CHAPTER

10

Introduction to Cognitive Development from a Neuroscience Perspective

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OUTLINE

10.1 INTRODUCTION

Newborns depend for their survival on caregivers, almost always mothers, who provide them with food, warmth, and comfort. They come into this world equipped with a set of reflexes, basic sensory capacities and preferences, and primitive means for signaling their needs. Over the first 2 years of life, infants undergo rapid developments in cognition and behavior, and their brains undergo exponential growth and change. During these early years, infants are transformed into toddlers capable of goal-directed actions and independent mobility; they develop sophisticated concepts of the world around them, acquire the basic use and understanding of language, and become equipped to navigate their social environment with ease. Nevertheless, at the age of 2, toddlers still have a great deal to learn, and developmental changes continue, at a steadier rate, over the next two decades.

In this volume, the authors follow this remarkable journey in human development with particular emphasis on the early years. Studies of child development began almost a century ago; however, the conceptual frameworks and information about what children know as they grow have shifted over the years, driven largely by the introduction of new methods and technology that is now opening up the possibility of asking key questions about the neural and cognitive mechanisms that drive developmental change. This chapter serves as a roadmap to the basic frameworks and methods that have guided the field of child development over the past few decades and then introduces the chapters in this volume.

10.2 FRAMEWORKS AND METHODS

10.2.1 Conceptual Frameworks

The scientific field of cognitive development began with the seminal work of Jean Piaget, though its intellectual roots go back to philosophical questions about the origins of knowledge and mind raised by Plato, Aristotle, and others in ancient Greece. Piaget, who was a biologist by training, was the first to develop a comprehensive theoretical framework for how children acquire core concepts that are the foundation of human thought. His 'constructivist' theory claimed that fundamental concepts, such as space, time, and causality, are acquired by the baby operating on the environment. Through very basic processes, complex abstract concepts are built up through *actions* and *interactions* with objects

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and people. In Piaget's theory, children develop through a series of qualitatively distinct stages, each defined by a new form of mental representation. He was committed to a strong view on the biological contributions to cognitive development by arguing for the importance of evolution, maturation, and adaptation for understanding change over time; however, his empirical work focused exclusively on observable behavior, which clearly contributed to the significant role he attributed to action, especially as the foundation of representational knowledge (Flavell, 1996).

Piaget's work lies between the extremes of nativism and empiricism. He began writing in the early part of the twentieth century, but his work did not become well known in the English-speaking scientific community until the 1970s, when psychologists became open to ideas that were grounded in a more complex view of how biology intersects with experience. Nevertheless, even though Piaget firmly argued that developmental changes took place in children's cognition, he was not able to articulate how such changes were accomplished; instead, he focused more on generating the important questions to be addressed by developmental scientists that remain central to the field today.

Over the last few decades, developmental science has blossomed as it has taken on questions about what the starting point is for newborns, what the child knows at different ages, how this knowledge is organized and changes over time, and which factors and basic learning mechanisms contribute to these changes. These questions are being addressed using new tools that provide a more direct window into the minds and brains of babies and young children than simply observations of their behavior. While developmental scientists are informed by parallel research on other species, the unique social and linguistic abilities of humans transform the child's conceptions of the world in ways that require different frameworks and approaches for investigating developmental processes (cf. Vygotsky, 1978).

10.2.2 Eye Gaze

For Piaget, infants' actions on the world revealed their underlying knowledge; however, motor development is a slow process in humans and thus provides a very indirect assessment of their cognitive capacities. Beginning with the seminal work of Fantz (1958), researchers have been using eye gaze patterns to provide a more direct approach to what infants see, discriminate, prefer, remember, and expect. Because they have relatively good ocular-motor control, babies' eye movements are a reliable and valid way of revealing mental processing. Studies using eye gaze patterns, including measures of first fixations, time spent looking at images, and anticipatory looking patterns, have demonstrated that even newborns are not just a bundle of reflexes with basic sensory capacities. Instead, people now know that infants have perceptual preferences that are biased toward attending to particular events and entities in their environment, and rapid changes over the first few months of life consolidate and expand on these initial biases (see Chapter 37).

For many years, researchers relied on either manual on-line coding of eye gaze patterns or videotaping of infants' looking patterns and later laborious coding their eye movements by hand. It is the most common behavioral method in use today for studies on infant perception, cognitive, social, and language development (Aslin, 2007). The recent advent of automated eye trackers, particularly ones that do not require head-mounted cameras or complex calibration procedures, has led to changes in the ability to capture the microstructure of eye gaze patterns in infants including much finer temporal and spatial resolutions, without requiring manual coding that could potentially introduce error or bias. Nevertheless, despite the advantages of using automated eye trackers to capture eye movement patterns, there are still significant challenges about how data collected from these devices should be analyzed and interpreted (Aslin, 2012).

