et al. (71)	Prenatal phthalate exposure Children's sex-typical play behaviors in preschool	Study for Future Families n = 145 children and their mothers in Los Angeles, CA, Minneapolis, MN, Columbia, MO and Iowa City, IA	Maternal urine samples were collected in pregnancy Children's sex-typical play behaviors were assessed in preschool using parent report Pre-School Activities Inventory (PSAI) and Parental Attitude Scale	Prenatal phthalate exposure was linked to less masculine play behaviors for boys. There were no significant links for girls
Whyatt et al. (72)	Prenatal phthalate exposure (consumer products) Children's mental, motor, and behavioral development at age 3 years	CCCEH NYC n = 319 low-income birth cohort children and their African-American and Dominican mothers in New York City	Mothers were interviewed for demographic information and medical records and completed PERID and HOME scale Maternal urine samples were collected during pregnancy Children's mental, motor, and behavioral development were assessed at age 3 years using BSID-II and CBCL	Prenatal phthalate exposure was negatively linked to children's psychomotor development and girls' mental development It was positively linked to children's withdrawn and internalizing behavior problems
Miscellaneous toxicants (e.g. gas stove emissions)				
Guxens et al. (2012)	Prenatal indoor air pollution Maternal diet during pregnancy Infants' cognitive development at age 14 months	INMA-Sabadell Study n = 1889 children and mothers	Air sampling and land use regression models used to assess exposure to air pollutants (nitrogen dioxide and benzene) during pregnancy Mothers completed FFQ Infants' cognitive development was assessed at age 14 months using BSID	Prenatal indoor air pollution was negatively linked to cognitive development for children whose mothers ate fewer fruits and vegetables
Morales et al. (73)	Early life indoor air pollution exposure (gas appliances at home and indoor nitrogen dioxide concentration) Children's cognitive functioning and ADHD symptoms at age 4 years	n = 398 birth cohort children and their mothers in Menorca, Spain	Home environment was assessed for cooking appliances, heating and cooling systems, number of hours of ventilation and size of the house Dust samples were collected from the living room for nitrogen dioxide Blood and saliva samples were collected for DNA Children's cognitive functioning and ADHD symptoms were assessed at age 4 years using MSCA and ADHD-DSM-IV form	Early exposure to gas appliances was negatively linked to cognitive functioning and positively linked to ADHD symptoms; indoor nitrogen dioxide exposure was negatively linked to executive function There was a genetic interaction for general cognitive functioning

ADHD, attention-deficit hyperactivity disorder; BMI, body mass index; BPA, bisphenol A; CPF, chlorpyrifos; DDE, dichlorodiphenyldichloroethylene; DDT, dichlorodiphenyltrichloroethane; ETS, environmental tobacco smoke; OP, organophosphate pestisides; PAH, polycyclic aromatic hydrocarbons; PCB, polychlorinated biphenyls; VEP, visual evoked potentials.

12 months of age (21). Moreover, the negative association between OP pesticides and processing speed was stronger for girls than for boys (23). Prenatal exposure to pesticides was also negatively linked to neuropsychological functioning (i.e. attention, memory, reaction time) in early and middle childhood (ages 6–11) in girls but not boys (16). Additionally, the negative links between pesticide exposure and cognitive development were strongest for children experiencing additional adversity [i.e. socioeconomic disadvantage, family dysfunction and stressful life events; (28)].

In a study of mothers and children in New York City, prenatal exposure to pesticides (organophosphorus pesticide chlorpyrifos) using cord blood measurements was negatively associated with cognition (working memory and IQ) when children were 7 years old (75). However, the research on prenatal pesticide exposure and children's cognitive functioning is far from conclusive because some studies have reported nonsignificant associations between pesticide exposure and cognitive development (20, 23, 76, 29). Further some of the mentioned studies used self reported data whereas other studies used biomarkers. Importantly, the mentioned studies examined different types of pesticides. More studies are needed to understand if specific types of pesticides are linked to different domains of development.

