1 Introduction to Developmental Cognitive Neuroscience

While out walking the dog this morning, one of us (Heather) encountered two very different parenting styles that exemplify the complex interaction of genes, brains, and environment that underlies the development of human cognition and behavior. Coming towards me was a young father on a walk in the neighborhood with his toddler. As the pair came nearer, I heard the child making the sounds of someone having difficulty learning to speak. He did not form any discernible words, although he clearly was trying to talk about – and with – my dog. I also could hear that the father was engrossed in a cell phone conversation, towering above the little boy, and all but ignoring us. Two blocks later, I found myself approaching another father with his toddler. This boy was commenting on everything around him in the way that children in the early throes of language learning do. The second father kneeled down to be at eye level with the boy, answering every question and commenting on each of the boy's observations. This father was engaged in conversation with his son, and the boy spoke in the manner typical of a three-year-old.

Unless these encounters were anomalous snapshots of these two young lives, these children living in the same place at the same moment in time are having very different experiences. How will their levels of achievement, happiness, and overall quality of life differ? What might be the relationship between those outcomes and their early experiences? Questions like these drive the research presented in this book.

In this introductory chapter, we provide an overview of Developmental Cognitive Neuroscience and how it came to be a field in its own right. We review its background concepts, such as historical approaches to understanding how the brain develops, how children learn, and the nature–nurture debate. This history is the basis for this exciting and novel approach to understanding human development. We outline key theoretical positions and contextualize them with data acquired across a range of methods, including many made possible by technological advances introduced in just the last several years. Our emphasis throughout this book will be on the three component parts of Developmental Cognitive Neuroscience, development, cognition, and neuroscience, whose theoretical perspectives, methodological approaches, and findings have contributed to the emergence of this entirely new field.

1.1 What Is Developmental Cognitive Neuroscience?

Developmental Cognitive Neuroscience (DCN) is an interdisciplinary field focused on the neural basis of cognitive and socioemotional development in typically and atypically developing populations, and how it underpins behavior. Most research in this field focuses on child development, from infancy through adolescence; however, there are also DCN researchers studying prenatal development, and others who study development across the entire lifespan. Findings from DCN inform our understanding of neurodevelopmental disorders and point to possible therapeutic approaches. So, too, do these findings help us explain individual differences: that is, why we have different traits and abilities from one another. DCN also elucidates brain organization and brain function more generally. After all, we understand a system far better if we know how it was assembled!

A thread throughout this book is the fact that your brain is not simply a product of your genes; rather, your genes participate in an ongoing, inherently noisy developmental process that is shaped by your experiences and your own behaviors in the world. The DNA contained in your cells is the starting point for how a brain region or neural network emerges via the developmental process to take on a particular function. DCN research aims to characterize how well-specified these networks are at birth, as well as how they are shaped by the particular inputs they receive throughout an organism's existence.

A key factor in the explosive growth of DCN in recent years has been a set of advances in how we study brain structure and function. Neuroscientific discoveries have been crucial to our understanding of psychological processes, and nowhere is this more evident than in the field of **cognitive development**, a discipline focused on the perceptual and conceptual changes that emerge in concert with a brain that is growing and changing. Over the past several decades, researchers have found new and better ways to look "under the hood" in humans to understand the processes supporting developmental change. These technologies have expanded the focus of cognitive development research to include structural and functional mechanisms that help characterize human growth and development. Collectively, these efforts have had considerable impact on the way research on human development is conducted, culminating most recently in the founding of the field of DCN.

