Disrupted beginnings: Neurodevelopmental outcomes of COVID-19 lockdowns in early childhood (Review)

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Abstract. Early childhood development depends on stable routines, social interaction and responsive caregiving. The 2019 coronavirus disease pandemic disrupted these supports through lockdowns, reduced early-education access and elevated caregiver stress. The present review synthesized empirical studies (2020-2025) of children aged 0-5 years and found consistent evidence of modest increases in emotional and behavioral difficulties, particularly where caregiver stress or socioeconomic adversity was elevated. Cognitive, language and executive-function (EF) outcomes were found to be more heterogeneous and appeared most affected in the contexts of reduced stimulation or limited access to early learning, with EF processes showing particular sensitivity to stress-related and environmental disruptions. Biological findings (cortisol, DNA methylation and infant brain measures) showed a number of converging signals, particularly in higher-risk contexts, but remained preliminary given modest sample sizes, methodological heterogeneity and limited replication. Overall, this suggested that pandemic-related disruptions disproportionately affected children in vulnerable family contexts. Therefore, the present study suggested targeted caregiver mental-health support, preservation of early-education access during emergencies and longitudinal follow-up of high-risk cohorts.

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Key words: 2019 coronavirus disease, early childhood, socioemotional, neurodevelopment, lockdown, caregiver stress, epigenetics, cortisol, executive function, preschool

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1. Introduction

Due to the outbreak of the 2019 coronavirus disease (COVID-19) pandemic and its accompanying public health measures, which were implemented to curb the rapid spread of the virus, daily life across all age groups has been markedly disrupted. From the outset, the COVID-19 pandemic was recognized as a potential threat to both physical and mental health (1-3), particularly among vulnerable populations, including young children and their families (4,5).

Early childhood (0-5 years) is a period of rapid brain development and heightened sensitivity to environmental conditions. During this developmental period, stable routines, responsive caregiving and access to early learning experiences support the emergence of socio-emotional skills, language, executive functions and foundational neural circuits (6). The COVID-19 pandemic disrupted these developmental supports through lockdowns, social-distancing measures and widespread closures of early childhood education and care settings (7). These disruptions introduce unique challenges, especially for young children, whose developmental growth depends on consistent routines, rich social interactions (such as responsive caregiver-child exchanges, peer play and opportunities for shared attention), and core educational experiences (including

language-rich activities, guided play, early numeracy and literacy exposure, and structured opportunities for exploration and problem-solving) (8-10).

Although multiple studies (11-13) are examining the developmental consequences of the pandemic, previous reviews (14,15) provide fragmented overviews. These reviews typically focus on single domains such as socio-emotional or behavioral outcomes (11), language development (12) or executive function (13), combining preschoolers with older children in their analyses (14,15), or summarizing findings from the early phase of the pandemic (1,4,7,8). As a result, integrated evidence describing how pandemic-related disruptions affect multiple developmental systems specifically in children aged 0-5 years, whose developmental needs and vulnerabilities differ markedly from those of school-aged children, is yet to be elucidated.

The present narrative review aimed to address the aforementioned gaps by summarizing empirical studies published from 2020-2025 across three interconnected domains: i) Socio-emotional and behavioral development; ii) cognitive, language and executive-function (EF) outcomes; and iii) biological and physiological markers of stress. By examining these domains together, the present study aimed to clarify the converging and diverging patterns across studies, identify contextual factors that affected the responses of children to pandemic-related stressors, and highlight the methodological limitations that constrain interpretation. Therefore, the present integrated, early-childhood-specific review provided an understanding of how pandemic disruptions influenced developmental pathways and where evidence remains preliminary or inconsistent.

2. Methods

PubMed (https://pubmed.ncbi.nlm.nih.gov/), Embase (https://www.embase.com/), PsycINFO (https://www.apa.org/pubs/databases/psycinfo) and Web of Science (https://www.webofscience.com/) were searched for empirical studies published between January 2020 and June 2025 (the full search strings are outlined in Table SI). Empirical studies (cross-sectional, cohort and longitudinal), systematic reviews and meta-analyses reporting data for children aged 0-5 years (or separate analyses for this age group) were included. Eligible studies examined pandemic-related restrictions (such as lockdowns and early childhood education and care settings) and used validated outcome measures in socio-emotional, cognitive/language or biological domains. Non-empirical commentary, studies that combined preschoolers with older children without separate reporting and studies that lacked validated outcomes were excluded. Only peer-reviewed studies published in English were included; studies published in other languages or in non-peer-reviewed sources were excluded.

