

Environmental contaminants and child development: Developmentally-informed opportunities and recommendations for integrating and informing child environmental health science

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ABSTRACT

Child environmental health (CEH) science has identified numerous effects of early life exposures to common, ubiquitous environmental toxicants. CEH scientists have documented the costs not only to individual children but also to population-level health effects of such exposures. Importantly, such risks are unequally distributed in the population, with historically marginalized communities and the children living in these communities receiving the most damaging exposures. Developmental science offers a lens and set of methodologies to identify nuanced biological and behavioral processes that drive child development across physical, cognitive, and socioemotional domains. Developmental scientists are also experts in considering the multiple, hierarchically-layered contexts that shape development alongside toxicant exposure. Such contexts and the individuals acting within them make up an overarching “child serving ecosystem” spanning systems and sectors that serve children directly and indirectly. Articulating how biobehavioral mechanisms and social–ecological contexts unfold from a developmental perspective are needed in order

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to inform CEH translation and intervention efforts across this child-serving ecosystem. Developmentalists can also benefit from integrating CEH science findings in their work by considering the role of the physical environment, and environmental toxicants specifically, on child health and development. Building on themes that were laid out by Trentacosta and Mulligan in 2020, this commentary presents recommendations for connecting developmental and CEH science and for translating such work so that it can be used to promote child development in an equitable manner across this child-serving ecosystem. These opportunities include (1) Using Developmentally-Informed Conceptual Models; (2) Applying Creative, Sophisticated, and Rigorous Methods; (3) Integrating Developmentally-Sensitive Intervention Considerations; and (4) Establishing Interdisciplinary Collaborations and Cross-Sector Partnerships.

KEYWORDS

child health, developmental, environmental toxicants, intervention, translation

1 | INTRODUCTION

Over the past few decades, the field of child environmental health (CEH) science has identified powerful effects of early life exposures to common environmental toxicants widely spread through air pollution (Perera, 2017), water (Hanna-Attisha et al., 2016), soil (Simcox et al., 1995), pesticides and other chemicals (Boucher et al., 2014; Eskenazi et al., 2013; Lanphear et al., 2005; Whyatt et al., 2012). CEH scientists have also documented that risk is unequally distributed in the population (Morello-Frosch & Shenassa, 2006; Persico et al., 2016; Sampson, 2022). Childhood exposures are costly not only for individual children but for society given burdens of long-term disease, disability, and loss of productivity over the lifespan (Landrigan et al., 2002; Lanphear et al., 2005). Guided by Developmental Origins of Health and Disease (Gluckman et al., 2016) and life course health development theories (Halfon et al., 2014), CEH science has highlighted how the impacts of environmental toxicants can vary by type and timing of exposure across sensitive developmental periods (Golub, 2000; Rice & Barone, 2000). Methods used in this work have included large epidemiological studies, natural experiments, and mechanistic animal and human studies, and CEH research has resulted in actionable findings by, for example, lowering the threshold at which blood lead levels are deemed to be harmful (Ruckart et al., 2021).

Despite such findings, there remain gaps in translating CEH knowledge to promote child health (Birnbaum, 2018; Trentacosta et al., 2016; Trentacosta & Mulligan, 2020). One reason for such gaps is a lack of a developmental framework to characterize CEH impacts across a range of outcomes, inform intervention strategies, and help families understand and respond to CEH findings and changing guidance. The importance of working with

communities to translate environmental health science has been described (Finn & Collman, 2016; Israel et al., 2005; O'Fallon & Dearry, 2002), but limited work has integrated developmental expertise into CEH translation efforts. The National Institute of Environmental Health Sciences (NIEHS) strategic plan (Birnbaum, 2018) endorses a lifespan perspective, a focus on individual differences in susceptibility, and overlapping contexts of exposure, all of which are core developmental science constructs. Developmental science offers a lens and set of methodologies to study nuanced biological and behavioral processes that drive child development across physical, cognitive, and socioemotional domains. Furthermore, developmental scientists are expert in considering the contexts that shape development alongside toxicant exposure. Articulating how mechanisms and social–ecological contexts unfold from a developmental perspective may help inform CEH translation and intervention efforts.

Developmentalists can also benefit from integrating CEH science findings in their work. In recent decades, developmental scientists have focused less on how physical (e.g., chemical exposures, air pollution) compared to social environments (e.g., psychosocial adversity) shape development. Yet, “riskscape” (this issue) and “exposome” frameworks (Louis et al., 2017; Trentacosta & Mulligan, 2020) highlight how physical and psychosocial (or chemical and non-chemical) exposures influence child development. Determining how to mitigate such impacts is urgent considering that children who are growing up in historically marginalized communities experiencing systemic structural disadvantage and racism are often exposed to chronic and high levels of co-occurring social adversities and environmental injustices (Morello-Frosch & Shenassa, 2006). These populations are the focus of some papers in this Special Issue of *New Directions for Child and Adolescent Development*, and social and racial justice are appropriately and increasingly at the forefront of developmental science (Cooper et al., 2022). Applying developmentally-informed conceptual models and sophisticated methods to better understand nuanced impacts of such exposures on child development—and point to avenues for intervention—is thus both timely and of great public health importance.

