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Developmental Cognitive Neuroscience

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Developmental cognitive neuroscientists study the baby, child, and adolescent brain to learn when and how cognition develops. Neuroscience techniques—electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS), magnetoencephalography (MEG), and functional magnetic resonance imaging (fMRI), among others—can provide insights into the neural mechanisms that underlie cognition and its development. These tools can also measure cognition in populations whose behavioral repertoire is limited (e.g., babies). Developmental cognitive neuroscientists are often interested in understanding variation in brain and cognitive development, for example, in individuals with neurodevelopmental disorders, in hopes of learning how best to support young people.

History

For decades, developmental psychologists and neuroscientists conducted research in parallel with little cross-talk between disciplines. In the 1980s, several researchers highlighted common questions and methods across developmental psychology and neuroscience and articulated the promise of research that links the two fields (Crnic & Pennington, 1987; Diamond, 1990; Johnson, 1997). For example, Adele Diamond showed that neuroscience evidence for development in the lateral prefrontal cortex in rhesus monkeys (using the *delayed response task*—a task that measures the ability to remember an object's location and, after a delay, reach for it) mirrored evidence for developmental change in human infants' reaching behavior on the synonymous *A-not-B task* (Diamond & Goldman-Rakic, 1989). Together, this evidence led to a better understanding of the development of working memory and executive control (i.e., acting deliberately rather than impulsively) [see Working Memory]. It also raised questions about infants' understanding of object permanence (i.e., the understanding that an object still exists even if it is no longer visible; Spelke, 1990), which spurred increased use of experiments designed to measure infant cognition without significant task demands (e.g., eye tracking and "looking time" experiments, which measure patterns in eye movements; Stahl & Kibbe, 2022, although see Paulus, 2022). Some of the earliest fMRI studies with children built on the evidence from Diamond and Goldman-Rakic (1989), showing lateral prefrontal cortex responses during a working memory task in 8- to 11-year-old children (Casey et al., 1995; Nelson et al., 2000).

Developmental cognitive neuroscientists—then and now—argue that it is important for our understanding of the developing mind to be backed by evidence about the developing brain. To understand early origins of cognition, we can characterize responses in the brain networks or regions that support cognition in young babies or in nonhuman primates [see Animal Cognition; Uniquely Human Cognition]. To understand mechanisms of developmental change or individual differences, we can characterize differences in brain measures across people of different ages or with different experiences or behavioral profiles. Moreover, characterizing biological constraints—like windows of enhanced brain plasticity—may help to time interventions to maximize their effect (Nelson, 2000) [see Neuroplasticity].

Core concepts

Experimental designs

Most developmental cognitive neuroscience research uses a cross-sectional design (i.e., measures differences in some brain measure across people of different ages). Longitudinal studies, which measures change with age within the same individuals, provide more sensitive estimates of developmental trajectories and differences across people that are stable over time. Developmental cognitive neuroscientists also use intervention or training studies, which support making causal inferences about development (i.e., to understand predictors or drivers of development rather than just associations or correlations). Longitudinal and intervention studies are less common than cross-sectional studies because they require the same people to contribute data across multiple timepoints. In response to this challenge, multisite collaborations have developed to facilitate longitudinal developmental cognitive neuroscience research (Casey et al., 2018; Nelson et al., 2024).

Tools

Developmental cognitive neuroscientists use a range of tools to measure brain activity and its correlates (for a detailed overview, see Olson et al., 2025). Briefly, EEG and MEG provide direct measures of brain activity; EEG measures electrical activity (generated by neurons) across the scalp, and MEG measures magnetic fields produced by the brain's electrical activity. fMRI and fNIRS provide indirect measures of brain activity; they measure the relative amount of blood oxygenation as a proxy for brain activity (brain regions that are more active use more oxygen; Malonek & Grinvald, 1996). Because blood flow is slow, fMRI and fNIRS have low temporal resolution. EEG and MEG are better suited for testing hypotheses that require precise information about when a brain response happens. However, fMRI has high spatial resolution, providing a relative measurement of blood oxygenation every 1 to 2 mm across the entire brain. EEG, MEG, and fNIRS measure signals at the scalp, and so researchers must infer (localize) where in the brain signals come from (the source). Because fMRI measures from the whole brain, it avoids the "source localization" problem inherent to EEG, fNIRS, and MEG. For this reason, fMRI is the best method for measuring from parts of the brain that are further away from the scalp (e.g., medial or subcortical brain regions).