Studies with diverse samples provide further evidence of the linkage between pesticide exposure and children's cognitive development. For example, researchers in Spain collected cord serum samples to assess prenatal exposure to pesticides (27). Children's cognitive and social behaviors were assessed at 4 years of age. The results demonstrated that prenatal pesticide exposure was negatively associated with children's later social competence, verbal ability and memory scores. Prenatal pesticide exposure has also been positively associated with attention deficit hyperactivity disorder (ADHD) symptoms in 4-year-old children (27, 26). Additionally, there is evidence in research conducted in South Africa that maternal exposure during pregnancy to insecticides used to control malaria negatively predict general socioemotional scores and language development among 1-year-old children (22). Negative associations between childhood pesticide exposure and children's cognitive performance (verbal learning abilities, ability to discriminate colors and working memory) were also documented among 4- and 5-year-old children in Costa Rica (19). Importantly, the link between pesticide exposure and working memory was significant for boys but not girls. Children's exposure to pesticides was also assessed in a sample of 6–11-year-old children in Spain. The results suggest that children's exposure to pesticide was negatively linked to their cognitive processing speed, intelligence and memory, and the effects were stronger for boys than girls (24). Finally, de Joode and colleagues (19) found positive associations between childhood pesticide exposure and children's behavior problems and ADHD symptoms.

Overall, the results suggest adverse associations between exposure to pesticides and children's cognitive functioning. The research on children's socioemotional/behavioral development, however, is relatively sparse. Additionally, the majority of the research examined prenatal maternal exposure as opposed to children's postnatal exposure. More research is needed on children's exposure in a variety of contexts. Notably, across several studies examining both prenatal and childhood exposure, gender differences have been documented; although in some studies negative effects were stronger for boys, and in other studies negative effects were stronger for girls. These results highlight the importance of considering cumulative effects (children's exposure in addition to parental exposure) while also considering moderating factors (e.g. socioeconomic status, family demographic factors, child gender) that might protect children or place them at higher risk for negative outcomes.

A relatively new area of research is investigating the role of exposure to multiple toxicants or cumulative exposure in predicting cognitive outcomes among children. While research in this area is still relatively limited, there is one relevant studies. As part of the CHAMACOS project, Coker and colleagues (18) examined prenatal exposure to 15 classes of pesticides and children's intelligence at age 7 years. The results demonstrated that prenatal exposure to multiple types of pesticides simultaneously negatively predicted children's IQ at age 7 years, and that high levels of prenatal exposure to multiple pesticides was most predictive of children's IQ.

Bisphenol A (BPA) and developmental outcomes

BPA is a compound that is often found in plastics (77). Children may be both directly and indirectly exposed to BPA in a variety of situations. Direct exposure may result from contact with plastics containing BPA (e.g. children's toys, dishes, food from metal cans lined with BPA). Children may also be exposed indirectly via parental contact with BPA that is passed to children prenatally or through postnatal contact (77). Additionally, BPA can travel through the air and is often dispersed with other particles, including dust (78). Researchers have documented negative links between childhood exposure to BPA and children's cognitive functioning, including verbal comprehension and working memory (29); however, prenatal exposure was not significantly predictive of outcomes. In research utilizing a prospective birth cohort in Ohio, BPA was assessed in maternal urine prenatally and in children at 1, 2 and 3 years of age. Parents reported on children' problem behaviors and executive functions at 3 years of age. In girls, prenatal BPA levels were positively associated with anxiety and depressive symptoms, as well as emotional control and inhibition. These results were not significant for boys, however (30).