Trentacosta and Mulligan (2020) identified four research themes emerging from CEH science regarding impacts of environmental exposures on child development. These were (1) disparities in exposures; (2) complexities of exposures; (3) mechanisms linking exposures to child outcomes; and (4) protective factors that mitigate exposure risks. Many of these themes appear in this Special Issue. Some studies concern populations who experienced disproportionately high exposures, including an Inuit Bastien (this issue) and two Mexican birth cohorts Merced-Nieves, Robledo (this issue). Others address complexity by examining specific mixtures (e.g., Merced-Nieves, Robledo, Schildroth (this issue) or broad exposures (e.g., Ugarte (this issue)), and some study candidate bio-behavioral explanatory mechanisms (e.g., inflammation, Parenteau (this issue); ANS reactivity, Ugarte (this issue); learning tasks, Merced-Nieves (this issue). Finally, some studies identify possible protective factors that moderate the impact of exposure (e.g., weight status, Robledo (this issue); hippocampal volume; Miller (this issue). This issue thus begins to illustrate how developmental scientists are contributing to CEH science. Building on the themes laid out by Trentacosta and Mulligan, I reflect on four opportunities and recommendations to connect developmental and CEH science and move such work forward to promote child development in an equitable manner. These are outlined in Table 1 and include (1) Using Developmentally-Informed Conceptual Models; (2) Applying Creative, Sophisticated, and Rigorous Methods; (3) Integrating Developmentally-Sensitive Intervention Considerations; and (4) Establishing Interdisciplinary Collaborations and Cross-Sector Partnerships.

TABLE 1 Recommendations and opportunities for developmental science to integrate and inform child environmental health science

Recommendation/ Opportunity	Relevance for CEH	Application examples
<i>1. Use Developmentally-Informed Conceptual Models</i>	Direct and indirect influences across the Child-Serving Ecosystem (CSE) overlap and interact to shape environmental exposure(s), child health and development Effects of toxicant exposure may differ across individuals and stages of post-natal development; may appear discontinuous	Consider exposures and potential for intervention across the CSE Borrow developmental models such as biological sensitivity to context to identify moderators Use longitudinal designs with multiple datapoints to test complex, non-linear models, identify sleeper effects
<i>2. Apply Creative, Sophisticated, and Rigorous Methods</i>	Impacts on early development may be subtle and require specialized assessment of developmentally-relevant constructs and processes Need novel methods to assess complex and individual exposures Innovative measurement strategies can engage communities, spark change	Employ developmentally-sensitive assessments to capture nuanced biobehavioral constructs, and change Use personal exposure monitors for children and members of the CSE Conduct community mapping, in combination with personal exposures data
<i>3. Integrate Developmentally-Sensitive Intervention Considerations</i>	Developmentally-sensitive periods of risk call for developmentally-informed/targeted interventions Environmental Health Literacy is limited among CSE stakeholders Increasing connections across the CSE can provide opportunities to integrate CEH interventions throughout	Consider how developmental changes in behavior may drive exposure risk Test behavioral interventions to mitigate risk (e.g., relational health interventions in early childhood) Engage youth directly as advocates Promote Environmental Health Literacy among CSE stakeholders
<i>4. Establish Interdisciplinary Collaborations and Cross-Sector Partnerships</i>	Need to translate CEH findings from animal models to human context Must engage cross-sector stakeholders to make change in CEH Communities who are most impacted need to be engaged in solutions	Develop cross disciplinary partnerships Employ citizen science, report back study designs to engage and build community partnerships Embrace an Environmental Justice orientation

2 | DEVELOPMENTALLY-INFORMED CONCEPTUAL MODELS

2.1 | Social–ecological nesting: The child-serving ecosystem (CSE)

Trentacosta and Mulligan (2020) note how developmentally-informed conceptual models include multiple social–ecological contexts in which children are embedded. Such contexts can be hierarchically nested (e.g., the prenatal environment is nested in mother’s social and environmental exposure histories) or somewhat independent (e.g., home vs. school settings). Social–ecological contexts also change over individual/developmental and historical time, or chronosystem (Bronfenbrenner, 1979). An example of developmental change is when children are exposed to new peer groups and activities during adolescence. Historical

changes include events that impact a cohort distinctly as a function of their developmental stage (e.g., infants during the Flint Water Crisis; adolescents during the COVID-19 pandemic) or broader socio-cultural shifts, such as maternal employment changes. Finally, social-ecological contexts interact to shape development. For example, recent federal policy changes noting no safe levels of lead exposure have driven local changes in blood lead testing protocols, and, in combination with the COVID-19 pandemic, reduced capacity to detect and treat child lead poisoning (Woolf & Brown, 2022). Developmentally-informed conceptual models that articulate the contexts in which children are embedded and how they interact can aid in (1) detecting impacts of environmental exposures and (2) developing intervention strategies to prevent and/or mitigate impacts of exposure.