The tools that are most commonly used by developmental cognitive neuroscientists tend to differ by the developmental stage of participants. For example, EEG and fNIRS are considered particularly infant friendly because they involve sensors worn as a cap on the head, are silent, and are relatively inexpensive. By contrast, fMRI is particularly sensitive to participant motion, loud, and expensive (MEG machines are also expensive). For these reasons, initial neuroscience studies with babies and young children acquired data while they were sleeping (Dehaene-Lambertz et al., 2002; Redcay & Courchesne, 2008), which limited the aspects of cognition that could be studied, or used tools with lower spatial resolution (e.g., EEG and fNIRS), which limited the specificity of claims about which parts of the brain were engaged during the experiment. However, methodological advances have led to the acquisition of fMRI data with awake

young children (e.g., Olson et al., 2026; Richardson et al., 2018) and awake babies (e.g., Deen et al., 2017; Ellis et al., 2020).

Early emergence and continuity

fMRI and fNIRS studies with awake babies have revealed perhaps surprisingly mature organization of brain responses early in life (O'Doherty et al., 2026; Yin et al., 2025). For example, there is evidence that babies recruit the same parts of the brain as adults during face (Deen et al., 2017; Kosakowski et al., 2021), body (Kosakowski et al., 2022), and scene perception (Kamps et al., 2025; Kosakowski et al., 2022); theory of mind reasoning (Hyde et al., 2018); music processing (Kosakowski et al., 2023); attention (Ellis et al., 2021a); statistical learning (Ellis et al., 2021b); and some aspects of memory (Yates et al., 2025). This evidence suggests early emergence and continuity in the neural systems that support different cognitive processes. A rich interpretation of this evidence is that there are at least somewhat similar cognitive processes in adults and babies, despite different overt behaviors and evidence for continued development in these neural systems (e.g., Yates et al., 2021; Yin et al., 2025).

Neural correlates of cognitive development

Developmental cognitive neuroscientists often aim to characterize the underlying mechanisms of cognitive development [see Cognitive Development]. As children get older, they gain qualitatively new cognitive skills and understanding (e.g., learning to read or learning new concepts), and they also undergo quantitative cognitive change (e.g., developing higher memory capacity or faster processing speed). These different cognitive changes have different underlying neural correlates (Amso & Casey, 2006). For example, when children (and even adults) learn to read, they develop selective brain responses for processing letters (Dehaene et al., 2015; Dehaene-Lambertz et al., 2018). Higher working memory capacity correlates with development in lateral prefrontal cortex (Thomason et al., 2009).

Following this logic, developmental cognitive neuroscience evidence can lead to a better understanding of developmental change when its underlying neurocognitive mechanisms are unknown or contested. *Equifinality* is the idea that the same behaviors/neural profiles can have different developmental pathways and/or mechanistic causes. Neuroimaging evidence can help to tease apart these different pathways/causes when there are specific predictions about what they look like in the brain. For example, are older children better at *theory of mind* tasks because they have more sophisticated theory of mind reasoning or because they have more developed language and executive functions—which help them to do better on the task [see Theory of Mind]? Pediatric fMRI studies have provided evidence that higher performance on theory of mind tasks is accompanied by more mature responses in brain regions recruited for theory of mind reasoning, suggesting that doing better on theory of mind tasks at least in part reflects a more sophisticated theory of mind (e.g., Richardson et al., 2018). Note, however, that this does not mean that other cognitive capacities do not also contribute to better performance on theory of mind tasks or to theory of mind development, itself (see, e.g., Astington, 2006; Carlson & Moses, 2001).