Titles and abstracts were screened independently by two reviewers and full texts were retrieved if studies were judged to be potentially eligible. Disagreements regarding eligibility were resolved by consensus. To aid interpretation, each included study received a simple quality rating (high, moderate or low) based on sample size and representativeness, study design, biomarker assay validity, and control for confounding (the ratings and brief justifications are reported in Table SII). Subsequently, studies were organized into three interconnected areas: i) Socio-emotional and behavioral development; ii) cognitive, language and executive function outcomes; and iii) epigenetics and biological markers of stress.

3. Integrated summary of results

Across studies, a number of consistent patterns emerged in socio-emotional, cognitive, language and executive function, and biological domains. Table I summarizes converging and diverging findings across these domains and highlights key moderators as well as the strength of the evidence.

Socioemotional and behavioral development. Across studies of socio-emotional and behavioral development (16-28), there was a consistent pattern of elevated difficulties among children exposed to the COVID-19 pandemic period, with evidence from meta-analyses indicating a higher prevalence of emotional and behavioral problems compared with pre-pandemic estimates (11,14). Additionally, longitudinal cohorts documented increases in emotional and peer problems over time, with changes observed from the pre-pandemic period (2018-2019) through the early pandemic phase (2020) and into later phases (2021-2022) (15). A subset of children followed persistent high-symptom trajectories across the pandemic period, particularly in emotional and oppositional-defiant domains (16). These trajectories were strongly shaped by family-level stressors, including elevated parental psychological distress, job or income loss, increased caregiving burden and disruptions to daily routines. Such family-level stressors were central to the observed patterns as they reduced the emotional and regulatory resources available within the family environment, thereby heightening children's vulnerability to socio-emotional difficulties during periods of prolonged uncertainty and disruption. Broader caregiver stressors, such as financial strain, household chaos, reduced childcare access and pandemic-related disruptions, were consistently associated with increases in children's internalizing symptoms (for example, anxiety and withdrawal) and externalizing symptoms (for example, irritability and aggression), sleep problems and behavioral dysregulation (17-19), with longitudinal evidence indicating stronger associations in families with less socioeconomic resources (15).

Among infants and toddlers, higher maternal depression and anxiety, increased parenting stress, reduced social support, and disrupted daily routines were associated with increased socio-emotional difficulties (20,29,30). Peer difficulties increased in preschoolers during the pandemic, with positive parent-child interactions buffering these effects, although these supports did not consistently mitigate emotional symptoms, which remained associated with caregiver stress and broader household disruptions (15,16,29). Despite these patterns, findings were not uniform. A number of studies reported relatively consistent socio-emotional functioning when family routines were preserved or when parental mental health remained stable (31,32). In addition, the magnitude of socio-emotional difficulties varied across cultural and policy contexts, where strict lockdowns, extended preschool closures and culturally specific caregiving patterns, such as reliance on structured early education in Germany and prolonged home confinement

Table I. Cross-domain synthesis of evidence on early childhood development during the 2019 coronavirus disease pandemic (2020-2025).