It can be further helpful to characterize these contexts and the individuals acting within them as an overarching “child serving ecosystem” or CSE (Miller, Stein et al., 2022). The CSE spans systems and sectors that serve children directly and indirectly. Individuals in the CSE include parents and caregivers, educators, and clinical care providers who *directly* shape child health and development, as well as (among others) the public health workforce and policymakers who shape child health *indirectly* (Miller, Stein et al., 2022). Indirect influences are particularly important for CEH considerations, as regulation of toxicants is driven by both local and higher-level policies, which are often siloed from each other and from systems meant to protect the public’s health (Korfmacher, 2020). Developmentally-informed conceptual models that articulate connections across the CSE can help identify and leverage opportunities to intervene in key contexts to protect CEH threats (Bachrach et al., 2010; Miller, Stein et al., 2022).

2.2 | Focus on process and patterns of growth

Another feature of developmentally-informed conceptual models is their focus on detailing processes, or mechanisms, within an individual and in interaction with the environment as they unfold across the lifespan (Lerner, 1991). Such mechanisms can be nuanced; carefully phenotyping expected or “normative” developmental trajectories is thus critical in order to understand how toxicants may disrupt them. Furthermore, what may appear “adaptive” in one context or at one point in development may become a liability later, or vice versa. Two studies in the current issue grappled with such findings. Miller (this issue) found that a smaller hippocampus, which has been associated with exposure to early adversity (Hanson et al., 2015), appeared to protect against a negative association between air pollution and telomere length. Ugarte (this issue) found that despite positive associations between housing burden and air and water pollution, housing burden was associated with adaptive responses to stress in a laboratory task, whereas water and air pollution were associated with less adaptive responses. These examples of nuanced associations highlight the need for conceptual models that articulate complex routes of transmission from environmental exposure(s) to child outcomes.

Luckily, developmentally-informed conceptual models can help contextualize such findings. These models can describe both continuous linear growth patterns and discontinuous, non-linear transitions that involve hierarchical reorganization and consolidation before moving to the next stage (Cicchetti & Toth, 2009; Lerner et al., 2011). Non-linear developmental models can address “sleeper effects”, such that children and youth may appear to be protected against harmful impacts during some phases of development but puberty-related biological and/or social changes, for example, may reveal the impacts of toxicants in a manner that appears discontinuous (Mayes & Ward, 2003; Spear, 2007). Differential susceptibility models of development describe how organisms can be differentially impacted by an external event such as an environmental exposure as a function of

individual characteristics such as genetic makeup (Belsky et al., 2019; Roisman et al., 2012). Such models (along with “biological sensitivity to context” or “vantage sensitivity” models) are increasingly invoked in the child maltreatment and psychological treatment literatures in an effort to explain differential responses to intervention (Bakermans-Kranenburg & van IJzendoorn, 2015; de Villiers et al., 2018; van IJzendoorn et al., 2020). Although policies aimed at toxicant exposure prevention are critical, using models to inform the design of post-exposure interventions tailored to specific individuals (e.g., based on pubertal stage, sex, protective factors) could help mitigate the impact of prior exposures. Some studies in the Special Issue apply such models by testing moderators of association between exposure and outcome, as recommended by Trentacosta and Mulligan (2020). For example, Robledo (this issue) found that associations between metal exposures and fat accumulation were stronger among adolescents with obesity. This issue found that air pollution was associated with shorter telomere length only among youth with larger hippocampal volumes. As with many models seeking to test moderation, sample sizes were relatively small, limiting power to detect effects, so future work should examine associations in larger samples.

2.3 | Data requirements

To test developmentally-informed models, it is important to examine associations longitudinally as well as within developmental periods. Only half of the studies in this issue included longitudinal assessments, and only one had more than two data points Bastien (this issue). Future work using longitudinal designs with multiple data points could employ more sophisticated modeling techniques to capture complex patterns of association and change over time. Developmental systems and cascade models, for example, specify how within-person systems adapt over time in response to dynamically shifting external contexts and seek to model these pathways as they shape the developing organism (Masten, 2021). Testing such models requires not only longitudinal data but also specialized analysis techniques such as system dynamics modeling. Although not explicitly developmental in nature, recent examples from the CEH literature illustrate how to apply complex systems thinking and analysis to address environmental impacts on child health and development (Hubal et al., 2022; Payne-Sturges et al., 2021).