10.2.3 Electrophysiology

If eye gaze is the method of choice for investigating the minds of babies, then electrophysiology is the method of choice for investigating their brain function. The broader field of cognitive neuroscience has relied on a range of technologies to probe brain structure and function in people; however, not all of them are easily adapted for use with infants. Electrophysiological recordings, including electroencephalography (EEG) and event-related potentials (ERPs), provide relatively good measures of temporal processing and dynamics of cognitive processes. Their primary advantages for their use in studying infants and young children include safety, ease of use, and tolerance of some movement.

The EEG signals collected from multiple electrodes placed over the scalp reflect ongoing electrical activity in the brain; ERPs are signals that occur in response to a specific stimulus and are most widely used as a neural assessment for a range of cognitive processes. The analysis of EEG activity is generally not time locked, but can be decomposed into constituent frequencies to quantify power in specific bandwidths, each of which reflects different aspects of neural processing related to cognition. ERPs are thought to detect postsynaptic potentials from pyramidal cells summed over a large number of neurons. Invariant stimulus-related electrical activity is extracted through an averaging process over a large number of trials in order to reduce the noise due to random components. The average ERP is then analyzed temporally, as a series of positive and negative components characterized by their polarity, peak latency, amplitude, and distribution over the scalp (Csibra et al., 2008). The introduction of high-density arrays, which include a large number of electrodes embedded in a net that is quickly and easily fitted over the scalp, provides more complete spatial coverage and has led to new methods of analysis with better spatial and temporal resolutions.

Different components in the ERP signal have been linked to specific behavioral tasks including, for example, attention, face processing, and a range of linguistic processes from speech to syntax (see, for example, Chapter 32 and Rubenstein and Rakic, 2013). Much of what is known about the cognitive processes associated with specific ERP components comes from studies of adults. There are significant developmental changes in the latency, morphology, and topography in the known ERP components, and while the precise roots of these changes are not yet fully understood, they are thought to reflect a combination of cognitive advances and more efficient neural processing. While electrophysiological methods are now widely used in human developmental neuroscience, they do have several limitations including their poor spatial resolution and lack of sensitivity to processing in subcortical brain areas.

10.2.4 Magnetic Resonance Imaging and Other Imaging Methods

The growing field of cognitive neuroscience has relied most extensively on magnetic resonance imaging (MRI) as the single most effective, noninvasive, and safe method for examining *in vivo* human brain structure and function. MRI provides high-resolution spatial information, and its application in developmental science has given people detailed information about volumetric changes in regional gray and white matter. The advent of diffusion tensor imaging (DTI), a variant of conventional MRI, has led to advances in the ability to identify and characterize developmental changes in white matter pathways (Wozniak et al., 2008).

Functional aspects of brain development, particularly in older children, have been tracked using functional MRI (fMRI), which measures changes in blood oxygenation levels (BOLD response), an indirect measure of increases in regional neuronal activity. fMRI provides excellent spatial resolution when local differences in the BOLD response are analyzed between tasks or groups. Advances in analytic methods such as connectivity analyses have led to new ways of tracking developmental changes in systems-level cortical representations.

Despite their importance in developmental cognitive neuroscience, there are several challenges in using MRI with young children, not least of which is the requirement to lie completely still in a noisy enclosed tunnel for relatively long time periods while the scan data are collected. This involves a good deal of cooperation from an awake child, which is possible in children over the age of 5 who have been carefully prepared, or the use of alternative approaches such as scanning during sleep or sedation. It is also not clear how developmental changes in brain morphology and metabolism may influence the BOLD response, and there are other technical concerns that need to be carefully considered when interpreting findings from fMRI studies conducted on young children or children with neurodevelopmental disorders (Casey et al., 2005).

The newest technology that has been introduced to investigate functional brain development, particularly in infants, is near-infrared spectroscopy (NIRS), which, like fMRI, measures changes in hemodynamic responses that are assumed to be related to regional brain activity. Optical probes placed on the scalp measure changes in blood oxygenation levels that reflect surface cortical activity, offering moderately good spatial resolution, depending on the number and location of the probes. Considerable methodological and technological advances have been made, and the number of studies using NIRS to investigate functional activity in the brains of very young infants is increasing each year (cf. Gervain et al., 2011). It has been used in studies of infant perception, cognition, and language; however, it cannot detect neural responses generated in structures that lie below the cortical surface, which limits its use in studying key aspects of memory, emotion, or social perception.

