EARLY CHILDHOOD SCIENTIFIC COUNCIL ON EQUITY AND THE ENVIRONMENT

Air Quality Affects Early Childhood Development and Health

WORKING PAPER 3

Center on the Developing Child
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Devon Payne-Sturges, DrPH
Professor, Department of Environmental Health Sciences, University of Michigan School of Public Health

Natalie Slopen, ScD
Associate Professor, Social and Behavioral Sciences, Harvard T.H. Chan School of Public Health

ADDITIONAL AUTHORS

Joseph G. Allen, DSc, MPH
Associate Professor, Harvard T.H. Chan School of Public Health

Rebecca Hansen, MFA
Senior Director of Communications, Center on the Developing Child, Harvard University

Al Race
Senior Fellow, Center on the Developing Child, Harvard University

Joseph Wilson, Jr., MHS
Harvard T.H. Chan School of Public Health

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Theresa Kennelly Mooney, Assistant Director of Communications

Anna Williams Sjörs, Senior Content Writer

About the Authors
The Early Childhood Scientific Council on Equity and the Environment, housed at the Center on the Developing Child at Harvard University, is a multidisciplinary, cross-organizational collaboration committed to improving our understanding of how influences from the broader environment affect early childhood development. Established in 2023, the Council aims to leverage both scientific and community-informed perspectives to help policymakers and leaders across a range of sectors understand and mobilize around a prenatal and early childhood perspective that is rooted in working toward fairness of place for all children, with particular attention to communities of color and people living in poverty. For more information, go to www.developingchild.harvard.edu.

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Air Pollution Affects Us All

This working paper is the third in a series focusing on the ways that conditions in developmental environments shape young children's health and well-being. Air quality is just one component of a set of interrelated conditions that affect how children's bodies and brains develop. This working paper offers a summary of current knowledge about how air quality, particularly air quality in indoor environments, impacts developing biological systems.

Beginning before birth, children's health and development are powerfully affected by influences from their developmental environment—the full range of experiences and exposures they have in the places they live, grow, play, and learn—with implications for their lifelong health and well-being. All of these influences, positive and negative, interact to shape the development of a child's brain, the integrated systems in their body—including the immune, metabolic, and cardiovascular systems—and even how their genes are expressed.[1] Clean air is an essential part of a healthy developmental environment, and ensuring that all of us have clean air to breathe in all the spaces where we spend time—indoors and out—offers a vital opportunity to support children's healthy development.[2]

The reduction of *outdoor* air pollution in the United States was, until recently, a great success story. The Clean Air Act of 1970 (with major updates in 1977 and 1990 in response to new data) reduced outdoor air pollution from a variety of sources by more than 70% and saved trillions of dollars in health care costs, even as the population, economy, and number of cars continued to grow substantially.[3] Through 2020, the Act was estimated to have prevented 2.4 million days of worsened asthma symptoms, 120,000 emergency room visits, 5.4 million lost school days, 200,000 heart attacks, and more than 230,000 premature deaths.[4] More recently, however, wildfire smoke fueled by excessive heat and drought brought on by climate change has increased some types of air pollutants, causing a significant deterioration in air quality in nearly three-quarters of the contiguous US—effectively erasing four years of air quality progress in reducing those pollutants.[5]

The importance of outdoor air quality for health has long been recognized. However, most adults spend more than 90% of their time enclosed in buildings and vehicles.[6] During pregnancy and early childhood, it's likely even more[7]—in childcare facilities, schools, community centers, summer camp buildings, offices, cars, and homes. In all these places, the air contains a wide range of particles and chemicals, some of which have the potential to adversely affect children's development and health. In addition, the Environmental Protection Agency (EPA) estimates that levels of indoor air pollutants can be two to five times higher than outdoor levels due to poor ventilation; chemicals released from furniture, carpets, and cleaning products; indoor sources of pollution, such as byproducts of gas stove use; tobacco smoke; and outdoor pollution coming in.[8,9]

While many factors contribute to how much outdoor pollution gets indoors—from "leaky" buildings with poorly sealed walls, windows, and doors to missing or low-grade air conditioning filters—on average, about half of what's in the air outside makes its way in. And, because we typically spend more than 21 hours inside every day, the majority of our exposure to outdoor air pollution actually occurs indoors.[10]

When it comes to air quality, our indoor air environment itself has changed

significantly in the last 50 years. As composite-wood furniture, synthetic carpets, polymeric flooring, flame-retardant fabrics and additives, foam cushions, "forever chemicals" known as PFAS, and scented cleaners (e.g., personal care products, cleaning agents, laundry soap, and dryer sheets) have become nearly ubiquitous indoors, so has an array of airborne chemicals known as "volatile organic compounds" (VOCs).[11,12] Concentrations of VOCs, many of which are known to cause cancer, can be one hundred times higher indoors than outdoors.[13] These compounds are emitted as gases from numerous household products and materials, including those noted above, as well as auto emissions or attached garages that can penetrate into buildings.[9] As one example of the known harms of VOCs, studies associate frequent use of cleaning products during infancy and pregnancy—particularly scented spray products—with a higher risk of wheezing in early childhood and the development of asthma and lower respiratory tract infections in childhood.[14] Additionally, evidence suggests that exposure to VOCs in cleaning products preconception and during pregnancy is associated with an increased risk of asthma in children, and occupational exposure to these compounds has been associated with higher rates of lung cancer and cardiovascular mortality.[14,15]

Most adults spend more than 90% of their time enclosed in buildings and vehicles. During pregnancy and early childhood, it's likely even more—in childcare facilities, schools, community centers, summer camp buildings, offices, cars, and homes.

Actionable solutions to improve indoor air quality already exist. These range from policy and regulation options; to pollutant-free cleaners, healthier housing and furniture materials, and new building technologies; to simply maintaining and using ventilation systems with high-quality filters. Yet, these solutions have not been widely adopted. And all of the pollutants outlined above disproportionately affect families with fewer resources and families of color because discriminatory zoning, lending, and housing policies have left many low-income and minoritized communities living in overcrowded housing constructed with poor-quality materials and often situated near congested roads and industrial pollution.[16,17] Solution strategies should prioritize marginalized communities as we work to improve air quality in the spaces where we spend the most time during pregnancy and early childhood.

Indoor Air Pollution Has Especially Powerful Effects on Babies and Young Children

Not only are babies and young children *exposed* to more indoor air pollutants, but they are also more *affected* by this pollution than most adults because they breathe more rapidly, they inhale a larger volume of air relative to their body size, and their respiratory, reproductive, endocrine, immune, digestive, and neurological systems are still developing.[18] The flip side of this increased sensitivity is the powerful opportunity it presents to support healthy development by improving indoor

air quality during pregnancy and early childhood. During pregnancy, hormonal and physical changes lead to an increase in the amount of air breathed in and out.[19] When microscopic airborne particles and chemicals such as flame retardants or PFAS are inhaled, they enter the lungs, then the bloodstream, through which they can cross the placenta and reach the fetus, where the lungs, brain, and reproductive, immune, and endocrine systems are undergoing rapid development and are especially sensitive to such exposures.[20]

During early development, the body's systems "read" the environment around them and adapt to what they experience. For example, if an infant experiences significant or prolonged exposure to contaminants in the air, it can set off a chain of consequences. The immune and inflammation systems respond protectively, activating cells and proteins that can cause changes in the structure of the lungs, excessive mucous production, and scar tissue formation near the airways. These changes can lay the foundation for developing asthma during childhood.[21] In the short term, biological adaptations like these immune and inflammatory system reactions are healthy and help our bodies respond to the environment—without that short-term immune response, we could not survive. But, if conditions are prolonged or extreme, some short-term adaptations can become harmful in the long term by over-activating systems that were meant to be activated temporarily.[1]

> **During pregnancy, hormonal and physical changes lead to an increase in the amount of air breathed in and out.**

It's Never Too Late: The Power of Developmental Plasticity

While the consequences of exposure to airborne particles and chemicals during pregnancy and early childhood can be dire, they are not inevitable. The biological systems in the human body—from the brain to the immune, cardiovascular, and metabolic systems—have a powerful ability to adapt throughout life in response to influences from the environment. Scientists call this "developmental plasticity," and while the body is *most* plastic in the early years, it never loses the ability to adapt.[1] Every developmental outcome is the result of an interaction among genes, exposures, and experiences, and the timing of those exposures and experiences during development. In other words, the health outcomes for any individual exposed to air pollution depend on the nature, length, intensity, and timing of their exposure in combination with the individual's genetic predispositions. This explains why two people—even twins—can have the same exposure, but one may be unaffected while the other is severely affected.[22] The studies cited in this report all relate to the increased *likelihood*—but not inevitability—of adverse outcomes after exposure to toxicants present in indoor air.

