Environmental threats to child brain development: A window of opportunity for broad societal impact

Overview

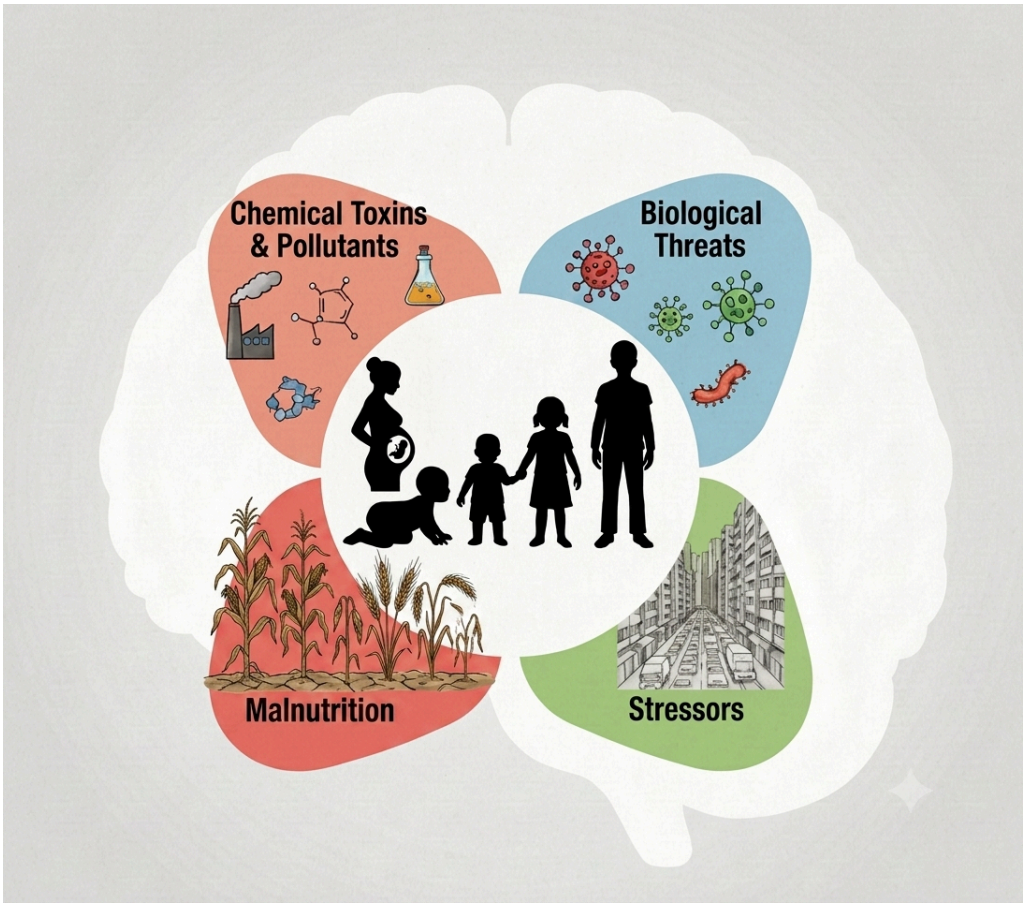
The developing brain is uniquely shaped by environmental exposures and forms of deprivation, in ways that can profoundly alter the lifecourse and affect multiple sectors of society. Crucially, many of these impacts are largely *preventable*, which presents an opportunity. *Proactively* protecting children from these threats could have positive, measurable effects – both immediately and over the decades to come. Investing in the *prevention* of harm to children, rather than merely attempting to address preexisting harms, is more effective, paying dividends for California's investments in public health, healthcare, education, labor, housing, and public safety systems. To make effective change, policymakers must be aware of known and credible risks to brain development, and why seemingly minor threats can snowball into large problems for both individuals and the state as a whole.