3 | CREATIVE, SOPHISTICATED, AND RIGOROUS METHODS

3.1 | Assessing developmentally-meaningful outcomes

CEH science has historically focused on the impact of exposures on health outcomes such as asthma rather than social-emotional or behavioral functioning (Davis et al., 2019). Measuring the impact of exposures across multiple outcomes or nuanced indicators of bio-behavioral functioning can be challenging. Studies in the current issue assessed various bio-behavioral processes in relation to exposures. Two studies examined complex memory Bastien (this issue) and learning Merced-Nieves (this issue) tasks. Two others assessed physiological responses that are considered to index integrated bio-behavioral responses to stress Parenteau, Ugarte (this issue). Still another study examined telomere length, considered to index chronic stress exposure Miller (this issue). These are exciting directions that illustrate the power of studying nuanced bio-behavioral processes as explanatory mechanism(s) of transmission from environmental exposures to a broader range of child developmental functioning and outcomes.

Of note, none of the studies in this issue tested outcomes in children younger than age 5 years. Yet, early childhood is a critical period for brain and organ development and vulnerability to chemical exposures (Bennett et al., 2016; Rice & Barone, 2000). Interventions to mitigate impacts of exposures may also be more effective in early compared to later childhood (Barouki et al., 2012; Bennett et al., 2016; Braun, 2017; Hirtz et al., 2017). Yet, deleterious effects of varied toxicant exposures on behavior, learning outcomes, and/or biological stress responses may be subtle and thus difficult to identify in young children (Konijnenberg, 2015; Lewis et al., 2014; Mayes & Ward, 2003). A recent review documented associations between environmental exposures and young children's social and cognitive development (prior to age 7), although few of these studies examined multiple or post-natal exposures (Davis et al., 2019). As early childhood is characterized by rapid change, using developmentally-appropriate and valid measures to capture these changes is important. As such, developmental expertise may be needed to conceptualize meaningful areas of early childhood functioning. Identifying the impacts of toxicant exposures on rapidly emerging and potentially subtle bio-behavioral processes is essential in order to identify developmentally-sensitive targets for intervention, and provides a natural and important point of connection between developmental and CEH scientists.

3.2 | Assessing complexity of exposure(s)

CEH science has been critiqued for examining exposure to one toxicant at a time, as multiple exposures are more common than not (Buck Louis et al., 2017; Davis et al., 2019; Payne-Sturges et al., 2021). For example, cumulative risk assessments have been proposed to systematically examine cumulative and interactive impacts of both chemical and non-chemical (e.g., psychosocial stressors) environmental exposures (Payne-Sturges et al., 2018). Measuring and assessing the impact of exposure even to a single toxicant can be complex, however. Over half of the papers in this issue considered exposure to heavy metals, either singly or in combination. Robledo (this issue) analyzed lead and mercury exposure individually and found they were differently associated with fat deposition patterns but only among adolescents with obesity. Studies that used sophisticated statistical methods to model combined exposures (e.g., Bayesian Kernel Machine Regression; Schildroth (this issue), Weighted Quantile Sum [WQS] regression; Merced-Nieves (this issue) found that interactions among heavy metals were associated with multiple indicators of iron deficiency Schildroth (this issue) and that prenatal exposure to metal mixtures—specifically lead, cadmium, and arsenic—was associated with poorer accuracy and response rate on a learning task Merced-Nieves (this issue). Bastien (this issue) considered exposures to mercury, lead, or polychlorinated biphenyls [PCBs] across three developmental periods and found specificity related to type and timing of exposure on performance in a spatial memory task. Together, findings suggest that even when considering the role of a single toxicant, there are nuances to measurement, analysis, and interpretation. Developmental scientists are practiced at modeling such complexities, identifying where and how they are likely to occur within the CSE, and how associations may change with development.

Measuring the complexities of developmentally-salient exposures and outcomes is complicated. Yet, measurement challenges present opportunities for collaboration among CEH and developmental scientists. Matching administrative data on neighborhood or community-level environmental exposures to individually-assessed outcomes is one option, although there are limitations to the precision of this method, as noted by the authors who used this approach. A benefit of using administrative data is that results can be replicated across studies, a key goal for developmental science (Shrout & Rodgers, 2018). As

methods to assess environmental exposures become more sophisticated and “light touch” we may also be poised to make great strides in assessing individual levels of exposure on a large scale. For example, although none of the studies in this Special Issue employed personal exposure monitors, research using such devices suggests exposure biomarkers vary by individual (Liang et al., 2019). Indeed, technologies are being marketed commercially and conducting research using individual-exposure measurement approaches may soon be more cost-effective, feasible, and acceptable (Caplin et al., 2019; Steinle et al., 2013; Xie et al., 2021).