Domain	Consistent findings	Divergent or mixed findings	Key moderators	Evidence strength
Socioemotional and behavioral	Small to modest increases in internalizing and externalizing symptoms across the majority of cohorts; higher parental stress, anxiety and depression predicted greater child emotional and behavioral difficulties; prenatal and postpartum maternal mental health problems associated with higher infant negative affect; greater pandemic-related family disruption associated with more sleep problems, anxiety and behavioral difficulties; higher quality teacher contact during remote learning associated with improved social and behavioral outcomes.	Minimal socioemotional differences when parental mental health was stable or when family routines remained intact; peer problems increased primarily in lower-education families, not universally; meta-analytic estimates showed high heterogeneity, with varied effect sizes across regions, tools and timing.	Caregiver mental health (stress, anxiety and depression); parenting practices (harsh or inconsistent vs. supportive parenting); SES and caregiver education; household chaos, routine disruption and daily stability; parent-child relationship quality (bonding, attachment and positive parenting); child biological sensitivity (such as basal cortisol moderating effects of harsh parenting).	Moderate-high (large-pooled samples and multiple longitudinal cohorts; consistent patterns despite heterogeneity; heavy reliance on parent-report measures).
Cognitive and language	Small reductions in communication and problem-solving; increased probability of screening positive for delay inpandemic-born infants; stronger effects where ECEC access was reduced.	No differences when maternal infection was mild/asymptomatic; motor outcomes largely stable.	Access to ECEC; home learning environment and language-rich interactions; prematurity and VLBW status (amplifying developmental vulnerability); SES and digital access; severity of educational disruption.	Moderate (large population-based samples; evidence drawn from both parent-report screening and standardized assessments across studies).
Executive function and regulatory capacity	Maternal stress associated with poorer infant regulatory capacity; working memory and attentional processes sensitive to environmental instability; working memory, attention and cognitive flexibility sensitive to environmental	Minimal differences in cohorts with stable routines and strong family structure; a number of EF domains, such as inhibitory control, exhibited relative stability in numerous cohorts.	Parenting stress; social support; household chaos and routine disruption; quality of early caregiving interactions.	Moderate (longitudinal evidence across multiple cohorts, though samples are generally small and EF often measured indirectly).

Table I. Continued.

Domain	Consistent findings	Divergent or mixed findings	Key moderators	Evidence strength
	instability; reduced social support associated with poorer early regulatory behaviors.			
Biological and physiological markers (epigenetics, stress physiology and neurobiology)	Prenatal pandemic-related stress associated with altered methylation in NR3C1 and SLC6A4; severe maternal SARS-CoV-2 infection associated with widespread infant differential methylation and lower ASQ-3 scores at 12 months; prenatal maternal distress associated with altered infant brain structure and connectivity (such as smaller amygdala volumes and altered amygdala-PFC connectivity); pandemic exposure associated with broad epigenetic signatures in neonates vs. pre pandemic controls.	No methylation differences associated with mild/asymptomatic maternal SARS-CoV-2 infection; hair cortisol findings were largely null, as no pandemic-associated changes were reported, and prenatal stress was not consistently associated with maternal or infant cortisol; a number of stress biomarkers (such as hair cortisol or DHEA) were moderated by SES as opposed to pandemic exposure alone.	Severity of maternal infection; SES (moderating cortisol); timing of prenatal stress (trimester-specific effects); maternal inflammation (such as IL-6 and IL-17A) predicting infant neurodevelopment; maternal anxiety and depression (predicting infant amygdala structure and temperament).	Preliminary-moderate (small to moderate samples; heterogeneous biomarkers; strong mechanistic designs but limited replication).

ASQ-3, Ages and Stages Questionnaire-3; ECEC, early childhood education and care; NR3C1, nuclear receptor subfamily 3 group C member 1; SLC6A4, solute carrier family 6 member 4; SES, socioeconomic status; VLBW, very low birth weight; EF, executive-function; PFC, prefrontal cortex; DHEA, dehydroepiandrosterone; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2.

with limited outdoor play in China, were associated with more pronounced effects in settings experiencing prolonged lock-downs or greater household disruption (17,19). In these studies, household disruption referred to increased parental stress, job or income loss, crowded or unstable living arrangements and significant disturbances to daily routines. These variations highlight the importance of contextual factors in shaping the socio-emotional responses of children to pandemic-related stress. However, interpretation of these findings was constrained by numerous methodological limitations, including reliance on parent-reported measures, convenience sampling, heterogeneous exposure definitions and notable attrition in longitudinal cohorts. Therefore, caution is warranted when interpreting the magnitude of socio-emotional differences, even though the overall pattern of increased vulnerability remained consistent.