Our understanding of human cognition has benefited enormously from major technological, methodological, and theoretical developments in how we study the human brain, and DCN has benefited from advances in applying them to pediatric populations. Prior to having access to these tools, researchers often focused on dysfunction to deduce normal function (i.e., trying to understand how the brain works by seeing what deficits occur when the brain is damaged or impaired through case studies). Thus, several of the book's chapters include stories of early research on dysfunction, serving to couch our understanding in historical terms. While these early descriptions were focused on adult patients, DCN researchers owe a great debt of gratitude to the pioneering neurosurgeons and neurologists who pursued the neural underpinnings of cognitive and behavioral disorders. Likewise, while our focus is on human development, animal work serves as a foundation for characterizing the lowest structural levels of the brain and understanding how they function. Correspondingly, we draw on a wide array of findings from animal research.

1.2 Levels of Analysis and Levels of Structure

A human brain is a **complex system**, composed of many components interacting with one another to varying degrees. Complex systems can be described at different levels, both in terms of their structure and how they can be analyzed. Structural levels of the brain range from individual neurons to neuronal networks to individual brain regions to large-scale brain networks (Figure 1.1). The phenomena of interest in DCN are not easily ascribed to one or another structural level. For example, some seemingly "high-level" cognitive phenomena originate in the properties of individual neurons; for example, a form of memory called behavioral priming is rooted in a decrease in neuronal firing in response to a repeated stimulus. Other phenomena, such as the ability to comprehend language, emerge as a product of activation of an entire neural network across a number of different brain areas. In short, as the philosopher Mario Bunge wrote, behavior arises from interactions within and across levels of the complex system that is the brain (Bunge, 1980).

The dominant approaches in DCN may appear biased towards larger-scale structural levels – that is, towards brain regions or large-scale networks over single neurons. This is a product of affordances of the tools available for use with human participants. Currently available techniques mean that we most often operate at the level of brain regions and large-scale networks, but interpretation of information obtained at these intermediate structural levels is increasingly

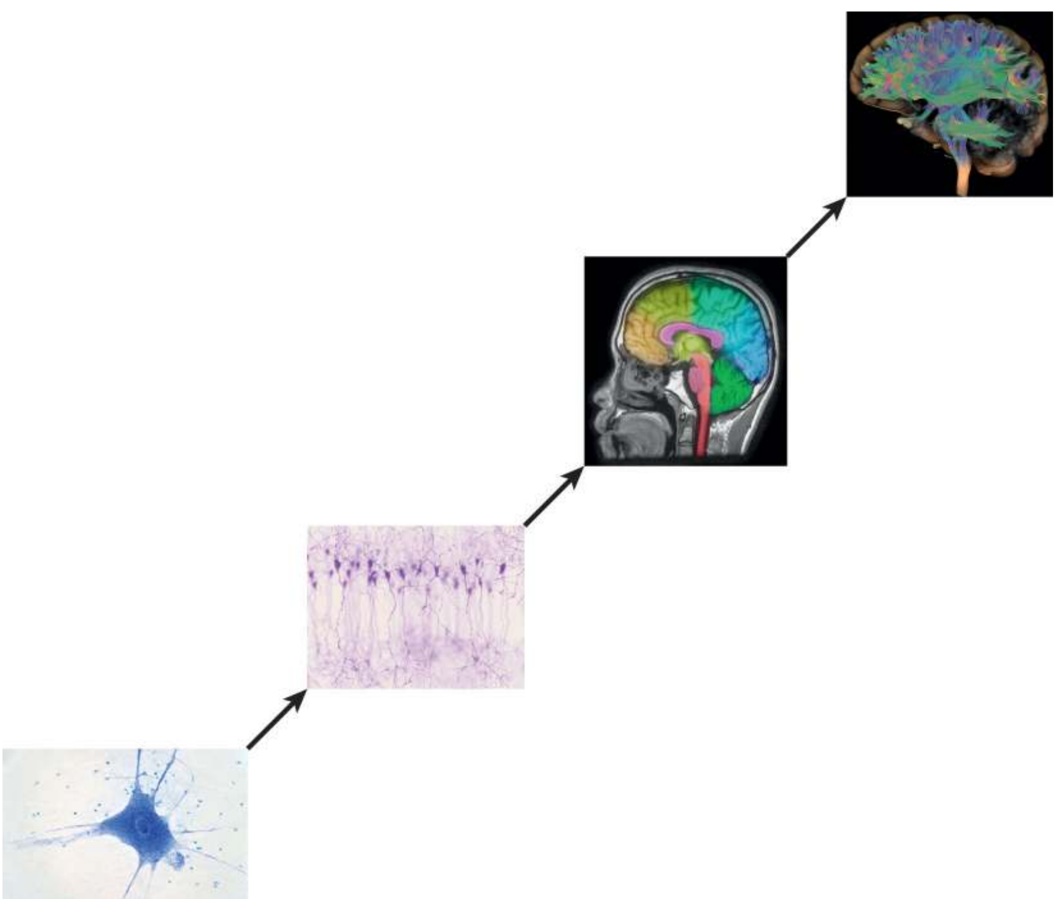
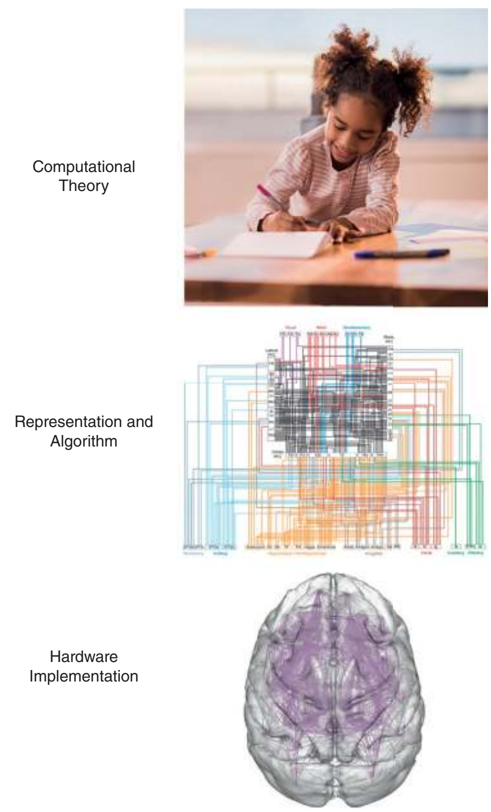