With this adaptability in mind, it is even more critical that we improve the quality of the air that surrounds us during pregnancy and early childhood—cleaner air is always beneficial, even when children have been exposed to pollutants in the past.

How Indoor Air Quality Affects Fetal and Child Development

As noted above, there are many sources of air pollution that originate indoors. However, knowing that up to half of what's in the air outside can also make its way in, it is critical to consider current research on air quality and children that is focused on outdoor air pollution. These studies and their findings, many of which we draw on below, offer important considerations related to the composition and effects of the indoor air our children breathe, as well as opportunities to make that air cleaner.

Out-of-balance immune response—When airborne particles, chemicals, and allergens (for example, mold spores) pass through the lungs and into the body, they trigger the immune system to respond. Inflammation, an important part of our immune response, protects the body from both physical particles and toxic components absorbed on the particles.[23] But too much inflammation for too long, especially if it occurs during highly sensitive periods when the organs and brain are still developing, can weaken the immune system and contribute to lifelong inflammatory conditions such as heart disease, diabetes, and autoimmune disorders.[1] Another part of the immune response is the release of signaling molecules known as "reactive oxygen species," which are normally kept in balance by antioxidants in the body.[24] Too many reactive oxygen species can overpower the antioxidant defense system and cause damage to cells.[25] This is known as "oxidative stress," a sign that the body's systems are out of balance, which is especially problematic during pregnancy when it can affect the placenta's ability to function as a protector and nurturer of fetal development.[26] Oxidative stress is connected to numerous pregnancy complications, including preeclampsia, gestational diabetes, poor fetal growth, pregnancy loss, and stillbirth.[25,26] For example, formaldehyde, a VOC emitted from many common furniture and building materials, as well as cleaning products,[27] can cause oxidative stress in fetal cells and tissues[28] and adversely affect the hormones necessary for fetal growth, which may explain the relationship between formaldehyde exposure and low-birth-weight babies.[19]

Altered gene expression—During fetal development, genes determine which cells will perform each of the body's critical functions and carry instructions for how the cells will do their jobs. But a child's experiences and exposures can activate proteins that attach to their genes in distinctive patterns, which control whether and how a gene's instructions will be carried out. This *epigenetic* process, which can lead to changes passed down from parents to offspring, affects the proliferation, differentiation, and stability of all cells in the body, including brain cells—and it can be altered by indoor air pollutants during pregnancy and the first years of life. The resulting epigenetic changes can affect organ development, sleep patterns, energy levels, and inflammation[20]—or even cause changes to DNA that increase the risk of autism, developmental delays, and cancer.[20,29] For example, black carbon, a tiny airborne particle that can be emitted from wildfires, gas and diesel engines, and coal-fired power plants, can cross the placenta and may enter the developing fetus.[19] When air pollution particles cross the placenta, they may cause epigenetic changes in how the placenta functions that can lead to disruptions in healthy fetal development.[20] For example, the placenta's capacity to repair damaged DNA in the fetus may be impaired, which may increase the risk

for cancer later in life.[20,23] It's unknown how many generations these kinds of changes affect—for example, there is evidence that epigenetic changes seen in mothers who were exposed to lead can be passed on not only to their children but also to their *grandchildren*.[30]

Preterm birth—When the immune and inflammation systems respond for an extended period of time during pregnancy, this takes energy away from fetal development.[1] This may explain why exposure during pregnancy to airborne particles and gases such as nitrogen dioxide (a typical ingredient of smog from car and industrial exhaust, which can make its way indoors) is associated with an increased risk of premature birth and low birth weight, both risk factors for a range of neurodevelopmental problems in childhood and later in life.[30] Preterm birth, defined as birth that occurs before 37 weeks, as well as being born with low birth weight, carries both short- and long-term risks, including higher risk of infant death, delays in developing cognitive and motor skills, vision and hearing problems, diminished lung capacity, and developmental disabilities such as cerebral palsy, as well as higher risk of chronic conditions such as obesity and diabetes.[26,31,32] Preterm birth and low birth weight are also linked to reduced lung function in babies,[25] which can lead to increased risk of asthma in childhood.[17] Treating the complications of preterm birth requires medical care, special education, and early intervention services that have been estimated to cost, on average, nearly $65,000 per child *more than* the costs of a full-term birth.[33] We can avoid such costs—and more effectively promote healthy development—by preventing these pollutants from entering children's developmental environments to begin with. In addition to the above implications for preterm birth, exposure to dust-borne contaminants such as flame retardants—even newer, "safer" retardants—has been linked to increased rates of miscarriage and decreased rates of fertilization and embryo implantation in couples undergoing in vitro fertilization.

Diminished lung function—Lung development is a dynamic process that begins early during prenatal development and continues throughout childhood and into early adulthood.[23] The lungs can be affected by air pollution even before birth.[26] When airborne chemicals or particles enter the lungs and bloodstream during pregnancy, they can cross the placenta and reach the fetus, where they can influence how fetal lung cells form, the number and quality of blood vessels in the lung, and how the lung's branches take shape, which affect how well they distribute oxygen to the rest of the body.[20] Exposure to air pollution can restrict the amount of oxygen sent to the fetus through placental blood and may cause the lungs to develop with a lower capacity to breathe.[33] Poor lung function itself early in life is problematic, but it can also lead to many forms of respiratory disease later, from asthma to bronchitis to chronic obstructive pulmonary disease (COPD).[26]

> We can promote healthy development by preventing pollutants from entering children's developmental environments to begin with.

Disrupted brain development—The early phases of brain development involve several processes that are critical to brain function across the lifespan. Neurons migrate to their ultimate location, begin to connect with each other, and optimize well-used connections between cells. At this early stage of development, the protective barrier around the brain has yet to fully form, which makes it easier for pollutants to move through the circulatory system into the brain than later in childhood and adulthood when the barrier is less permeable.[34] Even in later stages of development, the most common airborne

particles can affect the brain, entering through nasal passages and passing across the protective blood barrier into the brain. The regions of the brain where cells are most affected include those associated with memory, learning, reactivity to stress, and regulating emotions and behavior.[36] Inflammation caused by exposure to air pollution prenatally and in the earliest years can also damage brain cells and change gene expression in ways that increase the risk of brain diseases later in life, including Alzheimer's and Parkinson's.[29] Flame retardants, many of which can migrate into indoor air and dust, have been shown to readily pass through the placenta to affect development through negative effects on the neurological system, thyroid, and reproductive system of the fetus. [37,38]

Early in life, developmental disorders such as autism spectrum disorder (ASD) have also been connected to prenatal exposure to outdoor airborne particles, particularly in boys. These studies focus on exposure to outdoor air pollution, but because much of what starts outdoors comes indoors and stays there, it is reasonable to hypothesize that these pollutants may have similar adverse effects when they occur indoors.[39-41] These neurological outcomes may be the result of fetal oxidative stress disrupting the differentiation and organization of cells in the developing brain in combination with a genetic predisposition to the disorder.[39] Evidence increasingly suggests that exposure to a type of air pollution known as PM2.5 during critical periods of fetal development and infancy raises the risk of developing ASD, even when exposures occur at low levels.[42]

Endocrine disruption—Exposure to certain chemicals in the air can impact the body's endocrine system, which is responsible for regulating hormones. Chemicals found in air fresheners, personal care products, and building materials can mimic thyroid activity, impact the start of puberty, and potentially disrupt developmental pathways during pregnancy and early childhood. One study found that the mix of chemicals within indoor dust mimicked testosterone and estrogen, meaning even everyday dust can be hormonally active.[95]

Damage across systems—Different airborne chemicals have distinctive effects on the interconnected systems and organs in the body, including the respiratory and cardiovascular systems, with potential impacts on neurodevelopment, allergic reactions, cancer risk, and premature death.[12] As one example of how this works, when benzene—a toxic VOC found in car exhaust, tobacco smoke, some glues and paints, plastics, dyes, and detergents—is breathed in, it causes cells to stop working correctly in multiple ways. It can damage the immune system by changing levels of antibodies in the blood and causing the loss of white blood cells. Benzene is toxic to bone marrow's platelet and red blood cell formation, which can lead to anemia.[43] It can also alter the expression of numerous genes and proteins and may interfere with the liver's ability to detoxify blood and other body fluids. Combined, these gene, blood, and immune system changes can create the conditions for leukemia in children and adults and may also affect the lymph nodes, causing lymphoma.[1,44] And because such chemicals can have both indoor sources and outdoor sources that make their way in, levels of exposure can be multilayered.