3.3 | Using measurement innovations for change

Innovations in measurement have the potential to be used to effect change as well as prompt new research collaborations. Guidelines for conducting research where results are “reported back” to participants are emerging in the CEH field (Boronow et al., 2017; Haynes et al., 2016; Ohayon et al., 2017). This is important as individual and community-level exposure data can be used by community members to advocate for environmental policy changes (Caplin et al., 2019; Castner et al., 2022; Commodore et al., 2017; Wong et al., 2019). Mapping technologies that integrate community and individual-level exposure data—particularly as relevant to children—can be important tools for researchers and community members alike (Hartley et al., 2021; Stieb et al., 2019; Wong et al., 2019). Visual illustration of the complex systems involved in the pathways from exposure to impact can also be a helpful way to explain the mechanisms of transmission from exposure to child outcomes, and a potential tool to use in advocacy efforts (Hubal et al., 2022; Payne-Sturges et al., 2021).

4 | DEVELOPMENTALLY-INFORMED INTERVENTION CONSIDERATIONS: PERIODS OF RISK AND OPPORTUNITY

Developmental science can also inform strategies to prevent and mitigate toxicant exposures. Perhaps most clearly, developmentally-informed research on the mechanisms of effect, as reviewed above and in this Special Issue, can and should be used to identify new intervention targets and pinpoint developmental risks. For example, using differential susceptibility models to identify moderators may lead to targeted interventions to mitigate exposures based on “what works best for whom”. Exposures also have different implications for children than adults as they tend to take in more of a given toxicant for their body weight, have organs and metabolic systems that are still developing, and may engage in behaviors that can place them at risk (Bearer, 1995). Although prevention of exposure is ideal, many children and youth, particularly in under-resourced contexts experiencing adversities, are not reached by prenatal or even early intervention. Thus, identifying when, how, and where to intervene across different developmental periods is essential for designing and implementing effective interventions.

4.1 | Developmental periods of risk

4.1.1 | Prenatal, infancy and early childhood

The prenatal period is critical for intervention as many toxicants cross the placental barrier and affect fetal growth and development through organ damage and placental changes

(Dugershaw et al., 2020). Breastfeeding during infancy is generally protective but can also transmit some risk depending on maternal exposures and diet (Rebello & Caldas, 2016; Weisglas-Kuperus et al., 2004). Early childhood is important not only given rapid brain and organ development but also changes in child behaviors that can increase risk. For example, improved fine motor skills can increase pica, or eating of non-food items (Leung & Hon, 2019). New abilities to stand and “cruise” on furniture can result in a child mouthing windowsills that contain lead paint, and the onset of crawling and walking to independent play where a child may access contaminants in their home or in outside soil (Black et al., 2005; Mielke & Reagan, 1998). It is important to consider how these developmental achievements may also result in increased risk for exposures. Physical contexts in the CSE can also carry developmentally-specific risks, such as the use of toxic cleaning products in daycares (Alkon et al., 2022; Querdibitty et al., 2022) or poor indoor air quality (Gilden et al., 2021).

4.1.2 | Adolescence

Unique risks emerge in adolescence due to increased autonomy to engage in behaviors that elevate toxicant exposures such as drinking, smoking and vaping (Rubinstein et al., 2018), increased cosmetic use (Madrigal et al., 2016), and/or direct workplace exposures to pesticides, heavy metals, and/or solvents (Golub, 2000; Woolf et al., 2001). Adolescents are also at biological risk due to rapid changes in their reproductive system, brain and other organs across this period (Golub, 2000; Spear, 2007). Identifying the nature of behavioral as well as biologically-driven risks for environmental exposures at specific periods of development, including adolescence, is essential in order to embrace a lifespan approach to prevention, as recommended in the NIEHS strategic plan (Birnbaum, 2018).

4.2 | Opportunities for intervention across the CSE

Risk factors have historically been the focus of much CEH and often developmental scientific research. Yet, identifying factors and processes that function to mitigate risk is equally if not more important, especially for children who have already been exposed to toxicants (Trentacosta & Mulligan, 2020). Such protective factors are also often developmentally “located” and thus identifying CEH-relevant protective factors across the CSE may benefit from developmental science contributions.

4.2.1 | Parenting

Early caregiving relationships are foundational for healthy child development. Conceptualized broadly as “early relational health”, positive parent-child relationships are recognized for their potential to protect against numerous social-contextual stressors by supporting child abilities to cope with stress, develop trust in others, and engage in learning and exploration opportunities (Garner et al., 2021; Willis & Eddy, 2022). Establishing early relational health—which, importantly, includes supporting caregivers to care for their children (Willis & Eddy, 2022)—could thus be an important tool for mitigating effects of toxicant exposure. Relationship-focused interventions for young children who have experienced significant psychosocial adversities such as foster care can positively impact child biological stress responses (Welch et al., 2020) and behavioral and cognitive outcomes (Grube &

Liming, 2018). As well, nurturing care interventions to enhance relational health during the first 1000 days (0–3 years) of life are suggested as essential for counteracting the effects of poor nutritional and socioeconomic environments and promoting healthy development on a global scale (Lancet, 2016; Organization, 2018).