Plasticity and the role of experience on development

Babies are often considered exceptional learners. One hypothesis is that their capacity to learn is related to increased brain plasticity early in life (Kennard, 1936)—that is, a "sensitive period" when the brain is especially shaped by experience (Hensch, 2005; Hubel & Wiesel, 1970) [see Neuroplasticity]. A dramatic example of neuroplasticity is that some children show typical language development following a stroke early in life (Fuentes et al., 2016); for adults, recovery following a stroke is more modest (Karbe et al., 1998). Developmental cognitive neuroscientists are interested in characterizing the mechanisms of neuroplasticity and determining whether they can be reinstated to support learning and/or cognitive recovery (Gabard-Durnam & McLaughlin, 2020; Werker & Hensch, 2015).

Most evidence on the mechanisms and timing of sensitive periods comes from research with animals (Hubel & Wiesel, 1970; Sur & Rubenstein, 2005; Takesian & Hensch, 2013). Research with people tends to study impacts of different early experiences on brain and cognitive development. For example, there is evidence that brain regions that typically support vision instead support language processing in congenitally blind adults and children (Bedny et al., 2011, 2015) but not in individuals who become blind late in life (Bedny et al., 2012)—suggesting reduced plasticity in the visual cortex with age and experience. Several studies provide evidence for impacts of early psychosocial experiences (Nelson et al., 2019), language experiences (Romeo et al., 2018a, 2018b), and socioeconomic status (Farah, 2017; Noble et al., 2012; Troller-Renfree et al., 2022) on cognitive and brain development. This line of research suggests that early life experiences can have prolonged impacts on brain and cognitive development (Gabard-Durnam & McLaughlin, 2020) and may alter the pace of development in that children who experience stress appear to mature faster (Tooley et al., 2021).

Questions, controversies, and new developments

Infant cognition and domain specificity

Evidence for early organization of brain responses has contributed to a substantial debate about the cognitive capacities of human infants (Haith, 1998). This debate is shaped by an ongoing, separate debate among cognitive neuroscientists about whether selective brain responses reflect "domain-specific" representations or computational processes—that is, representations and processes that are specialized for a particular cognitive capacity ("domain"). Taking evidence for brain responses to faces (and not other visual stimuli) in two-month-old babies as an example, these selective responses could reflect early domain (face)-specific processing, perhaps driven by the evolutionary importance of perceiving and recognizing faces (Morton & Johnson, 1991) and/or babies' earliest social experiences and motivations (Powell et al., 2018). This hypothesis converges with evidence that babies prefer to look at faces early in life (e.g., Valenza et al., 1996) and show early preferential responses to faces in medial prefrontal cortex—a brain region reliably recruited for social stimuli (Grossmann, 2013; Kosakowski et al., 2022). Alternatively, these responses could reflect lower-level, nonspecialized organizing principles of the brain (Arcaro & Livingstone, 2021; Livingstone et al., 2018). Specifically, responses in visual cortex are organized by visual

features—like how curvy or focal (central) something is—and this organization is also present in young babies (Ellis et al., 2021c). These hypotheses are not mutually exclusive, but the extent to which they explain the evidence from babies has implications for infant cognition. Do babies see and prefer faces as such, reflecting early social capacities and motivations? To what extent are social capacities and motivations acquired through biological maturation and/or social experiences?

This debate also has implications for our understanding of cognitive development and neuroplasticity. For example, if babies have sophisticated knowledge in place for a particular cognitive domain, then this could imply less developmental change (via maturation and/or learning from experience) in that domain in childhood. On the one hand, this constraint on the amount of development during childhood could explain why there are early "sensitive periods" of neuroplasticity (i.e., experiences early in life are most impactful). On the other hand, evidence that brain responses are more organized in babies than previously assumed could contradict the hypothesis that early neuroplasticity reflects an early lack of specialized brain responses (Kennard, 1936).