Prenatal BPA exposure has also been positively linked to working memory in girls but negatively linked to working memory for boys (31). Perera and colleagues (33) also documented gender differences in prenatal BPA exposure and children's behaviors. BPA was related to emotional reactivity and aggressive behaviors at age 5 years for boys. For girls, BPA was associated with anxious/depressive symptoms and aggressive behaviors (33). Prenatal exposure to BPA has also been negatively linked to psychomotor development at 1 year of age in boys and girls (32). Two additional studies examined the associations between prenatal exposure to BPA and children's socioemotional outcomes. Prenatal exposure to BPA, assessed in maternal urine, was positively associated with emotional reactivity and aggressive behaviors in boys at age 5 years. For girls, prenatal exposure to BPA was positively associated with internalizing symptoms and aggressive behaviors (33). Roen and colleagues (34) examined BPA concentrations in maternal urine and in children's urine at ages 3 and 5 years, and the associations with children's behavioral outcomes. In girls, higher prenatal BPA urinary concentrations were associated with lower behavioral symptom scores (significant for withdrawn/depressed symptoms and internalizing problems) but with increased symptom scores in boys [significant for anxious/depressed symptoms, somatic complaints, thought problems, rule breaking behavior, aggressive behavior, and total internalizing and externalizing behaviors; (34)]. Overall, research on BPA exposure and children's development has focused on cognitive development and has identified a number of gender differences. Negative associations have been documented for both boys and girls, but the behavioral consequences of BPA exposure might differ. Future research should continue examining the differential patterns among boys and girls in the links between BPA exposure and developmental outcomes.

Polycyclic aromatic hydrocarbons (PAHs) and developmental outcomes

PAHs are organic compounds that are primarily produced by humans through the burning of fossil fuels, and are therefore present to varying degrees in the air that children are exposed to regularly. Children living in high traffic, urban areas may be particularly vulnerable to PAH exposure, as vehicle emissions are a primary source of PAH production (79).

There is emerging evidence that PAH exposure may be negatively associated with children's cognitive and behavioral development, including indicators of intelligence, and externalizing behaviors. Specifically, researchers have demonstrated relations between prenatal exposure to PAHs and cognitive performance (including verbal IQ) in early childhood (40, 41, 43). Prenatal exposure to black carbon (produced by traffic emissions) has also been linked to lower IQ scores when children were 5 and 7 years old (38, 46). Sunyer et al. (47) specifically examined PAH exposure inside and outside school buildings and children's cognitive development (i.e. working memory and attention). The results demonstrated that children attending highly polluted schools experienced significantly slower growth in cognitive development across both attention and working memory. Another study demonstrated a negative link between prenatal exposure to indoor air pollution (i.e. nitrogen dioxide and benzene) and children's psychomotor development but the link between exposure and cognitive development was not significant (39).

There is also evidence that exposure to PAHs may be related to children's socioemotional development. Parental report of PAH exposure has been positively linked with anxiety/depressive symptoms and attention problems for children at age 7 (44). Additionally, prenatal PAH exposure has been positively associated with children's ADHD symptoms (42, 45). Interestingly, boys with higher PAH exposure who also had parents who reported higher prenatal stress had the lowest attention concentration scores in early childhood (36, 37). Childhood exposure to PAH has also been associated with a greater likelihood of being enrolled in special education school programs, with the adverse association being stronger for boys than girls (35).

Taken together, most studies demonstrate significant relations between PAH exposure and children's cognitive, behavioral and socioemotional outcomes. Additionally, in some studies, the effects of PAH exposure varied by child gender (and parent characteristics) suggesting that boys might be particularly vulnerable to the effects of PAH exposure (when examining cognitive indicators such as intelligence and attention), and children living in stressful environments might also be at high risk for negative outcomes, including poor attention.

Tobacco smoke and developmental outcomes

Considering children's exposure to second (exhaled smoke from a smoker) and third [residue left behind from a lit cigarette; (80)] hand tobacco smoke is another important area of study. Despite decreases in smoking rates in the US, children are still vulnerable to second hand smoke exposure, and children from low-income communities may be especially vulnerable to tobacco smoke exposure due to higher rates of smoking in these communities (81, 82). Among diverse samples of youth, including low-income and ethnic-minority children, prenatal and childhood exposure to tobacco smoke has been linked to poorer cognitive performance, including measures of intelligence (49, 50, 53). Additionally, home environments might moderate the link between tobacco smoke exposure and cognitive development, as research has demonstrated that the negative link between tobacco smoke exposure and cognitive functioning is especially significant for children living in adverse, risky environments (50, 83).

