

NeuroView

# Neuroecological links of the exposome and One Health

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**This NeuroView assesses the interplay among exposome, One Health, and brain capital in health and disease. Physical and social exposomes affect brain health, and green brain skills are required for environmental health strategies. Ibanez et al. address current gaps and strategies needed in research, policy, and technology, offering a road map for stakeholders.**

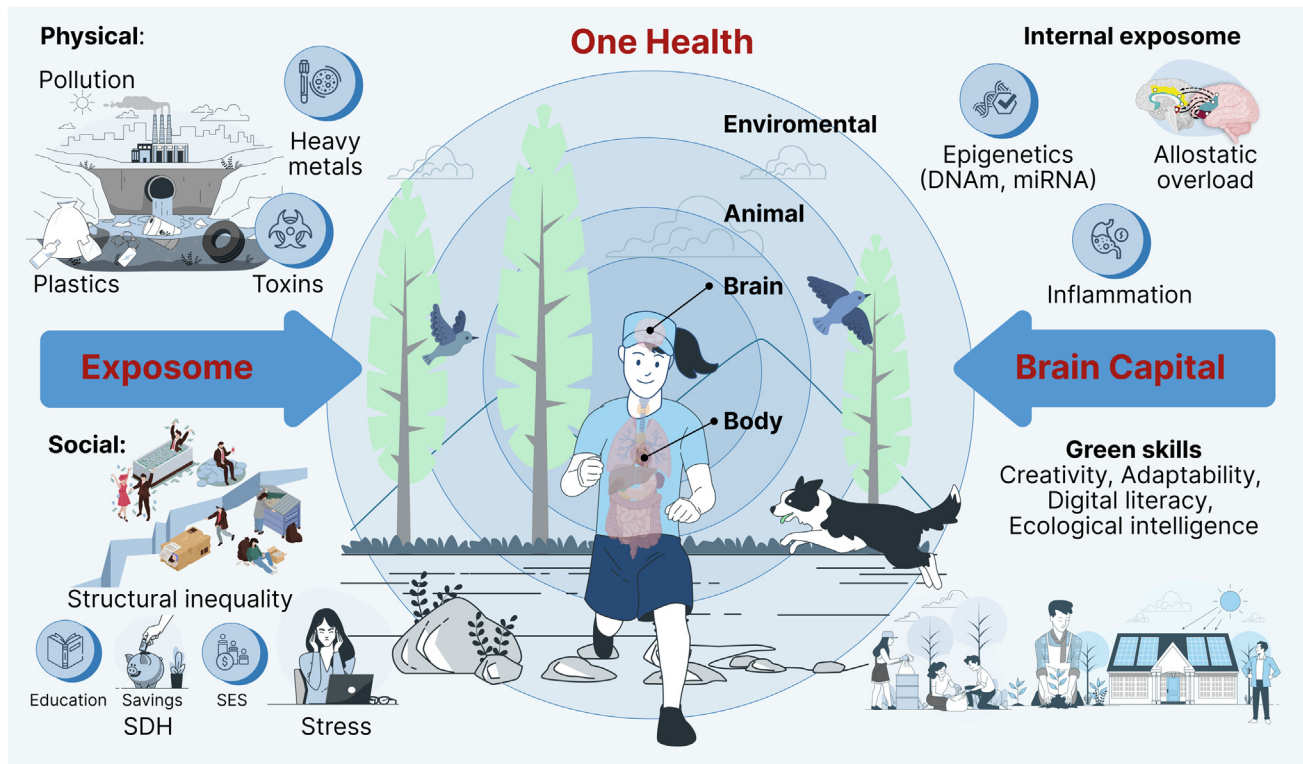
## Introduction

Escalating environmental and social challenges underscore the imperative need to understand these challenges' impacts on brain health and sustainability.<sup>1</sup> This NeuroView examines the interplay among environmental factors of the exposome, ecological approaches to health (or One Health), and the new concept of brain capital, highlighting these elements' joint importance in shaping the future of research and public health. "Exposome"<sup>2</sup> refers to all the environmental exposures individuals encounter throughout their lifetimes, offering a comprehensive framework for understanding the external factors that influence brain health and