4.2.2 | Child care

Early care and education contexts are critical CSE settings for preventing exposure to toxicants and mitigating their impacts. In the United States, federally-funded early education programs (e.g., Head Start) are mandated to provide quality nutrition and cognitive stimulation, which are recommended as strategies to counteract the effects of toxicant exposure (Binns et al., 2007; Engle et al., 2007; Hennig et al., 2012). High-quality childcare is characterized by positive relationships between young children and childcare providers and thus has the potential to mitigate impacts of exposures through early relational health pathways (Ettinger et al., 2019; Hanna-Attisha et al., 2022; Schnur & John, 2014). Specialized early intervention (EI) services for young children may also be more successful when families trust and feel supported by their providers, reflecting relational health between families and providers (Jimenez et al., 2012; Miller, Stein et al., 2022). A recent analysis found that EI services, which entail individualized service plans tailored to child and family needs, mitigated the impact of lead exposure on later math and reading scores (Stingone et al., 2022). Thus, in addition to identifying and eliminating the physical sources of environmental exposures when possible (e.g., as with the Flint Water Crisis), providing individual, developmentally-tailored interventions—including those that address relational health across CSE contexts during early childhood—may be promising strategies for addressing impacts of exposure.

4.2.3 | Caregiver environmental health literacy and community advocacy

Empowering caregivers to act collectively on behalf of children is a component of early relational health (Willis & Eddy, 2022). Children are at unique risk for environmental threats, and collective action can be critical in advocating for policies to reduce impact of exposures, such as ensuring access to high-quality childcare and/or EI services (Hamp et al., 2018; Hanna-Attisha et al., 2022). Environmental health literacy, or the knowledge and skills needed to take action based on environmental health data, is a foundational step toward advocating for community and policy changes to protect CEH (Finn & O’Fallon, 2017; Gray, 2018; Nutbeam, 2008). Although parents and other CSE stakeholders can be deeply informed regarding child development, they are not typically informed regarding the role of environmental exposures or how to influence local CEH-relevant policies. For example, recent studies assessing environmental health literacy among EI specialists (Zimmerman et al., 2018) and childcare providers (Koester et al., 2021) found that these early childhood professionals had low environmental health literacy and low confidence regarding this topic. Environmental health literacy and confidence around managing patients’ environmental concerns have been found to be lacking even among health care professionals (Brown et al., 2019; Kilpatrick et al., 2002; Zajac et al., 2020).

Environmental health literacy has been recognized as an important intervention lever (Claudio et al., 1998). Engaging and educating parents and providers who work with children across the CSE on local environmental exposures, risk factor screening, and the

role that such exposures may play in the life of a child offer important developmentally-informed intervention opportunities (Bennett et al., 2016; Miller, Varisco et al., 2022). Parents may express concerns but be uncertain about how to address them (Green et al., 2022). Some studies suggest that arming parents with environmental health literacy and personal exposure data can change individual behavior and create powerful community advocates (Commodore et al., 2017; Perovich et al., 2018; Ramirez-Andreotta et al., 2016; Wong et al., 2019). For example, providing feedback to parents around indoor toxicant exposures resulted in families making changes at home and becoming more aware of the need for policy-level change (Perovich et al., 2018; Ramirez-Andreotta et al., 2016). Using personal monitoring to identify child exposures in other CSE settings such as childcare could also yield actionable data. Interventions to increase environmental health literacy among childcare providers (Amoah et al., 2016; McKeon et al., 2021), train-the-trainer methods to promote eco-healthy childcares (Gilden et al., 2018), and efforts to promote environmental health literacy among health care providers have shown promise (Miller et al., 2016). Engaging parents to promote environmentally friendly childcares may also be a way to connect home and school contexts (Evans-Agnew et al., 2018). All of these approaches may benefit from involving developmentalists who have expertise working with parents and other CSE stakeholders.