Environmental threats

There are four major categories of environmental threats to child brain health, driven largely by human activity (**Figure 1**; see **Appendix I** in Additional Resources):

- **Chemical toxins and pollutants** include heavy metals like lead and mercury, pesticides used in agriculture and homes, air pollution from traffic and wildfires, industrial chemicals such as flame retardants and PFAS (so-called "forever chemicals"), and radioactive contamination.
- **Biological threats** include waterborne toxins from harmful algal blooms, foodborne contaminants, viruses, vector-borne diseases spread by mosquitos and ticks, and indoor hazards like mold.
- **Maternal and child malnutrition** includes deficits in protein and essential nutrients, including those caused by environmental degradation
- **Stressors** can be acute or chronic. They include aspects of the built landscape that impact brain health, like noise and light pollution, extreme heat, and lack of green space. They also include climate-change-driven life disruptions, like loss of stable housing, social networks, educational access, essential healthcare, and government services.

These exposures and deficiencies impact children's brains through numerous pathways, from the water and food they consume, the air they breathe, the places they live in, and the backyards and fields where they play.



Nano Banana Pro 2.0

Figure 1. Four major categories of environmental threats to the developing brain.

Environmental threats can inflict direct and immediate damage, as in the case of cyanotoxins from harmful algal blooms and West Nile Virus, both of which are prevalent in California. However, they can also pose cumulative downstream risks, as in the case of chronic stress and lost educational access following climate change-driven natural disasters. Despite being recognized for decades as harmful to children's brains, and subject to regulation, many well-known threats like lead and organophosphates remain ever-present risks across the state. More recently recognized dangers like air pollution, agricultural chemicals, and PFAS offer much broader and underappreciated menaces to healthy child brain development.

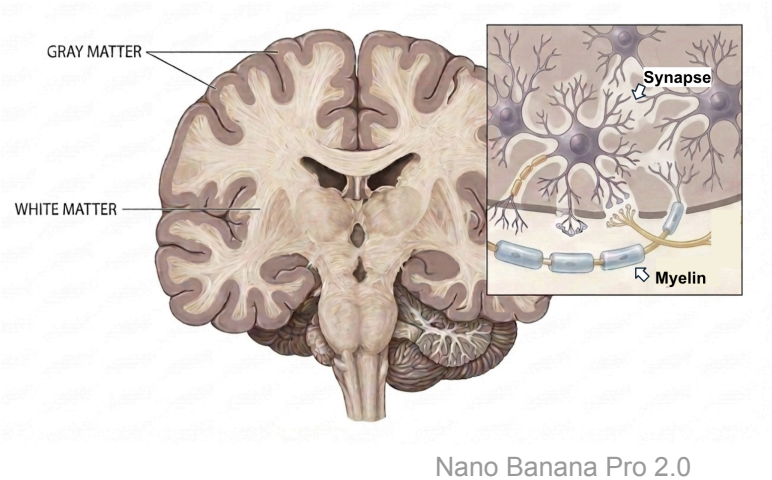
Impact on brain development & child outcomes

The brain is most sensitive to the environment while it is still developing – for better and for worse

The basic brain structure is 'built' prenatally and undergoes big changes through the first few years of life. It then continues to be refined over childhood and adolescence, as brain networks that underpin every aspect of behavior are organized and strengthened. Environmental threats can affect the brain at any point in a person's lifetime, but the impact is greatest during development. Brain networks are most *plastic*, or sensitive to experience, when they are undergoing the most dramatic changes early in childhood; these phases are referred to as "sensitive periods" for the development of specific capacities. However, these networks remain sensitive to experience during late childhood & adolescence, including during a second window of heightened vulnerability and plasticity in adolescence.

Multiple aspects of brain structure change during development

In a nutshell, the brain is made up of two distinct types of tissue: grey matter and white matter (**Figure 2**). Grey matter is where the brain's computations take place: where neurons integrate signals coming from connections, or synapses, with other brain cells. White matter functions as "communication highways", connecting distant brain regions into large networks that underlie every aspect of who we are and what we do. This infrastructure is constructed over time as neurons are 'born,' migrate to their final 'address,' gain and lose connections (synapses), and have their long-range 'cables' (axons) insulated with a fatty, white layer (myelin). These and other processes yield a brain that is highly attuned and *adapted to the context into which the child is born,* and are integral to the formation of a healthy adult brain.



Nano Banana Pro 2.0

Figure 2. Section of the brain, with a close-up view of the cells in the gray and white matter. Synapses are the connections between neurons. Myelin is the tissue that surrounds and insulates the neurons' long-range cables, or axons.