disease. Meanwhile, the **One Health approach** recognizes the inseparable connections among human, animal, and environmental health.<sup>3</sup> The One Health approach provides a multidisciplinary strategy to tackle complex issues such as zoonotic diseases (transmitted between animals and humans), food safety, antimicrobial resistance, environmental contamination, and the health impacts of climate change.<sup>1</sup> The brain capital<sup>4</sup> is a new economic asset that prioritizes, integrates, and optimizes human skills (e.g., resilience, creativity, and wisdom), including green skills. It encompasses the social, the emotional, and the diversity of cognitive brain resources of individuals

and communities. Brain capital is fundamental to understanding how humans contribute to the economy and how economic factors, in turn, shape our lives. Green skills are a set of knowledge, abilities, values, and attitudes needed to live in, develop, and support a sustainable and resource-efficient society.<sup>5</sup> Creativity, ecological intelligence, and digital literacy are green skills that constitute critical mindsets for the transition to a low-carbon, resource-efficient economy. Such a shift requires systemic changes involving individuals, institutions, and societies.

Here, we first outline how environmental and social determinants within



**Figure 1. Brain-environment interactions and One Health**

A framework connecting the exposome, One Health, and brain capital. The exposome (left panel) encompasses both physical and social dimensions. The exposome impacts the One Health approach (center panel), highlighting the links among brain, body, animal, and environmental health. The brain capital (right panel) emphasizes the bipartite components of the internal exposome and green skills for envisioning critical actions to improve One Health. SES, socioeconomic status; SDH, social determinants of health; DNAm, DNA methylation; miRNAs, microRNAs.

the exposome affect brain health. We address how integrating One Health strategies can mitigate these impacts and explore the role of brain capital in fostering resilience and green skills and advancing public health initiatives. Then, we tackle the current gaps in research, public policy, and technological development by envisioning future short- and long-term strategies. We underscore the urgency of adopting holistic and transdisciplinary approaches in neuroscience to safeguard brain health in the face of environmental and social challenges (Figure 1).

### The exposome and its relevance to One Health

Both the physical environment and societal structures impact brain and environmental health. The exposome<sup>2</sup> extends beyond genetic predispositions to encompass every external exposure an individual encounters throughout their life, including pollutants, dietary factors,

lifestyle choices, and socioeconomic circumstances.<sup>6</sup>

### The physical exposome and brain health

The physical exposome includes environmental factors such as air and water pollution as well as exposure to plastics, heavy metals, and other toxic substances.<sup>2</sup> These factors have been shown to profoundly affect overall health, specifically the brain, influencing the development, progression, and risk of diseases.<sup>7</sup>

Pollutants like fine particulate matter, nitrogen dioxide, and volatile organic compounds found in air pollution have been linked to neurodevelopmental delays and increased risk of autism and attention deficit disorders in children and adolescents and to cognitive decline and an increased risk of Alzheimer's disease, Parkinson's disease, amyotrophic lateral sclerosis, and related disorders in late adulthood. Heavy metals such as lead, mercury, and arsenic, even at low levels of exposure, can disrupt brain

development in children, leading to attentional deficits, reduced cognitive reserve, and behavioral problems. Plastics, particularly those that release bisphenol A and phthalates, have been implicated in neurodevelopmental disorders.<sup>8</sup> Recent studies have highlighted the alarming ability of micro- and nanoplastics to cross the blood-brain barrier, a protective shield designed to keep harmful substances away from the brain, in animal models.<sup>5</sup> Once these plastics infiltrate the brain, they can induce behavioral changes, trigger inflammation, and activate pathways that may lead to neurodegenerative diseases. Altogether, this evidence points to a potential hazard to human health and the need to focus research efforts to study these associations further.