Cognition, language and executive function. Across studies examining cognition, language and EF development (12,13,33-45), a number of points of convergence emerged regarding the developmental consequences of the COVID-19 pandemic for infants and young children. Firstly, modest but consistent reductions across communication, problem-solving and personal-social domains were observed across numerous large-scale and international cohorts (33,46), with communication and problem-solving demonstrating the clearest disruptions (14,33,46). Furthermore, a number of

studies reported increased probabilities of screening positive for developmental delay, which was driven in part by increased rates of language-specific delays (34-36). However, these patterns were not uniform across all children, as preterm (gestational age <32 weeks) or very low birth weight (<1,500 g) infants exhibited the most pronounced differences, with notably lower cognitive and language scores compared with pre-pandemic peers (37). Although these infants represented a subgroup that was biologically at-risk due to immature brain development, higher rates of neonatal complications and increased vulnerability to environmental stressors, their developmental profiles were consistent with broader international findings, which indicated small but reliable reductions in early problem-solving and communication abilities among pandemic-born infants (14), as well as early delays in social communication, including reduced meaningful word use, pointing and waving (38). Converging findings from cohort studies and a comprehensive review of international research documented consistent patterns of lower performance in morphosyntax, expressive vocabulary, phonological awareness and early literacy skills, with instructionally dependent language skills having the largest disruptions and children from lower socioeconomic backgrounds having the longest delays (12,39,40). Teacher-reported longitudinal data, analyzed in a study by Bub *et al* (47), indicated that early learning and social-emotional skills were shaped by the quality of remote learning supports, with marginalized children receiving a reduced number of resources and less frequent teacher contact. These population-level shifts were moderated by parental mental health and early-education environments, in which maternal depression amplified developmental delays, whereas higher-quality early care settings were associated with more favorable outcomes, including enhanced expressive vocabulary, better early literacy skills and more advanced socio-emotional competencies.

A second area of consistent convergence was the role of caregiver psychological functioning. Across diverse cohorts, prenatal psychological distress, measured through mental health symptoms, pandemic-related stress or reduced social support, consistently predicted less optimal infant socio-emotional, regulatory and socio-cognitive outcomes, often operating indirectly through postnatal maternal mental health and parenting stress (20-22,29,30). Postnatal maternal depression, anxiety and perceived stress had similar associations, and a systematic review identified associations between postnatal depression and poorer mother-infant bonding, alongside difficulties in infant motor, self-regulation and socioemotional development (23). Furthermore, individual cohorts demonstrated that higher maternal stress predicted increased infant crying, fussiness and regulatory challenges even after accounting for prenatal symptoms (24,29). In addition, early motor development had a similar sensitivity to maternal mental health; higher prenatal and postpartum depressive symptoms were associated with poorer neonatal fine and gross motor abilities, with the strongest effects observed among preterm and low-birth-weight infants (25,33). Population-level data in studies by Giesbrecht *et al* (48) and Perrigo *et al* (46) also demonstrated these patterns as large municipal and national datasets showed that children exposed to the pandemic exhibited developmental lags by preschool age, with widening variability in developmental outcomes. These population-level shifts were moderated by family mental health and early-education environments (26,47,49). Taken together, these findings suggested that pandemic-related disruptions influenced not only mean levels of development but also the distribution and heterogeneity of developmental functioning across cohorts.

Despite these areas of convergence, a number of divergences were noted. Studies examining the impact of maternal severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection during pregnancy yielded mixed results. Certain studies reported elevated developmental risk, particularly when infection occurred in the first or second trimester, was severe or co-occurred with prematurity (34,35,37). However, other studies found no association between prenatal infection and developmental outcomes (41-43). These discrepancies may reflect differences in illness severity, timing of exposure, sample characteristics and measurement tools, a pattern consistent with broader heterogeneity across pandemic-era cohorts. Additionally, findings regarding motor development varied across studies, as although a number identified delays, particularly among high-risk infants or in the context of maternal mental health difficulties (25,37,44), a large population-based study reported no pandemic-related differences in gross motor (namely, walking without assistance and climbing stairs with assistance) and fine motor (namely, building a tower of cubes) milestones at 2 years of age (45).