Figure 1.1 Levels of structural analysis include individual neurons, neuronal networks, individual brain regions, and large-scale brain networks.

Figure 1.2 Marr’s levels of analysis. (Adapted from Favela, 2020)



informed by findings at the cellular and systems levels. In short, DCN research is – or should be – guided by the principle that no single structural level is superior to or takes precedence over another.

Structural levels should not be confused with **levels of analysis**. In his pioneering work on computational vision, David Marr (1982) provided an influential framework outlining the process of vision as the construction of representations, starting with the visual image itself. A central theme in Marr’s approach – one that has had far-reaching influence in both neuroscience and cognitive science, as well as artificial intelligence – is levels of analysis. In **Marr’s framework**, these levels consisted of computation, algorithm, and implementation (see Figure 1.2).

Overlap exists between structural levels of the brain and Marr’s levels of analysis as they pertain to the characterization of cognition. For example, Marr’s computational level is associated with the highest structural level (i.e., the behavior that arises from brain processes), while his implementation level better aligns with the brain’s underlying biology. According to Marr, “an algorithm is likely to be understood more readily by understanding the nature of the problem [computation] being solved than by examining the mechanism (and the hardware) in which it is embodied” (Marr, 1982, p. 27). Unfortunately, because his framework reflected the dominant analogy in mid-to-late twentieth-century cognitive research – between the brain and a standard computer – the implementation level was often overlooked, or even dismissed as being “just” the underlying neurobiology. Cognitive scientists were encouraged by this to focus exclusively on the algorithmic and/or computational levels of the system without considering their relationship to the underlying implementation. Despite this limitation, Marr's levels-of-analysis framework is still useful today in establishing mechanistic accounts of how cognitive phenomena can be instantiated by a brain, particularly for researchers developing probabilistic models of cognitive or perceptual systems.