### The social exposome and brain health

The social exposome encompasses aggregate- and individual-level factors related to disparity and inequality.<sup>2,9</sup> Research has shown that stress-related

pathologies, including depression and anxiety, are more prevalent in populations facing aggregate levels of social and economic disparities. Measures such as the [Gini coefficient](#) or the [Human Development Index](#) provide a broader context for understanding how societal structures can influence health outcomes, including those related to the brain burden.<sup>5,7</sup> These structural inequalities, reflected in disparities in income, education, and access to health care, further contribute to a broader range of health disparities at multiple levels. Individuals from disadvantaged backgrounds also experience chronic stress, poor nutrition, and limited access to health care, all of which can impair brain health. Social determinants of health, socioeconomic status, education, access to health care, and exposure to stressors like discrimination and violence are also individual-level factors that impact brain health,<sup>7,9</sup> influencing the development of psychiatric and neurological diseases and also the resilience and capacity of the brain to cope with stress and injury.

### **Integrating external (physical and social) and internal exposomes**

Brain diseases result from complex interactions between the external exposome and internal vulnerability factors.<sup>1,6</sup> The internal exposome also includes biological factors (i.e., the microbiome) that play significant roles as both internal and external influences on brain health. Environmental toxins can exacerbate the effects of social stressors,<sup>2,8</sup> while socioeconomic factors can influence an individual's exposure to environmental hazards. These inequalities, in turn, can negatively impact the environment in the long term, creating a vicious circle that threatens all health.<sup>2,5</sup> The exposome also affects brain health via epigenetic modifications, i.e., alterations in chromatin organization that do not change the genetic makeup but play an essential role in the modulation of gene expression. Epigenetic regulation of gene expression, mainly via DNA methylation and microRNAs, is influenced by the environment and predisposed by biological constraints. These create a feedback loop of maladaptive stress responses, such that exposure to further stress causes additional and more severe cellular abnormal-

ities, eventually leading to brain system dysfunction and the manifestation of disease symptoms such as abnormal behavioral and emotional regulation.<sup>6</sup>

The exposome may have specific early effects on development. Due to their rapid brain development, immature immune systems, and social dependence on caregivers, children, especially those from marginalized communities, are especially vulnerable to physical and social exposomes. Early exposure to extreme weather events and pollution has been linked to increased incidence of anxiety, depression, PTSD, educational shortcomings, diminished self-regulation, and psychiatric disorders in later life. Even if the exposure happens at a very early stage, the neurodevelopmental impact of these exposures can be lifelong, resulting in a lifetime of suffering for both children and their families.

Given the high complexity and interrelationship of social, physical, and internal exposomes, approaches that tackle one or more aspects in isolation fall short. Transdisciplinary approaches are needed to address brain health's physical, environmental, and social factors, paving the way for long-term and multilevel interventions.<sup>6,7</sup> Researchers and policymakers can develop more effective strategies for preventing and treating brain diseases with synergetic and syndemic approaches integrating environmental and whole-body health and brain levels.<sup>1,6</sup>

### **Brain capital: From science to practice**

The brain capital underscores the critical importance of cognitive-emotional resources and mental wealth in driving economic and societal progress.<sup>4</sup> Moreover, green skills, part of the brain capital, are essential to developing long-term strategies for improving environmental health.<sup>5</sup> Sustainability and technology benefit mental health while fostering eco-friendly lifestyles for physical and mental well-being. Such skills in the workforce help cut waste, emissions, and toxic substance use, protecting health and the environment. Ecosystem skills boost biodiversity and water quality, contributing to climate resilience and essential health services like disease control. These skills are critical in One Health, for example,

because they reduce pollution and zoonotic diseases.

Neuroscientific insights into public policy and practice emphasize the need to invest in brain health across the lifespan. Global leaders and stakeholders are beginning to recognize and act upon the interconnections among brain health, environmental exposures, and societal well-being through initiatives and projects launched at international forums such as the [United Nations General Assembly](#) and the [World Economic Forum](#). One significant development is the anticipation of the [Global Plastics Treaty](#), which addresses the scourge of plastic pollution.<sup>8</sup> These international public-private partnerships can tackle environmental challenges that directly and indirectly impact brain health.<sup>3,8</sup> By reducing exposure to harmful pollutants found in plastics, which are part of the physical exposome, the treaty has the potential to mitigate neurotoxic risks and, thereby, promote global brain health. Green skills promoted by brain capital can influence the behavioral changes required to develop sustainable and pro-social behaviors. Such transdisciplinary interaction follows the principles of One Health,<sup>3</sup> which advocates for a holistic approach to protecting the health of people, animals, and the environment. Neither environmental nor social influences can be observed in isolation; instead, they form part of a complex set of factors jointly affecting brain health.