EF-related processes (for example working memory, inhibitory control, cognitive flexibility) also appeared particularly sensitive to these stress-related and environmental disruptions (13,24,50-53). A quasi-experimental study from Russia found that preschoolers assessed during lockdown showed slower gains in cognitive flexibility and working memory, while inhibitory control remained relatively stable; girls had increased attenuation in working-memory development, suggesting potential sex-based differences in sensitivity to disrupted routines (13). Other studies also documented EF-related disruptions. In preschoolers, working memory mediated associations between environmental routines and emotional dysregulation (51) and studies of infant regulatory behaviors showed that maternal stress and reduced social support were associated with poorer early regulatory capacity (24,52), an EF-precursor skill (53). Additional studies reported increased difficulties regarding attentiveness and distractibility in the context of family stress, disrupted routines or harsh parenting, defined as punitive, irritable or overreactive disciplinary practices measured using the Parenting Scale and the inconsistent-discipline items of the Alabama Parenting Questionnaire (18,27), reinforcing the role of early stress and environmental instability in shaping EF-related pathways. Collectively, these findings indicated that while cognitive and language disruptions during the pandemic were modest, EF processes had an increased sensitivity to stress-related and environmental instability, highlighting the role of caregiver wellbeing and daily routines in shaping early developmental trajectories.

Taken together, this evidence indicated that the COVID-19 pandemic exerted broad but heterogeneous influences on early development. The most consistent patterns suggested modest population-level shifts in communication and socio-cognitive

domains (33,46,54), increased vulnerabilities among biologically or socioeconomically at-risk infants (12,37), and robust pathways that associate caregiver psychological functioning with infant outcomes (39,47). Divergences across studies, particularly regarding prenatal infection and motor development, highlights the need for continued longitudinal follow-up and harmonized assessment approaches.

However, the interpretation of these findings is affected by a number of methodological limitations across these cognition, language and EF studies. The majority of cohorts relied on parent-reported screening tools, such as the Ages and Stages Questionnaire-3, which are sensitive to parental stress and reporting bias (55) and may not detect subtle cognitive or language differences (56). Numerous samples were convenience-based, highly educated or lacked socioeconomic and racial diversity, limiting generalizability. Exposure definitions also varied widely, from broad pandemic-period indicators to specific measures of maternal infection or family stress, complicating comparisons across studies. Studies investigating maternal SARS-CoV-2 infection often included mild or asymptomatic cases, reducing the ability to detect the effects of more severe illness. Follow-up periods were frequently short, particularly for infants assessed in the first year of life, leaving uncertainty regarding whether early differences persist or resolve over time. Taken together, due to these limitations, caution in interpreting the magnitude of cognitive and language differences is suggested, even though the overall pattern indicated modest disruptions associated with contextual, as opposed to viral, exposures.

Epigenetics and biological markers. Across studies examining biological embedding during the COVID-19 pandemic, findings indicate subtle yet marked alterations in infant and child stress-related biology, though effects vary across biomarkers, tissues and exposure definitions (31,54,57-61). An epigenetic study reported pandemic-related differences in DNA methylation of stress-regulatory genes. Infants exposed *in utero* exhibit altered methylation in nuclear receptor subfamily 3 group C member 1 and solute carrier family 6 member 4 (SLC6A4), with trimester-specific patterns suggesting that first-trimester exposure may represent a particularly sensitive window of vulnerability (57). Genome-wide comparisons of pandemic-exposed neonates with pre-pandemic controls identifies hundreds of differentially methylated sites enriched in neurodevelopmental pathways (synapse organization, neurogenesis and axon guidance) and immune pathways (cytokine-mediated signaling, interferon responses and leukocyte activation), whereas maternal SARS-CoV-2 infection itself is not associated with methylation differences (58). By contrast, severe maternal infection is associated with widespread differential DNA methylation in infants and elevated maternal IL-6 concentrations, reflecting a heightened inflammatory milieu during pregnancy. These biological alterations show modest, domain-specific associations with developmental scores at 12 months, suggesting that maternal immune activation may exert subtle but measurable influences on early neurodevelopment (59,61). Additional research shows that higher prenatal pandemic-related stress predicts increases in infant SLC6A4 methylation, which is associated with altered temperament at 3 months (60).

Neuroimaging studies provide converging evidence that prenatal stress is associated with early alterations in infant brain structure and connectivity (54,62). Increased prenatal maternal anxiety predicts reduced left amygdala volumes at 3 months, which are subsequently associated with increased negative affectivity at 6 months (54). Complementary work shows that greater prenatal maternal distress is associated with altered infant white-matter microstructure and altered amygdala-prefrontal connectivity, suggesting early deviations in neural circuits supporting emotional regulation (62). Taken together, these findings offer preliminary evidence that prenatal stress during the pandemic may be associated with early structural and connectivity in neural systems implicated in emotion processing and regulation.