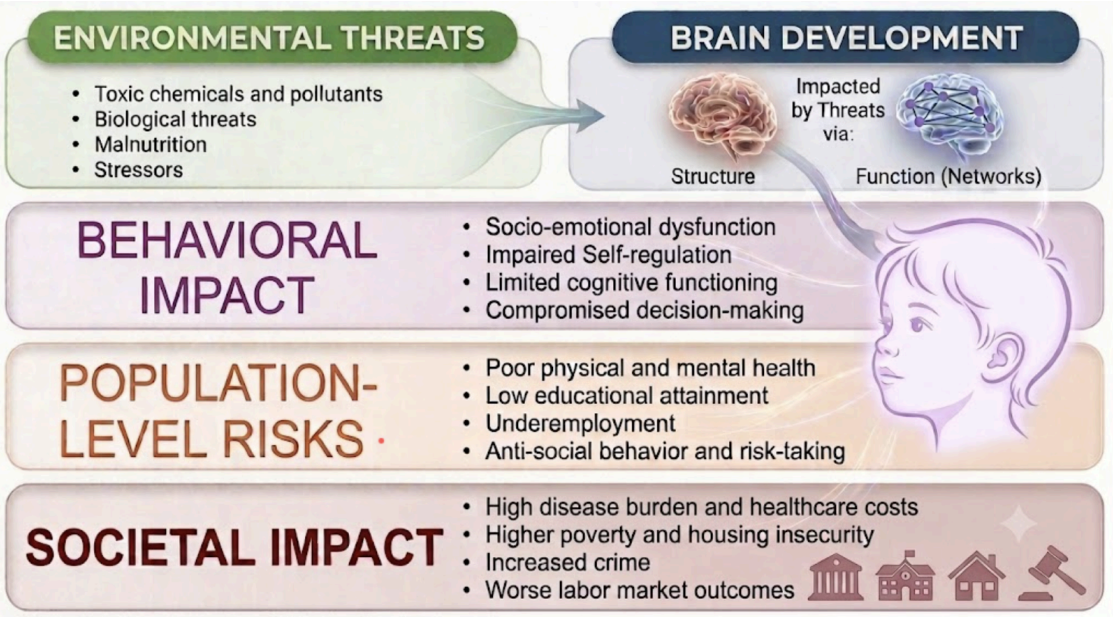
These neurodevelopmental processes are intricately coordinated, and minor disruptions can have profound consequences

During the prenatal period, the brain produces the majority of the approximately 86 billion neurons that will last a lifetime. In this phase, neurons undergo molecular specialization that determines their future function and then migrate to their correct location in the brain. After birth, the focus shifts from building cells to building circuits. The infant brain forms over one million synapses per second. This period of exuberant growth creates a surplus of connections that the brain then sculpts into circuits through a “use it or lose it” pruning process. Circuit sculpting is highly experience-dependent; healthy experience strengthens circuits while aberrant experience - including exposure to environmental toxins - can interfere with the brain’s ability to form stable circuits that underlie sensory processing, complex learning, and emotional regulation.

As circuits refine, the brain also invests heavily in white matter, insulating connections between neurons with myelin. This process continues into the early twenties, and allows for high-speed processing and large-scale networks needed for sound decision-making and self-regulation. A disruption in any of these processes can create a ripple effect that alters a child’s developmental trajectory. The brain’s heightened plasticity during this entire prenatal through adolescent developmental period creates both vulnerability and a window of opportunity for intervention.

Environmental threats can alter a child’s life course

Perturbations to brain development serve as *risk factors* for poor long-term outcomes for socio-emotional functioning, self-regulation, cognitive functioning, and decision-making (**Figure 3**). For example, research shows that prenatal or childhood exposure to lead, pesticides, or air pollution can increase the risk of autism, Attention Deficit Hyperactivity, and lower school achievement. *All* children are vulnerable to environmental threats – but particularly those who already face challenges. For example, socioeconomically disadvantaged children have a greater likelihood of direct chemical and biological exposures, as well as greater vulnerability to many downstream consequences of climate change, like wildfires (see next section). These threats can combine with other life stressors and obstacles to amplify harm. Environmental threats also trigger chronic stress that can lead to adverse lifelong outcomes.