The linkage among brain capital, the exposome, and One Health is even more foundational in the context of global challenges. Together, these concepts create a powerful narrative for advancing brain health initiatives, underlining the necessity of interdisciplinary strategies that span from science to practice. By leveraging the momentum from international forums and harnessing the potential of agreements like the [Global Plastics Treaty](#),<sup>8</sup> there is a clear pathway toward reducing environmental risks, enhancing brain capital, and promoting a healthier, more sustainable future for all.

### **Advocating for change**

A new framework for the ecology of minds and environment requires a more integrative view with mutual influence and dependence ([Figure 1](#)).<sup>1</sup> A healthy,

**Box 1. Paths for future synergetics of environment and brain health**

**RESEARCH**

**Short-term actions (0–5 years):**

- (1) Advanced biomonitoring technologies and decentralized capacity building for real-time tracking of exposome factors.
- (2) Large-scale longitudinal studies to understand the immediate effects of exposome components on brain health in animals and humans.
- (3) Global biobanks to store environment-related biological samples for exposome research.

**Long-term actions (5–15 years):**

- (1) Causative relationships between exposome components and brain health and disease.
- (2) Translation of findings into predictive models for brain health outcomes.
- (3) Personalized intervention strategies based on exposome data.

**PUBLIC POLICY**

**Short-term actions (0–5 years):**

- (1) Identification of exposome research components that allow actionable public health strategies and regulatory policies.
- (2) Educational programs to increase public awareness of the exposome and brain health.
- (3) International exposome-related policy development.
- (4) Transdisciplinary-based training for neuroscientists.

**Long-term actions (5–15 years):**

- (1) Enact global policies and agreements, such as the Global Plastics Treaty, to reduce harmful exposures.
- (2) Integrate exposome considerations into urban implementations and building regulations and consider tailored approaches encompassing the more extensive diversity and inequalities across different nations.
- (3) Monitor and evaluate the effectiveness of these new policies.

**TECHNOLOGY**

**Short-term actions (0–5 years):**

- (1) Integrate wearable sensors and other Internet of Things devices for personal health monitoring related to the exposome.
- (2) Employ AI for data analysis and pattern recognition in exposome research.
- (3) Use AI to predict the most vulnerable communities and create appropriate mitigation and prevention strategies.
- (4) Guarantee an adequate regulatory framework tailored to different nations and regions.

**Long-term actions (5–15 years):**

- (1) Achieve widespread use of AI for comprehensive and ongoing data analysis, including predictive analytics for brain health.
- (2) Develop and implement smart city technologies that reduce harmful environmental exposures.

sustainable environment fosters optimal brain health and, by extension, societal well-being and resilience.<sup>5</sup> More integrated approaches are required to address the impact of environmental and social factors on the brain and recognize the brain's potential to influence ecological outcomes through behavior, innovation, and policy. For this, a more significant synergy is required among the perspectives and expertise of a diverse array of stakeholders.<sup>1</sup> Neurologists, psychiatrists, neuroscientists, psychologists, and patient groups offer invaluable insights into the nuances of brain health and disease.<sup>7</sup> Simultaneously, environmentalists and ecologists bring to the table a deep understanding of ecological dynamics and the threats posed by pollutants, such as plastics, to both the environment and human health. By uniting these diverse perspectives, a comprehensive and multifaceted approach to policy-making can emerge, effectively addressing the complex links among the brain, health, and the environment.<sup>4</sup>

This collaborative task force necessitates a robust call to action for the neuroscience community to support global initiatives actively. Such support emphasizes the critical importance of reducing environmental risks to brain health and committing to broader One Health initiatives.<sup>3</sup> The health and scientific community can drive significant change, influencing policies that mitigate the adverse effects of the exposome and championing a holistic approach to health and environmental stewardship. This collective action is essential for building a sustainable future where brain health is recognized as a core component of global health and well-being, highlighting the indispensable role of an environmentally conscious and proactive brain health community in shaping the policies of tomorrow.