Fortunately for DCN, the quest to understand human development has embraced the importance of the hardware: the brain. In fact, DCN flips Marr's argument on its head, just as often examining the implementation to understand the algorithm as the other way around. Our perspective is that both frameworks – levels of structure and levels of analysis – are important to consider, as the processes and products of human development are **dynamic**, **multi-scaled**, and **emergent**. DCN as a field relies on researchers having access to data from different levels of structure (i.e., from single brain cells to whole brains) to address questions aimed at different levels of analysis (i.e., from implementation to computation). For example, on the structural side, whole-brain imaging can provide a network-level view that is critically informed by findings from other structural levels, whether those findings are from single-cell recordings from animals or from "lesioned" neural networks that are instantiated computationally.

1.3 What Do We Gain from Understanding How the Brain Develops?

The question of how a tiny clump of cells becomes a unique, thinking, feeling, and behaving person has long engaged scientists and non-scientists alike. For centuries, this question has been posed in terms of nature versus nurture, whereby researchers try to determine what portion of development is dictated by innate forces – such as our genes – versus the portion shaped by experience. In recent decades, new evidence has radically updated our understanding of genes and how they relate to the processes of individual development. The complexity of genetic impacts on fetal development, neuroplasticity, the functional organization of the brain, and cognition makes it clear that the nature–nurture debates are not just outdated; they are no longer helpful. To paraphrase an old saying about the difficulty of tracing a multi-level phenomenon back to its origin, "it's turtles all the way down," it's nature *and* nurture … all the way down.

DCN embraces the perspective that, from conception onward, there are diverse and complex developmental processes impacting how you process information and solve problems, how well you concentrate, and whether you are eager to learn new things. These ways in which you engage with the world strongly influence your sense of self and agency: whether you feel that you have some control over your life, or whether you perceive your life to be a series of events caused by the capricious will of others. Ultimately, all of this informs the way you position yourself in relation to others. The research we review aims to delineate the developmental processes underlying these interrelated events, and this outcome in worldview.

Thus, a clear benefit of understanding how the brain develops is that it can provide a window onto what drives variability in human behavior, helping us better delineate different periods

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of time during which the brain remains plastic, when its structure and function can be molded in response to new inputs. DCN research provides important insights into the possible mechanisms that impact human cognition and behavior in long-lasting ways.

Finally, we'll state the obvious: it helps to have parents, other caregivers, and educators with the necessary time and resources to help navigate the developmental journey. Although they may buy any number of how-to books on the subject, even the most engaged parents don't have all the answers on how to raise a child. Research findings from DCN can provide important insights regarding how children's minds will develop, how they will change as they grow, and how the brain itself is changing in the process. Such findings can be integrated into a coherent perspective on child development that will help caregivers and educators navigate the tsunami of information about which aspects of biology, the environment, and their own behavior impact the developmental process.

1.4 Brief History of the Field

DCN is young, but substantial foundational research from multiple domains led to its recognition as a field in its own right. Critical to its emergence has been research conducted by Mark Johnson, Adele Diamond, Charles Nelson III, Uta Firth, Michael Posner, Helen Neville, Joan Stiles, and Annette Karmiloff-Smith, among many others. These pioneers were inspired by findings from a wide range of domains, while often operating in the margins of each.

As with the field of **cognitive neuroscience**, which emerged in the 1970s (and was given its name during a taxicab ride that Michael Gazzaniga shared with George Miller), DCN grew organically from converging research findings at different levels of analysis. The emergence of cognitive neuroscience, together with the combination of behavioral findings from developmental psychology and animal work in developmental neuroscience and developmental biology, came to a head, with a new perspective.