Nano Banana Pro 2.0

Figure 3. Downstream effects of environmental threats, and far-ranging societal and fiscal impact of protecting child brain health.

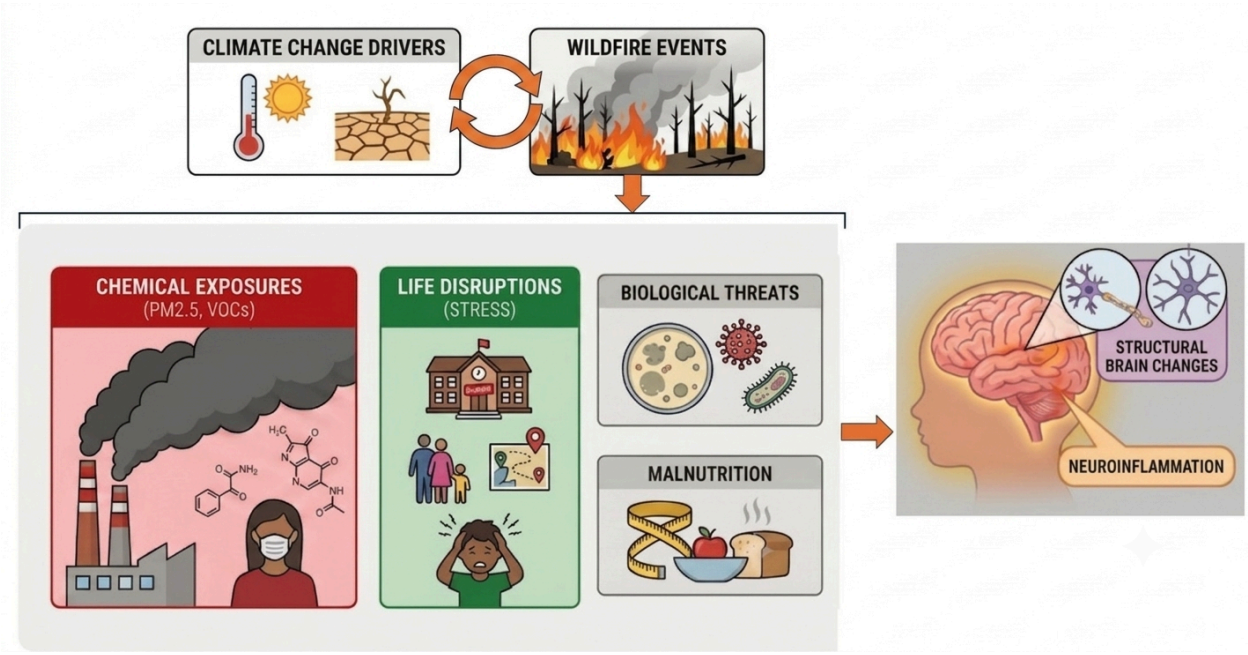
Altered brain trajectories have far-reaching consequences for all sectors of society

On a population level (**Figure 3**), environmental threats to brain development are associated with lower educational attainment and job attainment, higher levels of incarceration, and higher incidence of various conditions, including Attention Deficit Hyperactivity Disorder, intellectual disability, autism, and cerebral palsy, as well as those that can emerge decades later, like dementia. These effects, in turn, place substantial demand on public systems that support young people. They can be seen in increased need for specialized supports in K-12 schools, higher numbers of youth involved in the juvenile justice system, and greater demand for mental health services. Thus, the impact of environmental threats extends far beyond the experiences of an individual child, carrying long-term consequences for all sectors of society, including healthcare, education, labor, housing, and the judicial system.

How wildfires threaten child brain health

California's children are currently facing a neurological crisis hiding in plain sight. Climate change is driving more frequent and severe wildfires – and each wildfire season, millions of developing brains are exposed to conditions that scientists have linked to lasting neurocognitive harm (**Figure 4**; see **Appendix II** in Additional Resources). Wildfires implicate all four of the major categories of environmental threats

to child brain health, with the greatest risk in California coming from chemical toxins, pollutants, and stressors. These and other stressors can cause inflammation and structural damage in the brain.