The negative links between tobacco smoke exposure and negative development outcomes for children have been replicated among diverse samples in a variety of contexts. In one study, parents reported on pre- and postnatal tobacco smoking behaviors and children's outcomes at 7 years of age in Hong Kong. Exposure from parents was positively associated with children's depressive symptoms and negatively associated with self-esteem (52). Studies conducted in France have also demonstrated links between tobacco smoke exposure and children's cognitive and behavioral outcomes. Prenatal and childhood exposure to tobacco smoke was associated with internalizing symptoms and conduct problems, and these effects were exacerbated for children exposed during both the pre and postnatal period (48). Additionally, prenatal tobacco smoke exposure has been linked to children's hyperactive or impulsive behaviors (51). The relatively sparse recent research on tobacco smoke exposure and children's cognitive development is fairly consistent, suggesting an acceptance of the deleterious effects of tobacco smoke exposure on children's development. This is further supported by judicial decisions, which have created some well-established laws protecting children from their own parental smoking [see (84)].

Polychlorinated biphenyls (PCBs) and developmental outcomes

PCBs have been used in the production of electrical equipment such as coolants and lubricants and can also be found in plastics, adhesives, oil-based paints and floor finishes (85). Although production has been banned in the USA since 1979, their persistent use continues to expose the population (86). PCB exposure examined in maternal cord blood and breast milk samples has been negatively linked to cognitive development, including poorer verbal abilities, quantitative abilities, language delays and memory in early childhood (87, 88). Additionally, exposure to PCBs in food, assessed via a food consumption questionnaire, was linked to language delays in children at 3 years of age (54). The vast majority of research on PCB exposure and children's development has focused on cognitive development. Research on PCB exposure and behavioral adjustment of young children is still not well understood.

Childhood exposure to PCBs has also been linked to reduced visually evoked potentials, suggesting that PCBs may negatively impact perception and information processing in young children (9). Exposure to PCBs has also been linked to irritability and impulsivity in Canadian children. Specifically, prenatal exposure to PCBs was correlated with negative moods (11). One study also demonstrated that PCB exposure (assessed in breast milk and cord blood) exacerbated the negative impact of mercury on children's cognitive functioning (55). There is also some evidence that exposure to PCBs may differentially impact boys and girls. A study in Japan found that prenatal PCB exposure was negatively associated with mental processing, but the effects were stronger for boys than girls (56).

Overall, the majority of research shows clear links between PCB exposure and cognitive developmental problems. A few studies also suggest possible gender-related effects and interactions with other toxicant exposure that exacerbate negative outcomes. However, exposure to PCB and children's social behavioral functioning is much less studied.

Flame retardants (polybrominated diphenyl ethers) and developmental outcomes

Another environmental toxicant of interest is flame-retardants. Articles, which are often treated with flame-retardants, include carpets, upholstery fabric including crib mattress, car seats, cushions and plastics used as components in electrical appliances and equipment (59). Increasing numbers of US state policies are restricting or banning the use of polybrominated diphenyl ethers (PBDE) in children's products (89). There is substantive evidence that prenatal exposure to flame retardants is associated with children's cognitive development, including poorer executive functioning and self-regulation in early childhood (61, 62). Prenatal exposure has also been linked to mental development, including IQ and executive functioning in early childhood (58, 36, 37, 59). Childhood exposure to flame-retardants has also been linked to psychological symptoms in children [i.e. anxiety, withdrawal symptoms; (57)]. However, there is some evidence that these negative effects might fade over time (36, 37). Comparatively, there are few studies that have examined the links between exposure to flame retardants and children's sociobehavioral outcomes. For example, researchers showed that both prenatal and childhood flame retardant exposure was positively associated with hyperactivity and negatively associated with assertiveness (58, 60).

Taken together, there is evidence for links between flame retardant exposure and children's cognitive development. However, much more research is needed to examine such exposure and children's socioemotional and behavioral functioning in order to better understand the role of exposure to flame retardants in children's overall functioning.

Phthalate exposure and developmental outcomes

Another toxicant that children may be exposed to in their daily environments is phthalates. Phthalates are used in the production of plastics, detergents, adhesives and personal care products [e.g. soap, nail polish, hairspray, lotion; (90)]. Phthalates are also used in the production of toys, such as inflatable and plastic toys (90). Because phthalates are found in products commonly used in childcare centers and homes, considering their influence on children's development is an important area of inquiry.