A number of distinguished scientists featured in our "Scientist Spotlight" sections describe the early days, when there was simply no field to identify with or to work within. Their mix of interests, for example, motivated them to draw on a range of research domains, including developmental psychology, evolution, cognition, neuroscience, and biology, to think about and study brain development. These researchers simply didn't fit neatly into any one of those domains. As a result, the origins of DCN as a field can be traced back to a handful of impromptu conference sessions and small workshops that took place in the late 1980s. The field has grown up around those early researchers who envisioned it as a possibility.

For the next 20 years, DCN-minded researchers presented their work at the annual conferences of a range of societies, including the International Society for Developmental Psychobiology, International Society of Infant Studies, Society for Research in Child Development, and various neuroscience conferences. At the tail end of the aughts, some of these researchers started organizing conferences devoted to DCN, drawing several hundred participants. In 2013, the Flux Society for Developmental Cognitive Neuroscience was established by Beatriz Luna, with help from several colleagues (Bradley Schlaggar, Bruce McCandliss, and one of us: Silvia). The annual

Flux Congress has expanded to 500 attendees in 2023, and is expected to continue to grow. (If you've ever wondered why your professors miss lectures to go to conferences, this is one of the reasons: lots can happen at a conference, including the development of an entirely new field!)

In 1997, Mark Johnson, featured in this chapter's Scientist Spotlight (Box 1.1), published the first DCN textbook with Blackwell Publishing (now Wiley-Blackwell). Together with co-author Michelle de Haan, Johnson has updated this textbook several times. The most recent edition – that book's fourth – was published in 2015. Another notable contribution was a book published in 2006 by Charles Nelson, Michelle de Haan, and Kathleen Thomas, titled *Neuroscience of Cognitive Development: The Role of Experience and the Developing Brain*. The first journal dedicated entirely to the field, *Developmental Cognitive Neuroscience*, was started in 2011 and is now thriving.

Box 1.1 Scientist Spotlight on Mark H. Johnson (University of Cambridge)

Mark H. Johnson [Box Figure 1.1] is Professor of Experimental Psychology and Head of the Department of Psychology at the University of Cambridge, UK. His prior posts include a Professorship at Carnegie Mellon University in the US, and Founding Director of the Centre for Brain & Cognitive Development at Birkbeck, University of London, UK. One of the pioneers in developmental cognitive neuroscience, Johnson wrote the first textbook in this field. His laboratory studies typical, at-risk, and atypical functional brain development in human infants and toddlers, using brain imaging, cognitive, behavioral, genetic, and computational modeling techniques.

I knew from childhood that I was interested in the intersection of psychology and biology, and also in key issues about development and evolution. Two questions motivated me. First, how can human thought arise from the gray jelly in our head that is our brain? And second, how is it that we develop from just a bunch of cells into a complex human being that talks, thinks, and acts? Over time it gradually dawned on me that that those two questions could be mutually informative if you studied how brain development relates to cognitive and behavioral changes during infancy and childhood. However, when I started out in science I found myself mid-way between two fields. Brain development was studied in animals and was primarily focused on the cellular level. With regard to living humans, structural MRI and PET scanning were only just starting to become available, but there was no functional MRI at that point. On the other hand, there was the field of cognitive and behavioral development, where the prevailing view was that questions about human cognition should not be "reduced down" to the level of brain processes. So when I started out trying to link behavioral and cognitive changes to changes in brain development

Box 1.1 (cont.)

nobody knew how to categorize what I did – for example, most people in cognitive development thought I was some kind of biologist, but they weren't really sure what sort!

Things began to change when I went to the very first McDonnell Pew summer school in the late 1980s, as that was around the time that I first met other people who actually had the same research interests as me: Chuck Nelson, Helen Neville, Adele Diamond, and a few others. It occurred to us collectively that there was a coherent new field of study here. Since then it's been amazing to watch the rapid emergence of a whole new branch of science: developmental cognitive neuroscience. In the ensuing years there have been several influential handbooks and a textbook; then conferences began – such as the Flux meeting – and we've gone from a handful of people to hundreds, or even thousands, of people specifically interested in the topic. I've been privileged to see the field grow up from the obscure interest of a handful of people to a proper discipline now taught at undergraduate and Master's level.