Nano Banana Pro 2.0

Figure 4. Case study: Wildfires threaten child brain health in multiple ways.

The most immediate dangers come from air pollution. Wildfires release a toxic mixture of particulate matter, polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), carbon monoxide, nitrogen oxides, sulfur dioxide, and ground-level ozone. These pollutants impact both outdoor and indoor air quality. They do not disappear when the flames go out, but may remain in the air for months afterwards. Children in California are often exposed to these air pollutants at school as well as at home and elsewhere, as the state does not have an indoor quality standard that needs to be met for students to return to school (see **Appendix III** in Additional Resources).

The burning of homes, businesses, vehicles, and factories adds another layer of harm. Burning buildings and cars release heavy metals, industrial chemicals, and other toxic substances that contaminate water and soil, with particularly concentrated exposures occurring near fire debris dump and recycling sites—creating long-term health impacts. Wildfires also generate intense heat exposure, which can impact mothers during pregnancy and affect fetal brain development, as well as cause electrical grid failures that eliminate air conditioning and disrupt the sleep essential to children's brain health.

Putting out fires creates its own risks. Toxic chemicals in fire suppressants threaten anyone in the affected area, and water damage to buildings creates conditions for mold growth in homes, schools, and other structures. Firefighters, emergency responders, and others on the front lines face these threats in acute and concentrated form—which

can pose a danger to developing fetuses and young children when parents carry contaminants home on clothes and equipment.

The harms of wildfires are not contained to the moment of burning. Wildfires result in food contamination and insecurity, leading to nutritional deficiencies that undermine cognitive development, while altered ecological conditions following major burn events shift patterns of vector-borne diseases, increasing children's exposure to neurologically damaging infections. Moreover, by releasing massive quantities of carbon dioxide, black carbon, and other greenhouse gases, and by destroying forests that would otherwise absorb carbon, wildfires accelerate the very climate change that makes future fires more likely and severe—meaning that the full threat to child brain health must account for this compounding cycle.

The stressor-related harms from wildfires are equally extensive, impacting physical health, community cohesion, and local infrastructure. Physical displacement and housing instability force families from their homes and communities. At the same time, children's care providers and educators are also impacted, and the loss of daycare centers, along with school closures, cancelled enrichment activities, and disrupted instructional continuity deprive children of the stable educational environments critical to brain development. The loss of community anchors—churches, recreational leagues, neighborhood organizations—fractures the supports for healthy brain development, and the severing of attachment relationships, peer networks, extended family ties, and familiar teacher bonds can also inflict lasting harm. Wildfire-related stress, displacement, and loss can severely compromise the ability of families to provide the stable care, resources, and nurturing environments that children need for healthy brain development. Job loss, property destruction, and medical costs strip away the financial foundations that supports everything from nutritious food to enriching activities.

At the same time, wildfires undermine the government services that children and families depend on. Wildfire-related expenditures and reduced tax revenues force cuts to schools, nutrition programs, housing supports, and mental health services. Emergency services become overwhelmed, child protective services are strained, and healthcare access is disrupted—delaying prenatal care, well-child visits, and early intervention services that are essential to identifying and treating conditions affecting neurodevelopment.

Finally, both the experience of wildfires and general climate-change-related fears can drive anxiety, depression, and toxic stress in young people affecting brain development, while the destruction of green space eliminates vital opportunities for outdoor play, physical exercise, and independent exploration—experiences that are not peripheral luxuries but core drivers of healthy cognitive and emotional development.

Policy Implications

There is a strong moral, economic, and social case for urgent and wide-ranging government intervention to address environmental threats to brain development.

Children are the most vulnerable and sensitive population to environmental threats, but often lack the capacity, knowledge, resources, and political power to protect themselves. Many children's caregivers are unable to protect their healthy brain development by moving to an area with better air quality, paying for home renovations, providing excellent preventative healthcare, and the like. And even the most educated and wealthy parents are not in a position to hold polluting companies accountable when they threaten child brain development or escape broadening environmental catastrophes on their own. Only the government has the necessary capital, expertise, and capacity to lead the way.