One influential hypothesis is that babies have early "domain-relevant" (rather than "domain-specific") representations and processes alongside a strong capacity to learn (Johnson, 2011; Karmiloff-Smith, 1994). This view predicts more gradual development of functionally specialized brain regions. Although this prediction is potentially at odds with evidence for selective brain responses in young babies (at least in some domains, like face perception, in which the evidence is strongest), it is consistent with evidence for continued development in selective brain responses in children (e.g., Gomez et al., 2017). This view also emphasizes the developmental interactions between cognitive functions (e.g., theory of mind reasoning and language do not develop separately) and predicts that neurodevelopmental disorders, which arise through development, will therefore rarely impact a single cognitive function or domain (Karmiloff-Smith, 1998, 2009). There is growing evidence in support of this prediction (Bishop & Rutter, 2008; Pennington, 2006).

Rethinking posterior to anterior brain development

A traditional view of brain development is that the development of cortical functions follows the sequence of structural brain development—in which visual brain regions in the back of the brain develop early, and "higher order" brain regions in the frontal lobe develop last (Huttenlocher, 1979; Thompson & Nelson, 2001). Developmental cognitive neuroscience evidence suggests that there are exceptions to this account; for example, face-selective responses in the fusiform face area and medial prefrontal cortex in two-month-old babies (Kosakowski et al., 2022) suggest that at least some cortical functions in posterior and anterior brain regions develop in parallel (Saxe & Kosakowski, 2025). More broadly, evidence that the prefrontal cortex supports cognition in babies (Werchan & Amso, 2017; Werchan et al., 2015)—before it is structurally mature—has led to a debate about how we should view infant learning. Do babies primarily learn passively—taking in and learning from the patterns in their experience—or are they active learners—

engaging their prefrontal cortex to seek out information and curate their experiences (Raz & Saxe, 2020; Smith et al., 2018)?

Neurological markers/profiles for transdiagnostic care

Developmental cognitive neuroscience research has contributed to the move toward "transdiagnostic" research—that is, research emphasizing behavioral profiles and needs over diagnostic labels (Cuthbert & Insel, 2013). *Multifinality* is the idea that the same early experiences, or the same neural profiles, can lead to different developmental outcomes. In line with this idea, developmental cognitive neuroscience studies have provided evidence that children with different neurodevelopmental diagnoses can share the same underlying neural profiles (Carozza et al., 2023; Siugzdaite et al., 2020). This research highlights the challenges of identifying neural predictors of children who are at risk or mechanisms of resilience and, more broadly, the inherent complexity and interactive nature of developmental processes (Karmiloff-Smith, 1998, 2009).

Broader connections

From its conception, developmental cognitive neuroscience has been closely linked to comparative research with nonhuman primates, developmental psychology, and cognitive neuroscience (e.g., Diamond & Goldman-Rakic, 1989). Developmental cognitive neuroscience research informs clinical scientists, who study early predictors of behavioral profiles and diagnoses (Siugzdaite et al., 2020), and educational neuroscientists, who study neural correlates of educational achievements like learning to read (Gabrieli, 2016). Developmental cognitive neuroscience evidence can also shape laws and policies relevant to young people—for example, by contributing to debates about the age of criminal responsibility (Blakemore & Choudhury, 2006; Zeki et al., 2004) and about the benefits of social infrastructure for cognitive and brain development (Choudhury et al., 2023; Farah, 2017). Developmental cognitive neuroscience research that seeks to describe representations and mechanisms of learning at different stages of development has been informed by and inspired computational models of development, including those used in artificial intelligence (Astle et al., 2023; Cusack et al., 2024).

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