### Addressing the current gaps by envisioning future strategies

The complex interplay of the exposome, brain health, and ecological context calls for tackling research, public, and practice gaps.<sup>5</sup> Bridging these gaps requires short-term (0–5 years) and long-term (5–15 years) efforts across disciplines, leveraging new technologies and interdisciplinary approaches to deepen our un-

derstanding and enhance our capacity for effective intervention (Box 1).

A primary research gap lies in the need for longitudinal studies that can more definitively map the causal relationships between specific exposome components (e.g., microplastics and smaller nanoplastics, which, because of their size, are more likely to cross biological barriers) and brain health outcomes.<sup>6</sup> Such studies would benefit from integrating advanced biomonitoring technologies capable of tracking individual exposures with unprecedented precision and granularity.<sup>10</sup> Many communities suffering from sociodemographic disparities are also at risk for increased environmental stressors from global climate change. New research needs to engage these communities, mainly regarding inclusivity and ecological justice. Additionally, there is a crucial need for research that transcends traditional disciplinary boundaries,<sup>7</sup> combining insights from neurology, epidemiology, environmental science, and social sciences to holistically understand the impacts of the exposome on brain health.<sup>2,6</sup> Projects like the Healthy Brain Network, which aims to create a comprehensive database of brain development in children by combining genetic, cognitive, and environmental data, exemplify the power of interdisciplinary research.<sup>7</sup> Similarly, the ENIGMA-Environment group aims to elucidate environmental exposures' impacts on brain and behavior as well as the biological underpinnings of environmental risks for various disorders.

On the public and practice fronts, a significant gap exists in translating research findings into actionable policies and interventions that can mitigate the adverse effects of the exposome on brain health. This gap underscores the need for tighter collaboration among researchers, policymakers, and practitioners to ensure that scientific insights translate into effective public health strategies and regulatory actions. Moreover, there is a pressing need for public education initiatives to raise awareness about the importance of the exposome and brain health, empowering communities to advocate for change and adopt healthier lifestyles.

The potential for new technologies to revolutionize our approach to understanding and addressing the exposome and brain health is immense. For instance, sat-

ellite and remote sensing data can identify the exposome for retrospective exposures from multiple years earlier.<sup>11</sup> Wearable sensors and smartphone applications can provide real-time data on individual exposures and health outcomes, facilitating more personalized health monitoring and interventions.<sup>10</sup> Extensive cohort data are required for research, spanning different age groups from pre-conception onward and varying environmental and social exposures. Data integration, dimension reduction, and stratification into subgroups will pose a significant challenge, given the diversity of data sources. Artificial intelligence offers powerful tools for analyzing the vast datasets generated by such technologies, uncovering patterns, and making optimal predictions and inferences that can guide public health strategies and individual behaviors. Further development of biostatistical models will be required to detect associations with psychopathology and develop biomarkers.

Transdisciplinary approaches are equally vital, as they allow for the integration of diverse perspectives and expertise in tackling the complex challenges at the intersection of environmental exposures and brain health. One promising example is the collaboration between environmental scientists and neuroscientists to study the impacts of air pollution on neurodevelopment and cognitive aging. Similarly, partnerships among technologists, health professionals, and urban planners can lead to designing “smart” cities that minimize harmful exposures and promote brain health through green spaces, pollution control, and community resources.

### Conclusions

Understanding and mitigating the impact of the exposome on brain health is challenging and fraught with complexities.<sup>6</sup> Yet, new technologies and transdisciplinary collaborations offer unprecedented opportunities to advance more integrative knowledge and develop effective interventions. By prioritizing research that bridges existing gaps, embracing innovative technologies, and fostering transdisciplinary partnerships, we can pave the way for a future where the relationships among our environment, our brains, and our health are effectively managed to promote

well-being and resilience in the face of changing global landscapes.

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A.I. and H.A.E. designed the proposal and wrote the manuscript. All authors provided critical input and revisions and approved the final version of the manuscript for submission.

#### DECLARATION OF INTERESTS

S.D. is employed by the Minderoo Foundation, a philanthropic organization. Neither the Minderoo Foundation nor its benefactors had any influence

over the conduct, the findings, or the recommendations of this work.

#### DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used GPT4 to edit the text and correct typos. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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