10.2.5 Summary

Important advances in developmental cognitive neuroscience have been made in recent years based on the introduction of new conceptual frameworks and methods for probing cognition and brain processes. People are now beginning to be able to link behavioral and brain changes in ways that allow them to test theoretically grounded hypotheses about the neural bases of cognitive development. Yet, progress can only be made if their methods and technologies are used in the context of well-designed experiments and an appreciation of the limitations in the application and interpretation of findings from each available method. As noted, there are real challenges in using all the methods surveyed here with pediatric populations: they all require a considerable amount of cooperation and minimal movement. While young infants and older children can tolerate the requirements for most of these methodologies, toddlers and preschoolers are far more active than infants and far less compliant than school-aged children, and therefore, relatively less is known about development during these critical years. It is expected that technological innovations in the coming years will help to fill in these gaps to provide a more complete picture of cognitive development from birth through adolescence.

10.3 OVERVIEW OF CHAPTERS

This volume provides comprehensive and detailed coverage of the current state of research on cognitive development including both behavioral and neuroscience perspectives on the field. Each chapter highlights key developmental questions and illustrates the primary methods that have been used to address them. Throughout this volume, the emphasis is on typical development, but applications to atypical populations are discussed, particularly in those areas where more significant work has been conducted on children with neurodevelopmental disorders. The field is still young, and studies that attempt to address the developmental relationship between cognitive and neural processes have really only begun in earnest during the past decade. Each chapter concludes with a discussion of the future directions that people can expect to see in the coming decades.

In the opening chapter, Mark Johnson (see Rubenstein and Rakic, 2013) discusses the theories that have dominated the newly emerging field of developmental cognitive neuroscience. He highlights the importance of having theoretically driven research and evaluates the predictions and evidence from each theory using research from different cognitive domains. He concludes that the theory of interactive specialization, which has its roots in the Piagetian theory, offers the most promise of a framework that captures biological developmental change that is grounded in experience.

The next two chapters summarize the foundations of brain and behavioral development. Colby and his colleagues provide a detailed summary of what is currently known about postnatal structural changes in the brain based primarily on studies using MRI and DTI. They describe the very different trajectories in gray and white matter development, emphasizing the significance of developmental timing and key genetic and experience-dependent factors driving the dynamic processes of brain development that continue through late adolescence. Lamy and Saffran (see Rubenstein and Rakic, 2013) take on the central question about how infants learn, in particular, how they can acquire abstract and complex cognitive structure based on inputs from the environment. They focus on infants' capacities to extract different types of statistical regularities from the perceptual information that are central to the formation of linguistic and object categories. Evidence from studies conducted over the past decade suggests that infants actively use probability distributions, sequential structure, correlations, and associations in auditory and visual inputs, beginning early in the first year of life. These active learning mechanisms, which are presumably basic capacities that evolve via experience, are the building blocks that drive cognitive development.

For humans, vision is arguably the most important perceptual system that drives conceptual development, particularly for growth in understanding objects and events. It is also the system that is most well studied and understood across different species. In his chapter, Scott Johnson (Chapter 37) discusses how infants come to experience a world of stable objects beginning with limited but organized vision at birth that undergoes rapid functional changes during the first year of life driven by brain maturation coupled with learning from experience and manual explorations. More advanced aspects of visuospatial abilities are taken up by Stiles and her colleagues who discuss the development of ventral and dorsal neurocognitive processes including global and local pattern perception, spatial construction, localization, attention, and manipulation. The last part of their chapter describes research on these processes, particularly the vulnerability of the dorsal stream in children who have experienced brain injury or with neurogenetic syndromes.

Human memory serves a range of important functions that are carried out by different systems. In her chapter, Bauer describes the major forms of memory, each of which follows distinct developmental trajectories. She summarizes recent studies that document the emergence of both declarative and nondeclarative memory systems during the first 2 years of life, which is far earlier than has previously been thought. At the same time, Bauer argues that some aspects of declarative memory have a more protracted course not reaching maturity until middle childhood, paralleling what is known about the development of the underlying neurobiology of memory processing systems as demonstrated in studies of ERPs in children.

The earliest autobiographical memories are sparse and usually for events that took place during the preschool years. One reason that has been offered for this phenomenon is that encoding and retrieving these memories depend on language. By the time most children are 3 years old, they have mastered the fundamentals of language from sounds to words to grammar, which allow them to form narrative memories of their lives. In the next chapter, Tager-Flusberg and Seery (Chapter 32) describe the development of language covering the major milestones, as well as how language intersects with aspects of motor, conceptual, and social cognitive development. Much is known about the importance of left-hemisphere frontal/temporal cortical systems in adult language processing. These left lateralized systems emerge during the first year of life in typically developing children according to studies using ERP and NIRS with infants. Failure to lateralize language functions to the left hemisphere during this early sensitive period appears to be one hallmark finding among children with developmental language disorders.