Physiological biomarkers showed a heterogeneous pattern as opposed to a uniform rise in stress physiology during the pandemic. In a small prenatal cohort, prenatal COVID-19-related stress was not associated with maternal hair cortisol concentrations (HCC), although socioeconomic status moderated this pattern, with a stress-cortisol association emerging only among women with a higher socioeconomic status; maternal HCC did not predict infant temperament (31). In a separate pre- to post-pandemic cohort with repeated hair-steroid assessments, mean levels of cortisol, cortisone and related adrenal steroids, such as dehydroepiandrosterone and dehydroepiandrosterone sulfate, did not change across the pandemic onset. However, family income and parent-reported family functioning (conflict resolution, cohesion and COVID-19-related stress) moderated these patterns, with increases in child HCC occurring primarily in households with lower income or greater family stress, with social support buffering these rises (61). Children with higher pre-pandemic morning basal salivary cortisol showed greater physiological reactivity, exhibiting steeper increases in anger when exposed to harsh or inconsistent parenting, but the lowest anger level when exposure to such parenting was low. Harsh or inconsistent parenting was defined as more punitive, irritable or unpredictable disciplinary practices measured using the Parenting Scale and the inconsistent-discipline subscale of the Alabama Parenting Questionnaire, both validated parent-report instruments (27). Collectively, these findings suggest a possible biological-sensitivity-to-context interpretation, in which individual differences stress physiology heighten vulnerability in adverse environments but are buffered in supportive ones, rather than reflecting a population-wide increase in cortisol.

Taken together, these findings suggest preliminary evidence of possible biological embedding associated with prenatal and early-life stress during the pandemic. However, interpretation of this evidence is constrained by numerous methodological limitations. The majority of studies relied on peripheral tissues (buccal cells, saliva and hair), which may not capture central nervous system processes. Sample sizes were small to modest, reducing the statistical power to detect subtle effects and increasing the likelihood of false positives in genome-wide analyses. Furthermore, the majority of cohorts lacked pre-pandemic biological baselines, making it difficult to isolate pandemic-specific effects. Additionally, exposure definitions varied widely between studies, from broad pandemic timing to specific measures of maternal stress or infection, which complicates comparability across studies. Samples were