Unequal multiplier effects—We know that poor-quality indoor air can be more harmful when different chemicals combine. One recent study found that exposure to a mixture of air pollutants during fetal development was associated with poor memory functioning and increased attention problems during childhood.[34] Just as important to consider is the potential combined impact of indoor air pollution and psychosocial factors such as depression, exposure to violence, and economic status, all of which can influence levels of stress in caregivers and

children.[23] For example, the effects of indoor air pollutants may be exacerbated by the stress experienced by children living in disadvantaged environments because stress is also a potent cause of inflammation and oxidative stress.[45,46] Neighborhoods with the fewest resources due to lack of investment (e.g., limited access to health care and safe green space) and the most sources of stress (e.g., poverty, discrimination, and lack of opportunity) also show the strongest associations between ASD and prenatal exposure to airborne particles.[47] Other studies have noted that the combination of pollutants with high levels of psychosocial stress during pregnancy—for example, significant stress caused by poverty, racism, mental illness, violence in the home or community, or environmental disasters such as wildfires—is associated with hypertension, preterm birth, and respiratory illness.[23,48] There is likely a multiplier effect when stress and pollution—both known triggers for inflammation—combine to cause even greater and longer-lasting spikes in the inflammatory response.[1,23] This is important to understand, given the strong link between inflammation and a range of adverse health outcomes, including conditions like heart disease, depression, and cancer. To ensure that all children can thrive in environments that support their well-being, it is critical that we prioritize strategies aimed at lessening psychosocial stress *and* addressing air pollution in communities facing the greatest disadvantages.

What Pollutes Indoor Air

Over time, regulations have successfully reduced our exposure to indoor pollutants such as carbon monoxide, tobacco smoke, and radon due to their long-established, significant health risks. Many other sources of indoor air pollution are less well-known and remain unregulated. These pollutants are present in children's environments and can cause serious harm when exposure occurs.

Volatile organic compounds (VOCs)—VOCs are released into the air from many common household products and construction materials. VOCs can accumulate in the placenta and fetus, disrupt gene expression and organ development at the cellular level, and trigger inflammation and oxidative stress. They are associated with an increased risk of asthma, skin and throat irritations, and several forms of cancer.[12,13] Numerous products that use safer chemicals (tested by the EPA's "Safer Choice" service) and biobased solvents from citrus, seed, vegetable, and pine oils are readily available, yet products containing hazardous chemicals remain unregulated and widely marketed.[49] "Air freshener" sprays, plug-ins, and hangers do not clean the air; they add fragrances to it—and fragranced products have been associated with a range of adverse health effects, such as migraine headaches, asthma attacks, respiratory difficulties, neurological problems, mucosal symptoms, and contact dermatitis.[14,50]

Pesticides, phthalates, forever chemicals, and flame retardants—Dust in our indoor spaces often contains hazardous chemicals from plastics, cleaning products, flame retardants, pesticides, fragrances, and forever chemicals used in some fabrics and non-stick coatings.[13] Dust can enter our bodies when it is stirred

up off the floor and inhaled.[95] Dust can also land on our skin and permeate into our bloodstream, or it can be ingested.[10] Inside the body, these chemicals can mimic our body's hormones because of their chemical structure, leading to a range of disruptions in thyroid function and reproductive system development.

Particulate matter (PM)—Particles of varying sizes float in the air, both indoors and out, with a range of sources, including construction sites, smokestacks, wildfires, cooking, and aerosol air fresheners. Researchers have categorized particles of three distinct sizes (PM10, PM2.5, and ultrafine particles, or UFP), all of which can enter the lungs when we breathe. The smallest of these particles can cross into the bloodstream and, in some cases, the brain, where they may disrupt fetal brain development.[51] PM exposure has been associated with a number of adverse health effects, ranging from increased risk of preterm birth to reduced lung function and worsening of asthma in children.[52]

Wildfire smoke—It may begin outside, but wildfire smoke also gets *inside* buildings through open windows, invisible cracks and crevices in buildings, and air ventilation systems without high-quality filters.[53] A major threat to the health and development of young children, it includes a potent mixture of fine particles, black carbon, and chemicals such as carbon monoxide and nitrogen dioxide.[25] Exposure to wildfire smoke during pregnancy and early childhood can have a significant negative impact on healthy deliveries and both short- and long-term effects on young children, such as increased rates of asthma attacks, pneumonia, and decreased school performance. For more information on how wildfire smoke affects prenatal and early childhood development, please refer to the brief "Growing Up in a Warming World: How Wildfire Smoke Affects Early Childhood Development."

Germs, viruses, bacteria, microbes, and allergens—Any parent, teacher, childcare professional, or pediatric care provider can attest to the rapid spread of germs through the air among children, whether colds, flu, or RSV. The COVID-19 pandemic was a vivid, global reminder of the role of ventilation and high-quality filters in preventing the spread of viruses. Mold, household pests such as cockroaches or mice, and pets all shed microbial allergens that attach to dust or float in the air and can trigger asthma and other respiratory symptoms as well as skin rashes.[19]

Gases—Exposure to a range of gases can have adverse effects on people who inhale them. For example, ozone is a gas produced by chemical reactions in the atmosphere, particularly when heated. Due to our warming climate, cities around the world have increasingly exceeded acceptable levels of ozone in the air, and hot indoor air can contain even more ozone.[54] Inhaling ozone can inflame and damage the airways, make the lungs more susceptible to infection, and aggravate lung diseases such as asthma, emphysema, and chronic bronchitis.[55] Longer-term exposure is associated with developing COPD in adulthood.[56]

Heat—While not a direct source of pollution, temperature plays a significant role in shaping how various pollutants behave in a space and affect children's health and development, and heat is an important factor in indoor air quality. For example, extreme heat can cause winds to weaken, leading the atmosphere to stagnate, essentially "cooking" the air and everything in it—fine particles, chemicals, and VOCs.[57] When there is inadequate ventilation, indoor air also "cooks," causing the air to produce ozone more rapidly[54] and VOCs to be released from household materials in greater quantities. Once mixed in the air, ozone can interact with VOCs to increase concentrations of formaldehyde, which is known to cause cancer.[12]

Air Pollution Does Not Act Alone

The neighborhoods where children live, grow, play, and learn have a significant bearing on the quality of the air they breathe—indoors and out. As a result of discriminatory lending and zoning practices—both historical and current—a higher proportion of Black, Hispanic, and low-income families live in neighborhoods with lower-quality, substandard school buildings and housing compared with White and higher-income families.[17,58] These neighborhoods are disproportionately zoned for heavy commercial and industrial uses that expose residents to industrial air pollution and traffic.[17] Strategies that address inequities in zoning, housing, schools, and community buildings are critically important to public health overall and could have broad benefits for children and their caregivers.[59]

Instead, many current-day policies perpetuate longstanding inequities in housing. These practices include ongoing discriminatory housing and zoning policies, subprime mortgage loans, and other barriers to accessing affordable, healthy housing.[17] For example, the practice of zoning wealthy, primarily White neighborhoods as exclusively single-family and low-density further prevents multi-unit buildings with affordable rent from being available in communities with greater opportunity and cleaner air.[58] These kinds of policies represent decisions that determine which places benefit from investments in infrastructure and maintenance and which do not. Such investments—or the lack of them—have direct effects on the health and development of our children.