4.2.4 | Youth-focused interventions

Compared to early childhood, the adolescent CSE can involve different settings and stakeholders and more direct youth participation. Early adolescence (~10–15 years depending on pubertal status (Dorn et al., 2006)) is a powerful time for intervention as this is an age when new experiences and opportunities can provide inspiration and youth are open to envisioning their future (Crone & Dahl, 2012). Interventions that respectfully engage and empower youth to change their environments can establish new norms for sustained impact (Yeager et al., 2018; Zimmerman et al., 2013). CEH issues may appeal to youth given concerns around climate change (Lee et al., 2020) and related racial inequities (Roy et al., 2019). As youth environmental health literacy can be low (Bogar et al., 2017), youth may benefit from learning about their own exposures (Brickle & Evans-Agnew, 2017; Cardarelli et al., 2021). Studies have sought to engage adolescents using methods described earlier including personal monitoring and mapping of environmental exposure data. For example, Madrigal et al. increased youth environmental health literacy regarding exposures to endocrine-disrupting chemicals in cosmetics, resulting in youth advocating for changes in local stores and creating social media campaigns (Madrigal et al., 2016). In other work, youth “citizen scientists” used portable air monitoring devices and videos to collect data across their CSE during a typical day, creating maps and increasing their environmental health literacy and capacity for advocacy (Johnston et al., 2019). A recent study engaged 13–18 year-old farmworkers in creating infographics based on research findings about their exposure to excessive heat (Quandt et al., 2022). Another study trained American Indian pre-adolescents in water pollution concepts and how to be advocates for change, increasing youth environmental health knowledge and enthusiasm for taking care of their environment (Simonds et al., 2019). Multiple studies in the current issue concerned the preadolescent and early adolescent periods Miller, Parenteau, Robledo, Schildroth (this issue); engaging youth in processing and acting on such findings would be an exciting direction for future work. Finally, as adolescents are entering their child-bearing years, interventions that involve educating youth about the impacts of prenatal

toxicant exposures (Buck Louis et al., 2013, 2017) could have powerful intergenerational impacts.

4.2.5 | Connecting the CSE to promote CEH

The interconnected nature of chemical and non-chemical exposures is challenging for researchers trying to document specificity of effects (Buck Louis et al., 2017). Yet, because the child exists within overlapping physical and social environments, coordinated efforts across the CSE could address multiple exposures. Unfortunately, as with environmental health systems (Korfmacher, 2020) CSE systems and stakeholders are often siloed; they are not designed to function together, they communicate infrequently or ineffectively, and may even work at cross-purposes (Miller, Stein et al., 2022). Educating stakeholders across the CSE—families, pediatricians, educators, landlords, policymakers, product manufacturers, youth, and even researchers—about CEH may be a way to promote child health and development broadly (Bachrach et al., 2010). In addition to the above suggestions for working directly with parents, educators, and youth, connecting CSE stakeholders to regional CEH experts such as the Pediatric Environmental Health Specialty Units (PEHSUs) may yield collaborative opportunities to address CEH in CSE settings that do not primarily focus on environmental health concerns—for example, well-child pediatric visits or preschool orientation days (Zajac et al., 2020).

5 | PARTNERING ACROSS DISCIPLINES AND SECTORS

To achieve the goal of combining developmental and CEH science to protect child health, particularly for children in structurally disadvantaged communities who experience the compounded impacts of psychosocial stressors and environmental risks (Leech et al., 2016; Morello-Frosch & Shenassa, 2006), we urgently need to translate CEH knowledge into action(s). To do so, we need interdisciplinary collaboration among CEH scientists, developmental scientists, and others. We also need cross-sector partnerships that center individuals whose environments are most impacted and include those who have the power to change exposures across the CSE (e.g., policymakers, industry polluters, politicians (Bachrach et al., 2010)). Indeed, CEH scientists have been leaders in this type of approach by requiring community engagement in NIEHS funded centers (Birnbbaum, 2018; Lichtveld et al., 2016; O'Fallon et al., 2000; O'Fallon & Dearth, 2002). Each of these types of collaborative work are discussed in turn.

5.1 | Interdisciplinary collaborations

Interdisciplinary collaborative research can facilitate translating CEH findings, often based on animal models, to in vivo studies and beyond, to children in their natural environments. Effects of certain neurotoxicants that have been well-established in animal models are difficult to translate to the reality of child health and development (Bailey et al., 2016; Harry et al., 2022; Spear, 2007). This is understandable as emerging findings can lead to new concerns and changing guidance (Organization, 2010) and relative lack of control over human (particularly child) compared to animal lab environments (Bachrach et al., 2010; Bennett et al., 2016; Korfmacher, 2020; Korfmacher et al., 2016). This is an area where developmental scientists can contribute, having considered such complexities for decades. For

example, research on the impacts of early life stress and maternal behavior based on studies of “licking and grooming” rats (Beery & Francis, 2011; Orso et al., 2019) has prompted wide interest in translating findings from animal models to counteract the impacts of early life stress in humans (Heim et al., 2019; Nelson & Gabard-Durnam, 2020).

