

Fundamentals of Developmental Cognitive Neuroscience

An exciting introduction to the scientific interface between biological studies of the brain and behavioral studies of human development. The authors trace the field from its roots in developmental psychology and neuroscience, and highlight some of the most persuasive research findings before anticipating future directions the field may take. They begin with a brief orientation of the brain, along with genetics and epigenetics, and then summarize brain development and plasticity. Later chapters detail the neurodevelopmental basis of a wide variety of human competencies, including perception, language comprehension, socioemotional development, memory systems, literacy and numeracy, and self-regulation. Suitable for advanced undergraduate and graduate courses in developmental cognition or neuroscience, this textbook covers the prenatal period through to infancy, childhood, and adolescence. It is pedagogically rich, featuring interviews with leading researchers, learning objectives, review questions, further-reading recommendations, and numerous color figures. Instructor teaching is supported by lecture slides and a test bank.

Heather Bortfeld is Professor of Psychological Sciences and Cognitive and Information Sciences at the University of California, Merced. She has been a pioneer in the development of functional near-infrared spectroscopy (fNIRS) as a tool for measuring changes in brain activity in infants and toddlers as they engage with the world around them. She is currently the Emmett, Bernice, and Carlston Cunningham Endowed Chair in Cognitive Development at UC Merced, and an elected Fellow of the Association for Psychological Sciences.

Silvia A. Bunge is Professor of Psychology at the University of California, Berkeley, and directs the Building Blocks of Cognition Laboratory, which draws from the fields of cognitive neuroscience, developmental psychology, and education research. She studies the development of higher-level cognitive abilities, how they are shaped by experience, and how they support academic success. Professor Bunge is an elected Fellow of the Association for Psychological Sciences and the Humboldt Society of Experimental Psychologists.

Cambridge Fundamentals of Neuroscience in Psychology

Developed in response to a growing need to make neuroscience accessible to students and other non-specialist readers, the *Cambridge Fundamentals of Neuroscience in Psychology* series provides brief introductions to key areas of neuroscience research across major domains of psychology. Written by experts in cognitive, social, affective, developmental, clinical, and applied neuroscience, these books will serve as ideal primers for students and other readers seeking an entry point to the challenging world of neuroscience.

Books in the Series

The Neuroscience of Expertise by Merim Bilalić
The Neuroscience of Intelligence by Richard J. Haier
Cognitive Neuroscience of Memory by Scott D. Slotnick
The Neuroscience of Adolescence by Adriana Galván
The Neuroscience of Suicidal Behavior by Kees van Heeringen
The Neuroscience of Creativity by Anna Abraham
Cognitive and Social Neuroscience of Aging by Angela Gutchess
The Neuroscience of Sleep and Dreams by Patrick McNamara
The Neuroscience of Addiction by Francesca Mapua Filbey
The Neuroscience of Sleep and Dreams, 2e, by Patrick McNamara
The Neuroscience of Intelligence, 2e, by Richard J. Haier
The Cognitive Neuroscience of Bilingualism by John W. Schwieter and Julia Festman
Fundamentals of Developmental Cognitive Neuroscience by Heather Bortfeld
and Silvia A. Bunge

Fundamentals of Developmental Cognitive Neuroscience

Heather Bortfeld

University of California, Merced

Silvia A. Bunge

University of California, Berkeley





Shaftesbury Road, Cambridge CB2 8EA, United Kingdom
One Liberty Plaza, 20th Floor, New York, NY 10006, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India
103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment, a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/highereducation/isbn/9781108498760

DOI: 10.1017/9781108595827

© Heather Bortfeld and Silvia A. Bunge 2024

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press & Assessment.

First published 2024

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall

A catalogue record for this publication is available from the British Library

Library of Congress Cataloging-in-Publication Data

Names: Bortfeld, Heather, 1969– author. | Bunge, Silvia A., author.

Title: Fundamentals of developmental cognitive neuroscience / Heather Bortfeld, University of California, Merced, Silvia A. Bunge, University of California, Berkeley.

Description: Cambridge, United Kingdom ; New York, NY : Cambridge University Press, 2024. | Series: Cambridge fundamentals of neuroscience in psychology | Includes bibliographical references.

Identifiers: LCCN 2023034039 | ISBN 9781108498760 (hardback) |

ISBN 9781108595827 (ebook)

Subjects: LCSH: Cognitive neuroscience – Textbooks. | Developmental neurobiology – Textbooks. | Developmental psychology – Textbooks.

Classification: LCC QP360.5 .B67 2024 | DDC 612.8/233–dc23/eng/20231004

LC record available at <https://lccn.loc.gov/2023034039>

ISBN 978-1-108-49876-0 Hardback

ISBN 978-1-108-71256-9 Paperback

Additional resources for this publication at www.cambridge.org/FDCN

Cambridge University Press & Assessment has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

**For Pamela Johnson, Mark Lieb, Gretchen Lieb, Robin Lieb, and
Gabriel Lieb. You all helped me become who I am.**

– H.B.