The historical lack of investment in infrastructure for the common good and failure to ensure that housing is available at affordable rates not only affect public housing and urban schools—it can have other consequences that are equally hazardous to the health and development of young children.

Airborne particles, dust, chemicals, viruses/bacteria, vermin, and stress are all known contributors to a range of respiratory and allergic conditions, including asthma. Whether a child develops asthma or asthma symptoms become worse depends on how often and how much the child is exposed to these triggers and how the exposures *interact* with each individual's genetic predispositions.[60] In susceptible individuals, these triggers can initiate a more extreme inflammatory response in the body, which can damage cells in the lungs. Fine particles can also block passages in the lungs, contributing to reduced lung function.[26] Household mold and poor ventilation alone contribute to 21% of all asthma cases in the US,[61] and asthma disproportionately affects low-income Black and Puerto Rican children.[17,62] It has been estimated that the elimination of residential risk factors such as these would result in a 44% decline in physician-diagnosed asthma among US children under age 6.[63]

Strategies that address inequities in zoning, housing, schools, and community buildings are critically important to public health overall and could have broad benefits for children and their caregivers.

Beyond the inequities in housing outlined above, many children and caregivers in the US lack permanent housing altogether. This is a critical issue for child health and development, with major implications for indoor air exposures. In 2023, a minimum estimate of 100,000 children were without permanent housing in the US; nearly 60% of them lived in shelters.[64] While further research is needed to understand the exposures for children living in shelters, initial studies

demonstrate that there are two to six times more asthma cases among young children in these settings than the national average,[65-67] and children and youth who are unhoused are hospitalized for asthma at 31 times the rate of housed children.[68] Perhaps because shelters tend to be poorly ventilated and overcrowded, and many shelters are only available overnight,[17] those who use shelters are exposed to similar amounts of air pollution as unhoused people who do not. In one study, 90% of unhoused people reported seeking medical attention for conditions associated with poor air quality, with no significant differences between sheltered and unsheltered individuals.[69]

Solutions do exist, but they can be difficult to implement, pointing to the critical need to increase access to safe and healthy housing for everyone during pregnancy and early childhood. For example, during the COVID-19 pandemic, the Department of Public Health in Seattle and King County, Washington, distributed more than 4,000 portable air cleaners with HEPA filters to shelters. A follow-up study showed that these filters could be an effective short-term strategy for reducing indoor particle levels but also found that often shelters did not have the resources to keep the portable cleaners on and running.[70]

Effective Strategies to Advance Fairness in Air Quality Can Create a Multiplier Effect

Cleaner indoor air and improved lifelong health for our children are within reach, starting with better ventilation and filtration, particularly in the spaces where we spend the most time during pregnancy and early childhood. With this in mind, for greatest effect, improvement should begin by prioritizing childcare facilities, schools, kitchens, and bedrooms.[7,71] Other important indoor spaces include community centers, offices, medical facilities, single- and multi-family homes, apartment buildings, mobile and manufactured homes, shelters, and entertainment venues like movie theaters, as well as micro-environments such as cars, buses, and trains.[72,73]

A balanced approach to cleaner indoor air would include taking action across three distinct levels of solutions. First, we can **protect** children from the greatest harm through immediate actions that improve air quality in specific indoor spaces and support those who have been exposed to poor indoor air quality and are experiencing adverse effects as a result. Second, we can **adapt** our building, zoning, and public health practices to ensure full, equitable availability of indoor spaces with clean air. This includes allocating resources to retrofit or update spaces to enhance a variety of features that contribute to good air quality. Third, we must **prevent** the causes of air pollution at the source—through policies, pressure from the public on policymakers and leaders with decision-making power, and the same type of industrial ingenuity that took on the outdoor air pollution problems of the 1970s and ’80s. We must apply similar strategies to 21st-century air-quality problems, such as reducing the burning of fossil fuels that are warming our planet and leading to more intense heat and wildfires, as well as reducing the use of toxic chemicals in cleaning products and manufacturing and enforcing existing EPA regulations. Equally important is ensuring

that disadvantaged neighborhoods, especially those located close to sources of air pollution, receive equal monitoring compared with neighborhoods with more economic resources and higher percentages of White residents.[74] All these approaches are necessary, all have ready solutions, and all will contribute to dramatically improving the prospects of every child to live a longer, healthier life.

Protect: Take immediate actions to reduce harm

Monitor indoor air quality in early care centers and schools. To adjust systems to improve air quality, those responsible for public buildings, such as schools, need to know what substances are contaminating their air, where these pollutants come from, and how big the problem is. This can be done through inexpensive indoor air quality sensors in childcare centers and classrooms.

Switch to safer building, cleaning, and other household products. Commercial cleaning products, paints, and glues are a significant source of VOCs in indoor air.[14] Requiring the use of low-VOC products in childcare facilities, schools, camps, and offices would reduce exposure to these chemicals[12] during pregnancy and early childhood and decrease the risk of a range of lung conditions, including childhood asthma and respiratory infections.[14] Finally, requiring products that are free of forever chemicals, flame retardants, and phthalates in schools and childcare centers can significantly decrease exposure to these harmful pollutants. Find more about this topic in "Resources for Taking Action" below.

Use a hooded kitchen exhaust fan that vents to the outside. In homes and other buildings where these exhaust fans are already in place, using them consistently before, during, and after cooking can help because kitchen use is one of the biggest sources of indoor pollution in homes.[13,19] Venting to the outside is critically important, as many exhaust fans simply recirculate air into the home. Window fans can also be used to blow indoor air outside—air conditioner units in windows typically just recycle indoor air. Buildings can also be adapted to install exhaust fans or update the ventilation so that the uptake is vented to the outside rather than back into the kitchen.

Requiring products that are free of forever chemicals, flame retardants, and phthalates in schools and childcare centers can significantly decrease exposure to these harmful pollutants.

Utilize portable, room-based air purifiers with HEPA filters in childcare centers, classrooms, and homes as a supplement to improve indoor air quality. These free-standing filters are cost-effective and can be useful when heating, ventilation, and air conditioning (HVAC) system updates are not possible or as an additional way to ensure good air quality. They can remove 99.97% of airborne particles and bacteria, but they must be sized correctly for the space that they are in. Resources like the Portable Air Cleaner Sizing Tool (PACS) can be used to select an appropriately sized portable air cleaner based on factors such as building type and ventilation features. (Buyers should avoid portable purifiers with ionizers that also generate ozone, which can *reduce* air quality.[75]) By reducing indoor air pollution and airborne allergens, HEPA filters can also reduce asthma symptoms and improve lung function.[76] Location is important: For preventing illness, deploying a portable air cleaner at the center of the room is recommended, and adjusting it to sit at the breathing height of occupants (e.g., 3-4 feet for seated children in schools, closer to the floor for childcare centers) can enhance effectiveness in spaces with poor air mixing.[77] Allowing physicians

to "prescribe" HEPA or MERV 13 filters for air systems for childcare facilities and homes near polluted roadways and those in areas affected by wildfire smoke could give low-income families and childcare providers access to subsidies to improve air quality for children.