Interdisciplinary work takes time and effort and can face barriers, which can be especially daunting for early-career scientists (Gauvain, 2018). For example, simply the terminology used by CEH and developmental scientists to describe the prenatal to early childhood period varies (e.g., “first 1000 days”, “first three years”, “zero to three”), resulting in historically limited cross-fertilization of these literatures. There are many opportunities to build familiarity, however. Joint data collection efforts are an effective way to establish interdisciplinary collaborations. Including developmentally sensitive, nuanced assessments in cohorts with environmental exposure data is a critical step. Studies in the current Special Issue used the ELEMENT, Nunavik Child Development Study, and PROGRESS birth cohorts to do so, and the value of—and challenges in—conducting such work has been highlighted by CEH scientists (Eskenazi et al., 2005) and others (LeWinn et al., 2021). Creating synergistic models across human and animal cohorts is an excellent way to identify and test mechanisms, particularly when timing and level of exposures cannot be specified in human work. Industry or technology sector partnerships could facilitate use of personal exposure monitors to test mechanistic hypotheses regarding individual differences in susceptibility. Finally, connecting with risk communication scientists is essential in determining how to represent data and translate findings in a manner that is meaningful to key audiences, including families, communities, and policymakers (Raphael, 2019).

5.2 | Partnerships with communities

Community-based participatory research frameworks are central to CEH work focused on Environmental Justice (Israel et al., 2005; Korfmacher et al., 2016; Lichtveld et al., 2016; O’Fallon & Dearry, 2002; Raphael, 2019). Although less common in traditional developmental science, such approaches are increasingly recognized and appreciated (Mulvey et al., 2020; Rivas-Drake et al., 2016). Community partnerships are essential for translating research findings to foster positive outcomes for children. Engaging community stakeholders across the CSE is necessary not only to identify CEH threats and training needs, but also barriers and opportunities for developmentally-informed, community-relevant implementation of CEH findings. For example, if contaminants are discovered in a childcare or community playground, how can we ensure children continue to gain socialization and other benefits of childcare attendance and outside play without risking additional exposures? Developmental and CEH scientists could also connect with communities to advocate for CEH-informed policy recommendations regarding manufacture of child- and family-facing products in order to reduce toxicant exposures (Bachrach et al., 2010; Korfmacher et al., 2016).

Respectful community partnerships can guide meaningful research questions, connect systems, and create policy change. Communities who are most impacted by environmental toxicant exposures often have the least power or access to policymakers and limited time for advocacy, so it is important for both CEH and developmental scientists to support communities to engage in collective action and advocacy to protect their children and ensure that community voices are heard (Haynes et al., 2016; Lichtveld et al., 2016; Miller, Varisco et al., 2022; Raphael, 2019). Given the history of racist policies and mismanagement of environmental pollution, it is essential to build trust among historically

marginalized communities (Binder et al., 2022). Citizen science approaches provide a way to partner with community members to gather data and inform study designs that are community-oriented (Sandhaus et al., 2019). Key elements of successful partnerships include dedicating time and resources to build partnerships, addressing interdisciplinary and cross-sector issues, ensuring community representation, co-developing and exchanging knowledge, actively participating, and maintaining collaborative activities over time (Wine et al., 2017). Taking an Environmental Justice perspective is particularly important in the context of an environmental disaster, as communities know their own priorities and what will and will not work in their setting (Hanna-Attisha et al., 2022; Lichtveld et al., 2016; Raphael, 2019). A potential additional contribution of a developmental perspective could be an explicit focus on listening to the needs of children and families, centering those needs, and advocating for services that may be helpful to them (Hanna-Attisha et al., 2022; Mulvey et al., 2020; Rivas-Drake et al., 2016).

6 | TAKEAWAYS FOR DEVELOPMENTAL SCIENTISTS

This is an exciting and important time to apply developmental thinking and methods to study environmental toxicant exposures and learn how to mitigate the effects on children. Risks to healthy development can emerge not only as a result of direct exposure but also climate change-related impacts on access to clean water, clean air, and adequate nutrition on a global scale and the physical and psychosocial stressors this creates (Nations, 2014). CEH and developmental science researchers are increasingly examining the nuances of different levels, timing, mixtures, and types of exposure to risk and protective factors, rather than broad main effects, which should inform interventions (Trentacosta & Mulligan, 2020). Using developmentally-sensitive conceptual models and methods to guide research on the mechanisms of association between exposures and developmental outcomes and to model the contexts of child development will allow for more effective translation of CEH science findings to improve child health and development across the CSE. Developmental scientists are practiced at conceptualizing, measuring, and modeling complex and interconnected social-contextual influences on nuanced aspects of development. Given the urgency of CEH risks and increasing appreciation for the value of interdisciplinary and collaborative work, there should be ample opportunity and motivation for developmental scientists to reach out to CEH colleagues to engage with these issues in order to promote healthy development in children and across the lifespan.

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