When the field was quite young we began to get several new methods – such as functional MRI – and a lot of great data started coming out. However, we had very little way to put all the bits of data together into a coherent framework, and to a certain extent this is still true today. From the neuroscience side, people would suggest that a particular structural or functional change caused changes in cognition or behavior, while from the cognitive development side investigators sought neural evidence to support their favorite cognitive theories. In contrast, what I wanted was a theory of human functional brain development. And I still do. "Interactive Specialization" is a first step towards this. I don't see it as a complete theory but think about it more as a set of assumptions that, when taken together, leads you to think about developmental cognitive neuroscience data in a certain way. According to the Interactive Specialization view it's not that parts of cortex get turned on at certain points in development, as was previously thought, but rather that they gradually become more specialized, or better tuned, for specific functions, stimuli, or task demands. This increased specialization or tuning up process results from the interaction between different areas of cortex and subcortical areas, cortico-cortico interactions, and from the child behaving in the world and selecting certain parts of the external world to interact with in certain ways. The Interactive Specialization view is rooted in a constructivist view of development, where we don't just see the brain in terms of a mosaic of isolated regions with independent developmental schedules, but rather each region developing within the context of all its neighboring connections including their hierarchical connectivity structure.

1.5 Why Study Developmental Cognitive Neuroscience? (*or* How Do I Tell Grandma What I'm Studying?)

We tell our own families that we study how the brain changes in the early years of a child's development, and how those changes influence the course of that child's life. As one example, consider learning and the ways it can change the brain. When we first learn something, whether it's a new idea or a new behavior (like learning to ride a two-wheel bicycle), it can seem impossibly complex, perhaps alien. Repeated thinking about a concept or practicing a behavior changes the neural context for that process; eventually, our learning is reflected in the very wiring of our brains. Ask yourself: What experiences do you remember from your own childhood that seemed to profoundly affect your understanding of the world, of other people, or of yourself?

We are interested in understanding all the factors and situations that affect brain development – and managing those factors is in the interest of individuals and society. Much of this book was written during the Covid-19 pandemic, amidst tremendous political and social upheaval both locally and globally. The events of that period – a worldwide pandemic, widespread protests over inequality and systemic racism, and unprecedented environmental change – have deeply affected society. The social isolation and remote schooling associated with the pandemic-driven shutdown led people to wonder about the long-term impact on toddlers, children, and teens. Will the effects on academic achievement, social development, and mental health be long-lasting? Does Covid affect the developing fetus? As scientists and students of science we need to recognize this and help others to recognize it.

More broadly, what we know, and will continue to learn, about brain development needs to be reflected in **evidence-based health and education policies**. This research also holds lessons for the treatment of adolescents in the criminal justice system, immigration policies that separate children from their parents, and housing and community development. Together, these situations create the cultural and societal environments in which the developmental trajectories of children are established.

1.6 What to Expect

An important point to keep in mind as we review individual studies throughout the following chapters is that each study – in any field of research – has its idiosyncrasies; we gain a clearer picture by considering a body of evidence, not a single experiment. The field of DCN moves rapidly, and our understanding of brain development continues to evolve. As a result, some of the findings presented here will undoubtedly need to be amended in the coming years. As we write, new papers come out every day, and we have had to restrain ourselves from trying to incorporate every exciting new finding. Suffice it to say that a literature search on any of the topics we feature will reveal a wealth of new citations. This continual growth is a strength of the **scientific method**: it is a cumulative and self-correcting process. As new findings continuously emerge, they will influence future theories – strengthening, modifying, or replacing them – in the context of the many results reviewed here. Ultimately, we are sensitive to the fact that DCN is young. The training wheels may be off, but only just. Great adventures lie ahead!

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