Adapt: Allocate resources toward improving current systems, services, and infrastructure

Reduce and absorb emissions by creating vegetation barriers. Adding natural vegetation barriers near childcare centers, schools, and other buildings in high-traffic zones can help reduce exposure to air pollution both outdoors and indoors.[78] One study showed that barriers of bushes and trees that are sufficiently tall and deep can reduce polluting particles that reach the inhabitants of nearby buildings by up to 60%.[79]

Transition to less polluting appliances. In homes and childcare facilities that use gas heat and stoves, concentrations of harmful air pollution that contains nitrogen dioxide and airborne particles can be higher than outdoors.[76] Induction cooktops, which use a copper coil to create electromagnetic energy, are three times more efficient than gas stoves and produce 40 times fewer emissions of ultrafine particles.[76] Converting from gas to induction cooktops is costly, but subsidies for this transition would protect health, save energy, and reduce greenhouse gas emissions. Phasing out natural gas for heating and cooking will not only improve respiratory health by reducing hazardous by-products and secondary pollutants such as ozone but also will mitigate climate change impacts by reducing leaks of greenhouse gases such as methane.[76] US cities, like Cleveland, are already implementing kitchen appliance replacement programs to good effect to support efforts to improve indoor air quality and increase their communities' climate resilience.

Make buildings healthier. According to the Healthy Buildings Program at the Harvard T.H. Chan School of Public Health, an approach to providing air quality that truly supports good health would include implementation of the following measures by those responsible for building construction, maintenance, and oversight:

- using ventilation that controls indoor sources of odors, chemicals, and carbon dioxide and filters out at least 75% of particles;
- providing regular maintenance and monitoring of ventilation systems;
- choosing supplies, furnishings, and building materials with low chemical emissions;
- installing a vapor barrier (material that controls moisture and prevents mold); and
- implementing an integrated pest management plan with a focus on preventative measures such as sealing entry points, preventing moisture buildup, and removing trash.[80]

Install and maintain adequate ventilation and filtration systems in schools located in low-income neighborhoods and verify that their building systems are operating as designed. Filters for HVAC systems use an effectiveness rating system known as Minimum Efficiency Reporting Value (MERV).[79] Centralized HVAC systems are designed primarily for heating and cooling, but when equipped with high-efficiency MERV 13 filters, which are feasible in nearly all systems, they can remove up to 90% of airborne particles.[79] Upgrading filters in existing HVAC systems to those with ratings of MERV 13 or higher reduces children's exposure to indoor air pollutants that are generated indoors (including those generated by cleaning, vacuuming, cooking, or frequent printer use) as well as those that come from the outdoor environment but

make their way in (such as PM2.5 from traffic, wildfires, and outdoor dust).

Proper maintenance and use of recently retrofitted and upgraded HVAC systems in schools would improve children's health and school performance significantly yet is surprisingly rare. For example, a California study of schools with recently retrofitted HVAC systems found that only 5% of classrooms met minimum ventilation rates due to improperly selected equipment, incorrect fan control settings, and maintenance issues like not changing filters.[81,82] Installing and properly using these systems could have a significant effect on child health: One study of a school located near a high-traffic roadway found that using a ventilation system with fine-particle filters (rated MERV 14) reduced the exposure of schoolchildren to traffic exhaust by about one-third.[83]

Prevent: Address the root causes of poor indoor air quality by reducing our reliance on fossil fuels and investing in renewable energy sources

Enact regional, state, and local policies and regulations that improve indoor air quality by reducing pollution sources in all developmental environments. The federal Clean Air Act of 1970 and many examples of state and community policies have demonstrated the power of regulation to improve air quality and health. For example, New York City's 2012 Clean Heat Program supported the transition from fossil fuel heating sources to cleaner energy forms. In just four years, it achieved documented reductions in outdoor air pollution gases with a demonstrated impact on health outcomes.[76,84] In 2023, New York became the first state to pass a law phasing out gas and other fossil fuels in new residential buildings.[85] Expanding these and other policies that reduce outdoor air pollution would contribute to improving the air we breathe indoors as well, but they are insufficient without new regulations that specifically address indoor air quality. For example, it should be common sense and sound policy to require that the cleaning and building products, carpets, furniture, and cooking appliances we use in places where we spend the most time during pregnancy and childhood are safe and free of toxins.

Develop and enforce health-based regulatory standards for indoor air quality so this becomes the norm when buildings are designed, constructed, and renovated. The current standards for minimum ventilation rates for indoor air quality that were established by ASHRAE—an international membership organization focused on improving the sustainability of heating, ventilation, and air conditioning—are based on odor control, not on health, despite many studies that demonstrate that meeting these standards are insufficient for our health.[86] Higher ventilation rates are associated with improved performance on reading and math tests, decreased risk of respiratory infection, improved cognitive function scores, and a decrease in absenteeism.[87] Despite the robust research demonstrating the health and economic benefits of higher ventilation rates, the standards for "acceptable" rates continue to be the foundation for many building codes. Professional organizations, including a group of more than 40 international experts as well as the Lancet COVID-19 Commission,[88] have proposed indoor air quality standards for ventilation based on health, and these standards could be implemented across the range of spaces where children spend time, including schools, early care centers, and housing units.

Presently, no national standards exist for indoor air quality in schools, and the EPA does not require air monitoring in schools (although at the time of publication of this paper, proposed bipartisan legislation would empower the EPA to take steps toward addressing indoor air quality in schools), further driving

inequities in health and learning that are exacerbated by a lack of consistent funding for school facility maintenance and repairs. While many schools around the country have taken steps to address indoor air quality, the responsibility presently lies within the school districts rather than the state or federal government, leading to wide variability and inequities in indoor environments for children based on where they live.

Site new childcare centers and schools in areas with less air pollution. Across the US about 8,000 schools serving 4.4 million students—1 in 11 schools—are sited within 500 feet of a high-volume road (with daily traffic of at least 30,000 vehicles).[89] Living and going to school near busy roads is associated with a higher risk of asthma and chronic bronchitis, stunted lung development, and cancer,[90] as well as lower academic performance.[59] A 2024 study of infant care rooms in two different locations showed that the one closest to a highway had 68% higher concentrations of large particles indoors. The EPA has issued voluntary school siting guidelines,[91] and, in 2003, California enacted a law that prevents new schools from being built within 500 feet of busy roads to address air quality problems.

Develop policies and regulations that limit bus and vehicle idling near schools and residential neighborhoods and require buses that are electric or use cleaner-burning fuels to reduce children's exposure to particles carried by emissions that blow from roadways into buildings.[78] Children riding cleaner buses also experience less air pollution and tend to show less evidence of inflammation and more rapid lung growth over time, while schools see reduced absenteeism.[79,92] Researchers estimated the health benefits of replacing *one* diesel bus with an electric bus are $43,800 (largely from reductions in pollution-related deaths and new childhood asthma cases), with the greatest benefits coming from replacing the oldest buses in the most densely populated areas.[93] Establishing low-emission zones, as has been done in more than 200 cities in Europe, is another effective approach—a 2024 study documented a 13% reduction in prescriptions for asthma medications by age 5 for children who were in a low-emission zone in the first year of life and during pregnancy, compared to children outside the zone.[94]

Enacting all three levels of solutions—protect, adapt, and prevent—will require individuals and organizations in both private and public sectors to work together. While each of these solution levels is effective in addressing specific needs and opportunities, none will be sufficient in isolation, particularly because indoor air pollution does not act alone. Excessive heat, contaminated water, sociodemographic variables, and many other factors such as stress, poverty, discrimination, and lack of opportunity also affect whether children and their caregivers have what they need to thrive.[60] Investing in solutions at all levels is essential to ensuring the healthy development of all children. Longer term, the deeper solutions lie upstream—reducing the causes of air pollution and wildfires and eliminating the toxic chemicals hidden in products sold widely to the public. Although the challenges are significant, there are available solutions that we can implement now to protect ourselves and our children and to adapt local systems in response to our current needs. The future health and well-being of our communities—and our children—depend on it.