Some investigators examining prenatal exposure to phthalates have demonstrated negative links to cognitive functioning, including intelligence (66, 72). Postnatal exposure (children's direct exposure) to phthalates was also associated with poorer performance on cognitive functioning tasks among children in Taiwan (68). Interestingly, there is ample evidence of gender differences in the links between phthalate exposure and cognitive development. Specifically, one study demonstrated that prenatal exposure was negatively associated with cognitive development for girls only (72). Doherty and colleagues (63) similarly showed that prenatal exposure to phthalates was negatively associated with cognitive performance for girls, but the link for boys was weak. However, a study by Kim and colleagues (69) found the opposite pattern of relations such that prenatal exposure predicted poorer cognitive functioning in boys but not girls in a sample of Korean children. In a study of newborn infants, researchers demonstrated that among girls, there was a significant linear decline in orientation and quality of alertness scores as exposure increased. Girls also demonstrated lower motor performance with higher concentrations; however, boys experienced increases in motor performance with exposure (65). Notably, some studies have found no significant linkages between prenatal exposure and cognitive development in young children (67, 68) and, in a study conducted in Poland, childhood exposure was not associated with children's cognitive performance (70).

With regards to relations between phthalate exposure and socioemotional and behavioral outcomes, Engel et al. (64) reported positive associations between prenatal exposure and maladjustment, including aggressive behaviors, conduct problems, attention problems, as well as poorer executive functioning and higher depressive symptoms. Another study with preschool children found that boys with high prenatal phthalate exposure were likely to engage in fewer masculine types of play behaviors than boys with low phthalate exposure. However, phthalate exposure was unassociated with girls' play behaviors (71).

Currently, the research on exposure to phthalates and children's outcomes is mixed. While some studies suggest that exposure to such chemicals is linked to poorer developmental outcomes, other studies suggest gender specific links, and other studies report no significant associations between phthalate exposure and children's outcomes [see (67)]. Many studies also demonstrate gender differences, suggesting phthalate exposure might be particularly detrimental for girls. However, this lack of research precludes conclusive inferences.

Gas emissions and developmental outcomes

Another toxicant that has been examined in relation to children's development is exposure to gas emissions (primarily from gas stoves). Gas stoves can emit carbon monoxide, nitrogen dioxide, and formaldehyde, which can be dangerous for children's health (91). There is some research on the role of gas-stove emissions and other indicators of healthy development. One study (73) examined the associations between nitrogen emissions from indoor gas stoves and children's cognitive functioning. Exposure to nitrogen emissions was examined via assessment of individual's homes (size of house, ventilation systems and cooking appliances). Exposure to nitrogen was negatively associated with cognitive development and positively associated with ADHD symptoms.

While the research on the role of gas stove emissions in children's development is very limited, current evidence suggests that such exposure might be a risk factor for developing children. Moreover, there is evidence that using gas stoves in poorly ventilated homes, or homes without a ventilation hood, typically exceed the benchmarks set by federal agencies for suggested toxicant levels (92, 93). In general, however, research on gas stove emissions and children's outcomes is one of the least studied areas of common toxicants.

Conclusions and future directions

The research to date, alongside research findings from animal studies [e.g. (94, 95)], yields relatively consistent evidence that exposure to environmental toxicants is linked to cognitive and learning deficiencies, mental health difficulties and sociobehavioral problems. However, the present review demonstrates that there are many understudied areas concerning the influence of environmental toxicants on young children's cognitive and sociobehavioral development. Further, virtually no research has been completed to assess the influence of multiple, simultaneous exposures. This is in stark contrast to the numerous studies on children's exposure to specific toxicants, such has heavy metals, and physical health outcomes, such as asthma and allergies (96, 97).