The next four chapters are concerned with different aspects of social–emotional development. This has become a very active area of research in developmental science, in part because of the complexity and richness of human social lives and in part because of the important consequences when development in the social domain is impaired in children with genetic syndromes or specific forms of psychopathology. Righi and Nelson (see Rubenstein and Rakic, 2013) focus on the development of face-processing skills. They describe the initial rapid developments that take place during the first year of life in the foundational cognitive processes for identifying faces and facial expressions that depend on dedicated neural architecture in the fusiform region of the temporal cortex. At the same time, these early acquired abilities are followed by a more protracted period of development during which time more subtle behavioral advances are accompanied by volumetric changes in the fusiform 'face area' as well as temporal and morphological changes in the signature ERP signal elicited by faces, the N170. The development of the neural systems underlying more complex aspects of social perception, including the evaluation of a person's intentions, communicative signals, and psychological disposition from eye gaze and body motion cues, is addressed by Voos and his colleagues (see Rubenstein and Rakic, 2013) in the next chapter, drawing heavily on fMRI studies of school-aged children. This is followed by Gweon and Saxe's chapter (see Rubenstein and Rakic, 2013), which focuses on the development of children's theory of mind: the ability to reason about people's actions based on mental states such as thoughts or beliefs. The classic studies in this area concluded that the theory of mind emerges at about the age of 4 based on behavioral and ERP studies that used a task evaluating children's understanding of false beliefs. Gweon and Saxe review more recent behavioral studies suggesting that this understanding may already be in place at least in an implicit form by around 18 months. At the same time, fMRI studies suggest that the brain region that is crucially involved in the theory of mind processing, the right temporal–parietal junction, continues to show functional developmental changes through middle childhood, providing another example of the early emergence of a cognitive achievement followed by a more protracted developmental period into middle childhood. Decety and Michalska (see Rubenstein and Rakic, 2013) focus more on the affective components of social behavior: the development of the capacity to respond to another person's distress, or empathy. Their chapter summarizes the normal course of development in the psychological processes and neurobiological mechanisms that drive empathic behavior, and then how these might go awry in children with conduct disorder or related forms of psychopathy.

The next three chapters focus on the aspects of executive processing that cut across different developmental domains. Posner and his colleagues (see Rubenstein and Rakic, 2013) review the development of the complex set of networks that is involved in executive attentional processes and self-regulation from early infancy through middle childhood. An exciting recent advance in this area is a research that finds associations between common genetic variants with individual differences in specific attentional components; in turn, these differences influence environmental experiences of children as mediated, for example, by parenting behaviors. Lahat and Fox explore the development of two aspects of cognitive control that play important roles in decision-making and social behavior: inhibitory control and self-monitoring. The neural substrates for these advanced cognitive systems, as indexed by fMRI and ERP measures, depend on areas in the prefrontal cortex that do not reach the end point of development until late adolescence. Hughes (see Rubenstein and Rakic, 2013) summarizes the research on classic executive function measures in both typical and atypical children. She argues that because the executive functions and their neural substrates, which encompass multiple brain regions, develop incrementally over the entire period of childhood and adolescence, they are more susceptible to environmental influences. Her chapter describes examples of such influences including studies of training, parent–child interaction, and clinical populations.

The final two chapters in this volume are concerned with primary influences on behavioral and brain development. Gunnar and Davis (see Rubenstein and Rakic, 2013) focus on the effects of stress, drawing heavily on what is known from animal models to investigate whether the findings from that body of literature can be extended to current work on prenatal and postnatal stress responses in human development. Then, Beltz and her colleagues (see Rubenstein and Rakic, 2013) take up the issue of sex differences in development, which has important implications for understanding many neurodevelopmental disorders that differentially affect males and females for reasons that are still not well understood.

The cognitive neuroscience of human development is still in its formative years. The exponential growth of this field, as evidenced by the numbers of papers, journals, and books published over the past decade, has largely been driven by methodological advances that allow people to view more directly the minds and brains of babies and children and observe how they change over time. As these methods develop further, it is expected that greater progress will be made by asking broader questions about the significance of the developmental trajectories and timing within and across cognitive domains, the constraints that operate on individual variation and developmental plasticity, and the precise ways in which biological and nonbiological factors influence the developmental course of brain and cognitive development.

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