Resources for Taking Action

Agency for Toxic Substances and Disease Registry
Formaldehyde in Your Home

American Lung Association
Healthy Air Initiatives

Centers for Disease Control and Prevention
About Ventilation and Respiratory Viruses

Citizen Science
Learn how the public can get involved to advance inclusive research

Enterprise
How Affordable Housing Can Address Harm Caused by Air Pollution

Children's Environmental Health Network
Eco-Healthy Child Care
Fact Sheets: Air Quality

Johns Hopkins Bloomberg School of Public Health
How States Can Better Regulate Indoor Air Quality

Public Health Insider
How Childcare and Early Learning Programs Are Taking Simple Steps to Improve Indoor Air Quality

Respiratory Health Association
Advocacy opportunities

US Environmental Protection Agency

- Air Sensor Toolbox
- Clean School Bus Program
- Healthy School Environments
- Identifying Greener Cleaning Products
- Indoor Air Quality by Building Type
- Recommendations for Constructing Roadside Vegetation Barriers to Improve Near-Road Air Quality
- Regional and State Contacts for Indoor Air Quality

Further Reading

Designing vegetation barriers for urban air pollution abatement: a practical review for appropriate plant species selection (Barwise & Kumar, *Nature Partner Journal Climate and Atmospheric Science*)

Engaging communities in addressing air quality: a scoping review (Ward et al., *Environmental Health*)

Lancet: COVID Commission Report July 2022

The 9 Foundations of a Healthy Building

References

1. National Scientific Council on the Developing Child. Connecting the Brain to the Rest of the Body: Early Childhood Development and Lifelong Health Are Deeply Intertwined—Working Paper No. 15. 2020. developingchild.harvard.edu
2. Cedeno-Laurent JG, Williams A, MacNaughton P, et al. Building Evidence for Health: Green Buildings, Current Science, and Future Challenges. *Annu Rev Public Health*. Apr 1 2018;39:291-308. doi:10.1146/annurev-publhealth-031816-044420
3. Gardiner B. This landmark law saved millions of lives and trillions of dollars. National Geographic: The National Geographic Society; 2020.
4. US EPA Office of Air and Radiation. The Benefits and Costs of the Clean Air Act from 1990 to 2020. 2011. epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act-1990-2020-report-documents-and-graphics
5. Burke M, Childs ML, de la Cuesta B, et al. The contribution of wildfire to PM(2.5) trends in the USA. *Nature*. Oct 2023;622(7984):761-766. doi:10.1038/s41586-023-06522-6
6. Klepeis NE, Nelson WC, Ott WR, et al. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Anal Environ Epidemiol*. May-Jun 2001;11(3):231-52. doi:10.1038/sj.jea.7500165
7. Nethery E, Brauer M, Janssen P. Time-activity patterns of pregnant women and changes during the course of pregnancy. *J Expo Sci Environ Epidemiol*. Mar 2009;19(3):317-24. doi:10.1038/jes.2008.24
8. US EPA. How big a problem is poor indoor air quality (IAQ) in schools? US Environmental Protection Agency. https://www.epa.gov/iaq-schools/how-big-problem-poor-indoor-air-quality-iaq-schools
9. US EPA. Volatile Organic Compounds' Impact on Indoor Air Quality. US Environmental Protection Agency. epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality
10. Allen J, Macomber J. Healthy Buildings: *How Indoor Spaces Can Make You Sick—or Keep You Well*. 2022.
11. Weschler CJ. Changes in indoor pollutants since the 1950s. *Atmos Environ*. 2009/01/01/ 2009;43(1):153-169. doi:10.1016/j.atmosenv.2008.09.044
12. Vardoulakis S, Giagloglou E, Steinle S, et al. Indoor Exposure to Selected Air Pollutants in the Home Environment: A Systematic Review. *Int J Environ Res Public Health*. Dec 2 2020;17(23) doi:10.3390/ijerph17238972
13. Royal College of Paediatrics and Child Health. The inside story: Health effects of indoor air quality on children and young peopl. 2020. rcpch.ac.uk/resources/inside-story-health-effects-indoor-air-quality-children-young-people
14. Temkin AM, Geller SL, Swanson SA, Leiba NS, Naidenko OV, Andrews DQ. Volatile organic compounds emitted by conventional and "green" cleaning products in the U.S. market. *Chemosphere*. Nov 2023;341:139570. doi:10.1016/j.chemosphere.2023.139570
15. Tjalvin G, Svanes Ø, Igland J, et al. Maternal preconception occupational exposure to cleaning products and disinfectants and offspring asthma. *J Allergy Clin Immunol*. 2022/01/01/ 2022;149(1):422-431. e5. doi:10.1016/j.jaci.2021.08.025
16. Ferguson L, Taylor J, Davies M, Shrubsole C, Symonds P, Dimitroulopoulou S. Exposure to indoor air pollution across socio-economic groups in high-income countries: A scoping review of the literature and a modelling methodology. *Environ Int*. Oct 2020;143:105748. doi:10.1016/j.envint.2020.105748
17. Swope CB, Hernandez D. Housing as a determinant of health equity: A conceptual model. *Soc Sci Med*. Dec 2019;243:112571. doi:10.1016/j.socscimed.2019.112571
18. Holden KA, Lee AR, Hawcutt DB, Sinha IP. The impact of poor housing and indoor air quality on respiratory health in children. *Breathe (Sheff)*. Jun 2023;19(2):230058. doi:10.1183/20734735.0058-2023
19. Chiarello DI, Ustariz J, Marin R, et al. Cellular mechanisms linking to outdoor and indoor air pollution damage during pregnancy. *Front Endocrinol (Lausanne)*. 2023;14:1084986. doi:10.3389/fendo.2023.1084986
20. Ghazi T, Naidoo P, Naidoo RN, Chuturgoon AA. Prenatal Air Pollution Exposure and Placental DNA Methylation Changes: Implications on Fetal Development and Future Disease Susceptibility. *Cells*. Nov 5 2021;10(11). doi:10.3390/cells10113025
21. Tuazon JA, Kilburg-Basnyat B, Oldfield LM, et al. Emerging Insights into the Impact of Air Pollution on Immune-Mediated Asthma Pathogenesis. *Curr Allergy Asthma Rep*. Jul 2022;22(7):77-92. doi:10.1007/s11882-022-01034-1
22. National Scientific Council on the Developing Child. A World of Differences: The Science of Human Variation Can Drive Early Childhood Policies and Programs to Bigger Impacts: Working Paper No. 17. 2024. developingchild.harvard.edu
23. Christensen GM, Marcus M, Naude PJW, et al. Joint effects of prenatal exposure to indoor air pollution and psychosocial factors on early life inflammation. *Environ Res*. Jul 1 2024;252(Pt 1):118822. doi:10.1016/j.envres.2024.118822
24. Liu K, Hua S, Song L. PM2.5 Exposure and Asthma Development: The Key Role of Oxidative Stress. *Oxid Med Cell Longev*. 2022;2022:3618806. doi:10.1155/2022/3618806
25. Basilio E, Chen R, Fernandez AC, Padula AM, Robinson JF, Gaw SL. Wildfire Smoke Exposure during Pregnancy: A Review of Potential Mechanisms of Placental Toxicity, Impact on Obstetric Outcomes, and Strategies to Reduce Exposure. *Int J Environ Res Public Health*. Oct 22 2022;19(21). doi:10.3390/ijerph192113727
26. Veras MM, de Oliveira Alves N, Fajersztajn L, Saldiva P. Before the first breath: prenatal exposures to air pollution and lung development. *Cell Tissue Res*. Mar 2017;367(3):445-455. doi:10.1007/s00441-016-2509-4
27. US EPA. Facts About Formaldehyde. US Environmental Protection Agency. Accessed 7/4/2024. epa.gov/formaldehyde/facts-about-formaldehyde
28. Franklin P, Tan M, Hemy N, Hall GL. Maternal Exposure to Indoor Air Pollution and Birth Outcomes. *Int J Environ Res Public Health*. Apr 16

2019;16(8). doi:10.3390/ijerph16081364

29. Costa LG, Cole TB, Dao K, Chang YC, Coburn J, Garrick JM. Effects of air pollution on the nervous system and its possible role in neurodevelopmental and neurodegenerative disorders. *Pharmacol Ther*. Jun 2020;210:107523. doi:10.1016/j.pharmthera.2020.107523

30. Sen A, Heredia N, Senut MC, et al. Multigenerational epigenetic inheritance in humans: DNA methylation changes associated with maternal exposure to lead can be transmitted to the grandchildren. *Sci Rep*. Sep 29 2015;5:14466. doi:10.1038/srep14466