Several other inferences can be drawn from the existing research on young children's environmental toxicant exposure and cognitive and sociobehavioral outcomes. First, the majority of the research has focused on exposure to pesticides and BPA but research on other common environmental toxicants, such as polycyclic aromatic hydrocarbons, second and third hand tobacco smoke, polychlorinated biphenyls, flame retardants, phthalates and gas emissions, warrants further attention. Second, even within the research on environmental toxicants, most studies focus on young children's cognitive functioning. Research examining the links between environmental toxicants and social and behavioral functioning is comparatively less. And third, several studies yield evidence that toxicant exposure may interact with child characteristics (e.g. child gender), contextual factors (e.g. stress), and with other toxicants, but such research is limited. Nonetheless, the existing research suggests the need for integrative models that simultaneously account for main and interactive effects of toxicant exposure on young children's cognitive and social development.

Overall, the results of this review highlight the potentially deleterious effects of environmental toxicant exposure for young children. While there are consistently documented negative links between toxicant exposure and children's physical health (13), it is important to consider multiple domains of development, including cognitive, socioemotional and behavioral development in order to understand child development holistically. Recently, researchers have begun to examine the role of environmental toxicant exposure in children's cognitive development, with a focus on children's intelligence. Studies on behavioral and emotional adjustment are still limited, but there is initial evidence that environmental toxicant exposure might also predict social functioning in children. More research is needed to better delineate the links between exposure and multiple domains of development, while also examining moderating factors, such as child characteristics, family dynamics and the role of broader social contexts.

Methodologically, there have been some advances in the research on young children's exposure to environmental toxicants and developmental outcomes. Recently, research on environmental toxicants and developmental outcomes has increased, but the majority of these studies focus on cognitive functioning, such as attention, intelligence and executive functioning as the outcome of interest. Few studies examined socioemotional or behavioral development among young children. Most of the existing studies also examined exposure in two ways: maternal exposure and children's exposure in the home. It is important for future studies to examine other contexts in which children may be exposed, such as toxicant exposure in school buildings and broader communities (e.g. early childhood centers, neighborhood parks, church buildings, community centers). While there are a few longitudinal cohort studies examining exposure and children's development (e.g. CHAMACOS), more longitudinal research is needed to better understand the links between exposure to environmental toxicants and children's cognitive and social outcomes. Given the complexity and challenges of conducting long-term studies using multiple methods (e.g. biomarkers, self-reported surveys, physiological assessments) and the need for diverse, representative samples, there is a need for national and international coordinated efforts on this front.

There is evidence that the links between exposure and children's development might be moderated by individual and contextual variables. Specifically, the moderating role of gender was documented in multiple studies.

Such evidence suggests that boys and girls might be differentially impacted by exposure to specific toxicants, but the findings are not consistent, and more work is needed. Interestingly, one study found that children were at differential risk for negative outcomes when exposed to tobacco smoke depending on their home environments, as children in risky environments were at higher risk for negative outcomes when exposed to tobacco smoke (50). Children living in low-resource, impoverished communities might be at elevated risk for exposure to harmful substances depending on their contexts. For example, children in rural communities might be exposed to relatively high levels of pesticides (98), while children in urban areas might be exposed to traffic pollution at high levels [e.g. (99)]. Children in low-resource communities might also be exposed to poorer quality housing and school buildings that contain relatively high levels of toxicants in the air. Therefore, understanding the role of toxicants as a risk factor for children living in specific communities is essential in order to gain a more holistic understanding of the role of toxicants as an environmental risk factor in children's cognitive and socioemotional development.

Overall, there is evidence that toxicants found in the air may place children at risk for negative cognitive, socioemotional and behavioral outcomes. These findings are important as they demonstrate an additional contextual risk factor that has historically not been a primary focus among developmental scholars. Healthy cognitive development (i.e. including regulation abilities, information processing and attention) is important for children's academic success [see (100, 101)], and therefore it is important to understand contextual factors that may impede these developmental processes. Additionally, considering children's cognitive and socioemotional adjustment is important in order to promote social competence, healthy relationships, and psychological and behavioral well-being (1). These findings are important from a practical perspective, as parents, teachers and policymakers should be aware of the products used in and around children's homes and schools that may place children at risk in order to help promote optimal development.

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