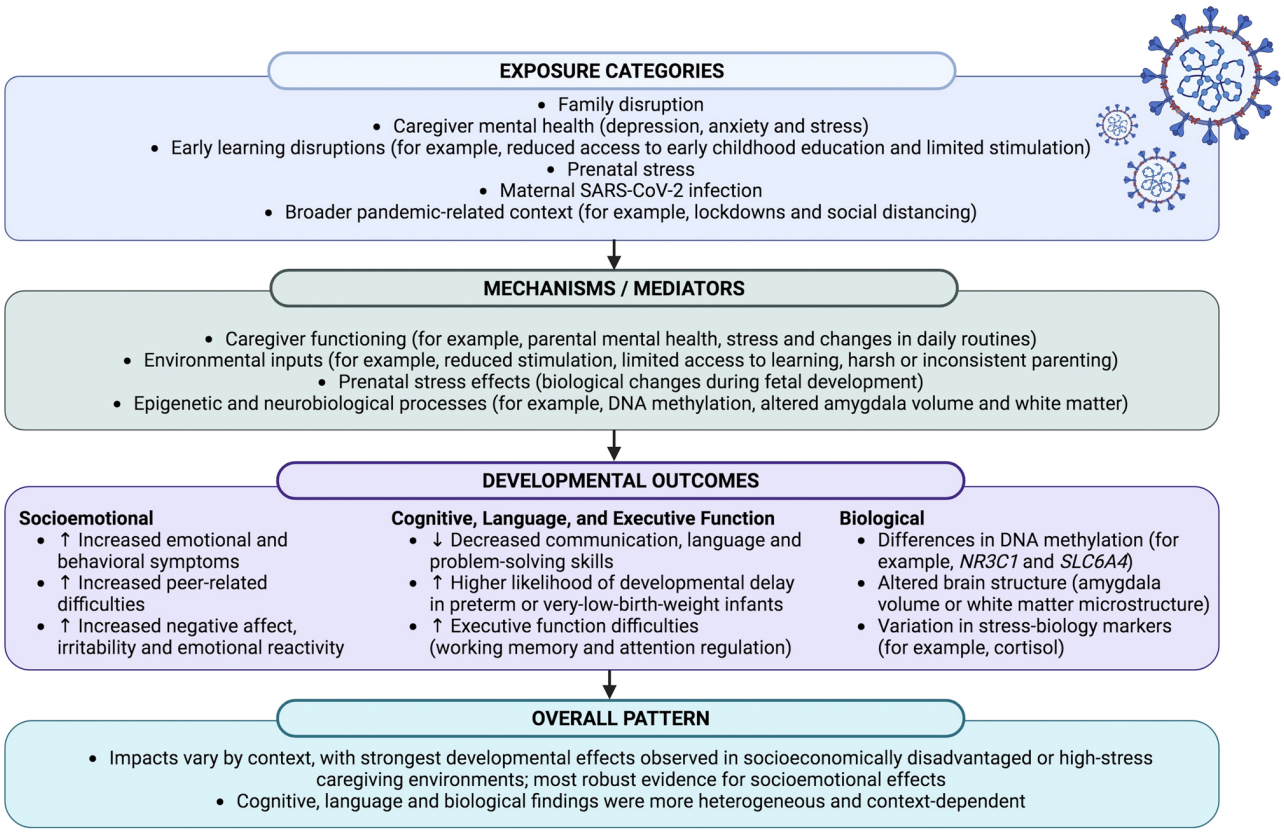

Figure 1. Conceptual pathway model integrating caregiver mental health, biological stress pathways and environmental inputs as mediators associating pandemic-related exposures with early childhood developmental outcomes. The present model summarizes the evidence regarding how pandemic-related exposures may have influenced socioemotional, cognitive and biological development. Key exposure categories included family disruption, caregiver mental health challenges, disruptions to learning in early childhood (such as reduced access to early childhood education and limited stimulation), prenatal stress and maternal SARS-CoV-2 infection. These exposures may influence developmental outcomes through interconnected pathways involving caregiver functioning, environmental inputs, prenatal stress effects and biological embedding (including epigenetic and neurobiological changes). Observed developmental outcomes included elevated socioemotional difficulties (such as emotional and behavioral symptoms or peer problems), modest cognitive, communication and language delays (particularly among preterm or high-risk infants) and biological alterations (such as DNA methylation differences or altered brain structure/connectivity). The overall pattern indicated possible context-dependent effects, with the strongest developmental disruptions observed in socioeconomically disadvantaged or high-stress caregiving environments. Mild or asymptomatic maternal infection was not consistently associated with developmental differences. Although interpretation was limited by methodological variability across studies, the present model summarizes converging evidence on early developmental vulnerabilities during the 2019 coronavirus disease pandemic. Images were generated using BioRender (https://www.biorender.com/). SARS-CoV-2, severe acute respiratory syndrome coronavirus 2; NR3C1, nuclear receptor subfamily 3 group C member 1; SLC6A4, solute carrier family 6 member 4.

also often highly educated and socioeconomically advantaged, limiting generalizability. In addition, neuroimaging studies were restricted to single time points, preventing assessment of developmental trajectories. Finally, the observational nature of all studies suggests the possibility of residual confounding from unmeasured prenatal or postnatal factors. These limitations highlight the need for cautious interpretation, even though the emerging evidence indicates potential biological embedded effects of prenatal stress during the pandemic.

4. Discussion and conclusion

Results of the present narrative review showed that pandemic-related disruptions acted as a multisystem stressor that altered caregiving (21,28), reduced access to early learning (15,33) and disrupted the daily routines of children (18,24). These disruptions also extended to sleep (31) which is suggested to be a multidimensional health process involving quality, timing and circadian regularity as opposed to duration alone (63). Socioemotional outcomes showed the most consistent evidence and were associated with caregiver mental health (29,30). By comparison, developmental outcomes were more strongly associated with pandemic-related psychosocial stressors such as caregiver distress, routine instability and reduced stimulation compared with direct viral exposure. Evidence regarding motor development and musculoskeletal outcomes remains limited, representing an important area of future research, particularly given concerns regarding potential motor delays associated with reduced physical activity during lockdowns (64). Cognitive and language effects appeared more variable, emerging in settings where stimulation or early-education access was curtailed (15,33). Biological measures provided preliminary, context-dependent signals that requires validation in larger, harmonized cohorts (54,61). These biological findings should be interpreted as early, hypothesis-generating biomarkers as opposed to established mechanistic pathways. Overall, the evidence indicated context-dependent impacts as opposed to uniform population-level effects, with children in socioeconomically disadvantaged or high-stress households disproportionately