31. K CA, Basel PL, Singh S. Low birth weight and its associated risk factors: Health facility-based case-control study. *PLoS One*. 2020;15(6):e0234907. doi:10.1371/journal.pone.0234907

32. US CDC. Preterm Birth. US Centers for Disease Control and Prevention. Accessed 7/13/24. cdc.gov/maternal-infant-health/preterm-birth/index.html

33. Cromar K, Gladson L, Gohlke J, Li Y, Tong D, Ewart G. Adverse Health Impacts of Outdoor Air Pollution, Including from Wildland Fires, in the United States: "Health of the Air," 2018-2020. *Ann Am Thorac Soc*. Jan 2024;21(1):76-87. doi:10.1513/AnnalsATS.202305-455OC

34. Goodrich AJ, Kleeman MJ, Tancredi DJ, et al. Pre-pregnancy ozone and ultrafine particulate matter exposure during second year of life associated with decreased cognitive and adaptive functioning at aged 2-5 years. *Environ Res*. Jul 1 2024;252(Pt 1):118854. doi:10.1016/j.envres.2024.118854

35. Vanbrabant K, Van Dam D, Bongaerts E, et al. Accumulation of Ambient Black Carbon Particles Within Key Memory-Related Brain Regions. *JAMA Netw Open*. Apr 1 2024;7(4):e245678. doi:10.1001/jamanetworkopen.2024.5678

36. Zundel CG, Ryan P, Brokamp C, et al. Air pollution, depressive and anxiety disorders, and brain effects: A systematic review. *Neurotoxicology*. Dec 2022;93:272-300. doi:10.1016/j.neuro.2022.10.011

37. Ruis M, Hoffman K, Stapleton HM. Brominated flame retardants and legacy organochlorines in archived human placenta samples: Sex differences, temporal analysis and associations with infant birth weight. *Chemosphere*. May 2023;322:138170. doi:10.1016/j.chemosphere.2023.138170

38. Leonetti C, Butt CM, Hoffman K, Hammel SC, Miranda ML, Stapleton HM. Brominated flame retardants in placental tissues: associations with infant sex and thyroid hormone endpoints. *Environ Health*. Nov 25 2016;15(1):113. doi:10.1186/s12940-016-0199-8

39. Rahman MM, Shu YH, Chow T, et al. Prenatal Exposure to Air Pollution and Autism Spectrum Disorder: Sensitive Windows of Exposure and Sex Differences. *Environ Health Perspect*. Jan 2022;130(1):17008. doi:10.1289/EHP9509

40. Dickerson AS, Rotem RS, Christian MA, Nguyen VT, Specht AJ. Potential Sex Differences Relative to Autism Spectrum Disorder and Metals. *Curr Environ Health Rep*. Dec 2017;4(4):405-414. doi:10.1007/s40572-017-0164-x

41. Yu X, Rahman MM, Wang Z, et al. Evidence of susceptibility to autism risks associated with early life ambient air pollution: A systematic review. *Environ Res*. 2022/05/15/ 2022;208:112590. doi:10.1016/j.envres.2021.112590

42. Lin C-K, Chang Y-T, Lee F-S, Chen S-T, Christiani D. Association between exposure to ambient particulate matters and risks of autism spectrum disorder in children: a systematic review and exposure-response meta-analysis. *Environ Res Lett*. 2021/05/28 2021;16(6):063003. doi:10.1088/1748-9326/abfcf7

43. US CDC. Facts About Benzene. US Centers for Disease Control and Prevention. emergency.cdc.gov/agent/benzene/basics/facts.asp

44. D'Andrea MA, Reddy GK. Health Risks Associated With Benzene Exposure in Children: A Systematic Review. *Glob Pediatr Health*. 2018;5:2333794X18789275. doi:10.1177/2333794X18789275

45. National Scientific Council on the Developing Child. Connecting the Brain to the Rest of the Body: Early Childhood Development and Lifelong Health Are Deeply Intertwined: Working Paper No. 15. 2020. developingchild.harvard.edu

46. Volk HE, Perera F, Braun JM, et al. Prenatal air pollution exposure and neurodevelopment: A review and blueprint for a harmonized approach within ECHO. *Environ Res*. May 2021;196:110320. doi:10.1016/j.envres.2020.110320

47. McGuinn LA, Windham GC, Messer LC, et al. Air pollution, neighborhood deprivation, and autism spectrum disorder in the Study to Explore Early Development. *Environ Epidemiol*. Oct 2019;3(5). doi:10.1097/ee9.0000000000000067

48. Evans J, Bansal A, Schoenaker D, Cherbuin N, Peek MJ, Davis DL. Birth Outcomes, Health, and Health Care Needs of Childbearing Women following Wildfire Disasters: An Integrative, State-of-the-Science Review. *Environ Health Perspect*. Aug 2022;130(8):86001. doi: 10.1289/EHP10544

49. US EPA. Safer Choice. US Environmental Protection Agency. Accessed 7/15/24. epa.gov/saferchoice

50. Steinemann A. Fragranced consumer products: exposures and effects from emissions. *Air Qual Atmos Health*. 2016/12/01 2016;9(8):861-866. doi:10.1007/s11869-016-0442-z

51. Wang X, Li C, Zhou L, et al. Associations of prenatal exposure to PM2.5 and its components with offsprings' neurodevelopmental and behavioral problems: A prospective cohort study from China. *Ecotoxicol Environ Saf*. 2024/09/01/ 2024;282:116739. doi:10.1016/j.ecoenv.2024.116739

52. Health Impacts of PM2.5. State of Global Air. Accessed Apr 2 2025. stateofglobalair.org/health/pm

53. Ghetu CC, Rohlman D, Smith BW, et al. Wildfire Impact on Indoor and Outdoor PAH Air Quality. *Environ Sci Technol*. Jul 19 2022;56(14):10042-10052. doi:10.1021/acs.est.2c00619

54. Jacob DJ, Winner DA. Effect of climate change on air quality. *Atmos Environ*. 2009/01/01/ 2009;43(1):51-63. doi:10.1016/j.atmosenv.2008.09.051

55. US EPA. Health Effects of Ozone Pollution. U.S. Environmental Protection Agency. Accessed 7/17/24. epa.gov/ground-level-ozone-pollution/health-effects-ozone-pollution

56. State of Global Air 2024. Special Report. 2024. stateofglobalair.org/resources/report/state-global-air-report-2024

57. Burrows L. The complex relationship between heat and ozone. The Harvard Gazette: Harvard University; 2016.

58. Bryant-Stephens TC, Strane D, Robinson EK, Bhambhani S, Kenyon CC. Housing and asthma disparities. *J Allergy Clin Immunol*. Nov 2021;148(5):1121-1129. doi:10.1016/j.jaci.2021.09.023

59. Pastor Jr. M, Morello-Frosch R, Sadd

JL. Breathless: Schools, Air Toxics, and Environmental Justice in California. *Policy Studies Journal*. 2006;34(3):337-362. doi:10.1111/j.1541-0072.2006.00176.x

60. National Scientific Council on the Developing Child. Place Matters: The Environment We Create Shapes the Foundations of Healthy Development. 2023. developingchild.harvard.edu

61. Lemire E, Samuels EA, Wang W, Haber A. Unequal Housing Conditions And Code Enforcement Contribute To Asthma Disparities In Boston, Massachusetts. *Health Aff (Millwood)*. Apr 2022;41(4):563-572. doi:10.1377/hlthaff.2021.01403

62. Perez MF, Coutinho MT. An Overview of Health Disparities in Asthma. *Yale J Biol Med*. Sep 2021;94(3):497-507.

63. Lanphear BP, Kahn RS, Berger O, Auinger P, Bortnick SM, Nahhas RW. Contribution of residential exposures to asthma in us children and adolescents. *Pediatrics*. Jun 2001;107(6):E98. doi:10.1542/peds.107.6.e98