The strongest grounds for robust government intervention are found in the collective benefit to society that comes in ensuring child brain health. Everyone in society—whether they have children or not—pays the costs of our failure to protect children. Some of those costs are immediate, such as the medical, educational, and care costs for a six-year-old with autism-like behaviors and lower IQ linked to pesticide exposure in utero, but many of them are incurred years after a detrimental childhood exposure or deprivation. Failing to mitigate environmental threats to child brain development at one timepoint drives major future expenditures on prisons, public housing, healthcare, and unemployment and welfare programs, extending for decades, and squandering the brain power the adults of the future will need to solve ever more complex problems. Failing to invest in children's brain health is like failing to invest in developing and maintaining necessary societal infrastructure. In California, the threat of wildfires presents an urgent opportunity to take action (**Figure 4; Appendix II**), and while important efforts are currently underway (**Appendix III**), a more significant and sweeping state response is essential.

Addressing threats to children's brain health tends to pay for itself—and then some. Looking at lead paint alone, it is estimated that each dollar invested in remediation brings a net return of $17-$221 for society, measured in terms of reduced healthcare, educational, and crime costs and increased lifetime earnings and tax revenue (Gould, *Environ Health Perspect*, 2009). A key takeaway from research on brain development is that early childhood is the window of maximal opportunity for intervention, since acting as early as possible tends to yield the greatest net return. There is enormous upside in ensuring that children never ingest heavy metals or breathe in small particulate matter, but because the brain continues to develop throughout childhood there are significant gains to be had from ensuring that the many children who do suffer from environmental threats receive the early interventions that can help them recover and achieve the best possible outcomes as they enter adulthood. Indeed, the evidence supports the value of programs that target every stage of development, from prenatal precautions to elementary school building remediation to adolescent mental healthcare.

Despite the compelling arguments for major governmental action, several damaging patterns have emerged in efforts to address environmental threats. The government has generally adopted a minimalist reactive posture, waiting for incontestable evidence of harm before acting and selecting the most modest remedies. Only a small portion of the 86,000 chemicals on the EPA's Toxic Substances Control Act inventory have been subjected to rigorous testing for developmental toxicity. Indeed, the government has often focused on individual parents exercising responsibility for their own children's brain health, rather than engaging in system-level reforms to protect all children. And it has tended to emphasize the short-term costs of addressing threats, while ignoring the far larger long-term costs of inaction.

By recognizing the value to all of us of ensuring healthy brain development, it is possible to chart a better course, guided by a set of evidence-based policy recommendations:

- Account for the full costs of environmental threats to child brain health in all policy assessments
- Strengthen and enforce regulations around well-established threats, charging industries with rigorous testing and holding industries accountable for exposures from their products and production methods
- Expedite the development of regulations around new and emerging threats
- Proactively identify and avoid threats before new products and processes are adopted, funding independent scientific research and chemical safety testing
- Fund efforts to assess exposure levels via expanded testing by state officials and private individuals, through participatory science
- Provide incentives for businesses, organizations, and citizens to reduce their environmental impact
- Launch public health campaigns to raise awareness about risks to child brain health, offer advice, and provide support to help families, schools, and all community members protect children

Additional resources

To learn more about the environmental threats to child brain development, please visit the Environmental Threats tab on the website of the Child Brain Policy Initiative: [INSERT WEB ADDRESS]. This page includes links to four appendices that provide more detailed information about known risks to child brain development, common exposure pathways, research studies supporting the conclusions in this brief, and links to California-specific materials:

- Appendix I: Environmental Threats
- Appendix II: How Wildfires Threaten Child Brain Health
- Appendix III: California-Specific Resources and Initiatives
- Appendix IV: Further Reading

Credits

Prepared by Dr. Adam Benforado (Drexel University), Dr. Silvia Bunge (University of California Berkeley), Dr. Carlos Cardenas-Iniguez (University of Southern California), Dr. Jennie Grammer (University of California Los Angeles), and Dr. Jaimie Steinmetz (Institute for Health Metrics and Evaluation), on behalf of the Child Brain Policy Initiative (directed by Dr. Emily Murphy (University of California College of the Law, San Francisco)). This work was supported by the California Bench to School Initiative at University of California College of the Law, San Francisco.