affected (18,19). This pattern is consistent with broader evidence that indicated that children living in shelters experienced increased psychosocial stress and reduced access to supportive services during the pandemic (65). Biomedical complications, vaccine-related effects and rare post-infectious conditions fell outside the scope of the present developmental review, which focused on psychosocial and neurodevelopmental pathways; however, they are important areas for future clinical research.

The pattern of results supported a developmental-systems view in which caregiver functioning, biological stress pathways and environmental resources together moderate how children respond to acute societal stressors (Fig. 1).

These findings were consistent with mechanistic models of early life stress, showing that alterations in caregiver availability, predictability and emotional climate shape neural, endocrine and behavioral development through a number of interacting pathways (66). These pathways encompass alterations in corticolimbic circuitry involved in emotion regulation, changes in hypothalamic-pituitary-adrenal axis functioning, shifts in immune and inflammatory signaling, and disruptions in learning and predictability processes that guide children's emerging behavioral and socioemotional regulation. Socioemotional outcomes had the strongest and most consistent associations with caregiver stress (29,30), suggesting that interventions targeting caregiver mental health could yield rapid benefits for child well-being. Evidence further highlighted the notable mental-health burden experienced by parents of young children during the pandemic, with elevated anxiety and depression associated with contextual stressors such as childcare and school closures, financial strain, social isolation, work-family conflict and concerns about healthcare access (5). Cognitive and language outcomes reflect differential exposure to stimulation and early learning supports (15,33), which highlighted structural inequalities in access to protective environments. Biological findings, including cortisol, DNA methylation and infant MRI, provided early, hypothesis-generating signals in a number of high-risk samples (54,61); however, these were limited by modest sample sizes, assay heterogeneity and limited longitudinal follow-up. These emerging biological patterns were consistent with developmental-evolutionary models that proposed that heightened stress reactivity reflected a biologically sensitive and conditionally adaptive calibration to early environments, with effects that varied depending on the balance of adversity and support (67). Given these methodological constraints, the possibility of publication bias in pandemic-era research should also be acknowledged.

Small or non-representative samples, single-informant designs, heterogeneous measures and limited cross-cultural coverage reduced comparability and increased bias risk, making causal claims premature and highlighting the need for more rigorous, harmonized research. These limitations may also explain why socioemotional outcomes showed clearer patterns compared with cognitive or biological measures, which rely on more variable or resource-intensive assessments. Therefore, these methodological constraints indicated that the current evidence base supports possible associations as opposed to causal conclusions. However, despite these constraints, the present findings suggested numerous implications for practice, policy and future research, particularly in areas where evidence converged across domains.

Practical implications may include strengthening caregiver mental-health supports in pediatric and early-childhood settings and promoting programs that help families maintain predictable routines and positive parent-child interactions during periods of disruption. Policy implications suggested the importance of ensuring continuity of early-education services during emergencies, through prioritized reopening, remote supports tailored to low-resource families and proactive outreach, as well as providing economic supports to families with young children to mitigate cascading stressors. Furthermore, research implications highlighted the need for multisite, longitudinal cohorts with harmonized measures, integration of multi-modal biomarkers with behavioral and contextual data, and transparent reporting practices that include null findings and quality metrics.

Overall, pandemic-related disruptions may have amplified existing inequities in early childhood development, with the most notable impacts concentrated among children facing socioeconomic disadvantage and caregiver distress. Therefore, moving from preliminary associations to actionable knowledge may require coordinated, longitudinal and multi-modal research, coupled with policies that protect early-education access and support caregiver wellbeing.

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Ethics approval and consent to participate

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Patient consent for publication

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Competing interests

IG, VE, MS, PK, JNT and ER declare that they have no competing interests. DAS is the Editor-in-Chief for the journal, but had no personal involvement in the reviewing process, or

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