64. US HUD. The 2023 Annual Homelessness Assessment Report (AHAR) to Congress: PART 1: Point-In-Time Estimates of Homelessness. 2023. huduser.gov/portal/datasets/ahar/2023-ahar-part-1-pit-estimates-of-homelessness-in-the-us.html

65. Cutuli JJ, Herbers JE, Rinaldi M, Masten AS, Oberg CN. Asthma and behavior in homeless 4- to 7-year-olds. *Pediatrics*. Jan 2010;125(1):145-51. doi:10.1542/peds.2009-0103

66. McLean DE, Bowen S, Drezner K, et al. Asthma among homeless children: undercounting and undertreating the underserved. *Arch Pediatr Adolesc Med*. Mar 2004;158(3):244-9. doi:10.1001/archpedi.158.3.244

67. Cutuli JJ, Herbers JE, Lafavor TL, Ahumada SM, Masten AS, Oberg CN. Asthma and adaptive functioning among homeless kindergarten-aged children in emergency housing. *J Health Care Poor Underserved*. May 2014;25(2):717-30. doi:10.1353/hpu.2014.0099

68. Sakai-Bizmark R, Chang RR, Mena LA, Webber EJ, Marr EH, Kwong KY. Asthma Hospitalizations Among Homeless Children in New York State. *Pediatrics*. Aug 2019;144(2) doi:10.1542/peds.2018-2769

69. DeMarco AL, Hardenbrook R, Rose J, Mendoza DL. Air Pollution-Related Health Impacts on Individuals Experiencing Homelessness: Environmental Justice and Health Vulnerability in Salt Lake County, Utah. *Int J Environ Res Public Health*. Nov 13 2020;17(22)doi:10.3390/ijerph17228413

70. Huang C-H, Bui T, Hwang D, et al. Assessing the effectiveness of portable HEPA air cleaners for reducing particulate matter exposure in King County, Washington homeless shelters: Implications for community congregate settings. *Sci Total Environ*. 2023/09/15/ 2023;891:164402. doi:10.1016/j.scitotenv.2023.164402

71. Lizana J, Almeida SM, Serrano-Jiménez A, et al. Contribution of indoor microenvironments to the daily inhaled dose of air pollutants in children. The importance of bedrooms. *Build Environ*. 2020;183:107188.

72. Diapouli E, Chaloulakou A, Spyrellis N. Levels of ultrafine particles in different microenvironments--implications to children exposure. *Sci Total Environ*. Dec 15 2007;388(1-3):128-36. doi:10.1016/j.scitotenv.2007.07.063

73. Marinello S, Lolli F, Coruzzolo AM, Gamberini R. Exposure to Air Pollution in Transport Microenvironments. *Sustainability*. 2023;15(15):11958.

74. Su JG, Aslebagh S, Vuong V, et al. Examining air pollution exposure dynamics in disadvantaged communities through high-resolution mapping. *Sci Adv*. 2024;10(32):eadm9986. doi:10.1126/sciadv.adm9986

75. Holm SM, Miller MD, Balmes JR. Health effects of wildfire smoke in children and public health tools: a narrative review. *J Expo Sci Environ Epidemiol*. Feb 2021;31(1):1-20. doi:10.1038/s41370-020-00267-4

76. Nassikas NJ, McCormack MC, Ewart G, et al. Indoor Air Sources of Outdoor Air Pollution: Health Consequences, Policy, and Recommendations: An Official American Thoracic Society Workshop Report. *Ann Am Thorac Soc*. Mar 2024;21(3):365-376. doi:10.1513/AnnalsATS.202312-1067ST

77. Pei G, Azimi P, Rim D, Allen JG. A CFD study on the effect of portable air cleaner placement on airborne infection control in a classroom. *Environ Sci Process Impacts*. Jul 8 2024;doi:10.1039/d4em00114a

78. Mullen C, Grineski SE, Collins TW, Mendoza DL. Effects of PM(2.5) on Third Grade Students' Proficiency in Math and English Language Arts. *Int J Environ Res Public Health*. Sep 22 2020;17(18)doi:10.3390/ijerph17186931

79. Rawat N, Kumar P. Interventions for improving indoor and outdoor air quality in and around schools. *Sci Total Environ*. Feb 1 2023;858(Pt 2):159813. doi:10.1016/j.scitotenv.2022.159813

80. Allen JG. The 9 Foundations of a Healthy Building. Harvard T.H. Chan School of Public Health; 2017. 9foundations.forhealth.org/

81. Chan WR, Li X, Singer BC, et al. Ventilation rates in California classrooms: Why many recent HVAC retrofits are not delivering sufficient ventilation. *Build Environ*. 2020;

82. Mark-Carew M KG, Pampati S, Mead KR, Martin SB Jr., Barrios LC. Ventilation Improvements Among K–12 Public School Districts — United States, August–December 2022. *MMWR Morb Mortal Wkly Rep*. 2022;72:372–376. doi:10.15585/mmwr.mm7214a4

83. van der Zee SC, Strak M, Dijkema MBA, Brunekreef B, Janssen NAH. The impact of particle filtration on indoor air quality in a classroom near a highway. *Indoor Air*. 2017;27(2):291-302. doi:10.1111/ina.12308

84. Zhang L, He MZ, Gibson EA, et al. Evaluating the Impact of the Clean Heat Program on Air Pollution Levels in New York City. *Environ Health Perspect*. 2021;129(12):127701. doi:10.1289/EHP9976

85. Ramirez R, Nilsen E. New York becomes the first state to ban natural gas stoves and furnaces in most new buildings. CNN. cnn.com/2023/05/03/us/new-york-natural-gas-ban-climate/index.html

86. Allen JG. Recommitting to Ventilation Standards for Healthy Indoor Air Quality. *Am J Public Health*. 2024;114(10):991-993. doi:10.2105/ajph.2024.307809

87. US EPA. Evidence from Scientific Literature about Improved Academic Performance. US Environmental Protection Agency. Accessed Apr 2 2025. epa.gov/iaq-schools/evidence-scientific-literature-about-improved-academic-performance

88. Morawska L, Allen J, Bahnfleth W, et al. Mandating indoor air quality for public buildings. *Science*. 2024;383(6690):1418-1420. doi:10.1126/science.adl0677

89. Grineski SE, Collins TW. Geographic and social disparities in exposure to air neurotoxicants at U.S. public schools. *Environ Res*. Feb 2018;161:580-587. doi:10.1016/j.envres.2017.11.047

90. Wolfe MK, McDonald NC, Arunachalam S, Baldauf R, Valencia

A. Impact of School Location on Children's Air Pollution Exposure. *J Urban Aff*. Jul 7 2020;43(8). doi:10.1080/07352166.2020.1734013

91. US EPA. Healthy School Environments: View, Download, or Print the School Siting Guidelines. US Environmental Protection Agency. Accessed 7/31/24. epa.gov/schools/view-download-or-print-school-siting-guidelines

92. Adar SD, D'Souza J, Sheppard L, et al. Adopting Clean Fuels and Technologies on School Buses. Pollution and Health Impacts in Children. *Am J Respir Crit Care Med*. Jun 15 2015;191(12):1413-21. doi:10.1164/rccm.201410-1924OC

93. Choma EF, Robinson LA, Nadeau KC. Adopting electric school buses in the United States: Health and climate benefits. *Proc Natl Acad Sci U S A*. May 28 2024;121(22):e2320338121. doi:10.1073/pnas.2320338121

94. Klauber H, Holub F, Koch N, Pestel N, Ritter N, Rohlf A. Killing Prescriptions Softly: Low Emission Zones and Child Health from Birth to School. *Am Econ J Econ Policy*. 2024;16(2):220–48. doi:10.1257/pol.20210729

95. Young AS, Zoeller T, Hauser R, et al. Assessing Indoor Dust Interference with Human Nuclear Hormone Receptors in Cell-Based Luciferase Reporter Assays. *Environ Health Perspect*. Apr 2021;129(4):47010. doi:10.1289/ehp8054

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50 Church Street, 4th Floor, Cambridge, MA 02138
617.496.0578
www.developingchild.harvard.edu