**My deepest gratitude goes to Mario Bunge (1919–2020) and Marta
Bunge (1938–2022) for their inspiration and unwavering support.**

– S.A.B.

Contents

Preface	page xvii
Acknowledgments	xxii
1 Introduction to Developmental Cognitive Neuroscience	1
1.1 What Is Developmental Cognitive Neuroscience?	1
1.2 Levels of Analysis and Levels of Structure	2
1.3 What Do We Gain from Understanding How the Brain Develops?	5
1.4 Brief History of the Field	6
1.5 Why Study Developmental Cognitive Neuroscience? (or How Do I Tell Grandma What I’m Studying?)	8
1.6 What to Expect	9
References	9
2 Methods and Populations	11
2.1 Studying Behavior across Development	12
2.1.1 Study Designs	13
2.1.2 Converging Technologies and Methods	15
2.2 Behavioral Studies	15
2.2.1 Studying Infant Cognition	16
2.2.2 Studying Child and Adolescent Cognition	17
2.3 Probing Human Brain Structure	19
2.3.1 Structural MRI	21
2.3.2 Diffusion-Weighted Imaging (DWI)	22
2.4 Probing Human Brain Function: Measures of Electrical Activity	25
2.4.1 Electroencephalography (EEG)	25
2.4.2 Event-Related Potentials (ERPs) Derived from EEG	29
2.4.3 Magnetoencephalography (MEG)	31
2.5 Probing Human Brain Function: Blood-Based Measures	33
2.5.1 Cerebral Blood Volume and Flow	33
2.5.2 Overview of fMRI	35
2.5.3 fNIRS	37
2.6 fMRI Data Analysis	42
2.6.1 The Basics	42
2.6.2 Interpretation of Pediatric fMRI Data	43
2.6.3 Functional Connectivity	44

viii Contents

Summary	48
Review Questions	49
Further Reading	49
References	49
3 Genes and Epigenetics	54
3.1 Interactive Specialization	55
3.2 Tracking Sources of Individual Variation	56
3.2.1 Heritability	57
3.2.2 Developmental Variance	58
3.3 What Genes Are	59
3.3.1 Genes as Units of Inheritance	59
3.3.2 Genes as Protein Encoders	62
3.3.3 The Big Picture	65
3.4 Genetic Variation	66
3.4.1 Mitosis	66
3.4.2 Meiosis	67
3.5 Mutations	68
3.5.1 Point Mutations	68
3.5.2 Single Nucleotide Polymorphisms	70
3.5.3 Chromosomal Mutations	71
3.5.4 Environmentally Induced Mutations	71
3.6 Epigenetics	72
3.6.1 Evidence of Epigenetic Effects in Humans	73
3.6.2 DNA Methylation	74
3.6.3 Histone Modification	75
3.6.4 The Epigenome as a Product of Gene–Environment Interactions	75
3.7 “Genetic” Is Not Synonymous with “Heritable”	77
3.8 Neurodevelopmental Disorders (NDDs)	77
Summary	80
Review Questions	80
Further Reading	80
References	81
4 Brain Development	84
4.1 Basics of Brain Anatomy	85
4.2 Prenatal Brain Development: An Overview	89
4.3 From First Cell to Newborn	92
4.3.1 Gastrulation and Neural Induction	92
4.3.2 Emergence of Early Structure	93
4.3.3 Process of Neuronal Proliferation and Migration	96
4.3.4 Neuronal Differentiation and Death	96

	Contents	ix
4.4 Postnatal Brain Development		98
4.4.1 Early Cortical Expansion		98
4.4.2 Large-Scale Changes in Gray and White Matter		100
4.4.3 Gray Matter Thinning		102
4.4.4 White Matter Microstructural Changes		104
4.4.5 Reorganization of Functional Brain Architecture		106
Summary		109
Review Questions		109
Further Reading		110
References		110
5 Brain Plasticity		114
5.1 Learning and Development: Broad Categories of Plasticity		115
5.1.1 Experience-Independent Brain Development		115
5.1.2 Experience-Expectant Brain Development		116
5.1.3 Experience-Dependent Brain Development		116
5.1.4 A Continuum from Development to Learning		117
5.2 Foundations of Research on Brain Plasticity		117
5.2.1 Origins of the Idea		117
5.2.2 Dendritic Spines		118
5.2.3 Long-Term Potentiation and Hebbian Plasticity		119
5.3 Characterizing Brain Plasticity		119
5.3.1 Environmental Enrichment		119
5.3.2 A Critical Period for Plasticity		121
5.3.3 Types of Structural Brain Changes		124
5.4 Cortical Reorganization under Sensory Deprivation		126
5.4.1 Somatosensory Deprivation: The Case of the Phantom Limb		126
5.4.2 Visual Deprivation: Congenital Blindness		127
5.4.3 Auditory Deprivation: Congenital Deafness and Cochlear Implantation		129
5.5 Experience-Dependent Plasticity		134
5.5.1 Musical Training		134
5.5.2 Dynamics of Plasticity across Skill-Learning		136
5.6 Timing of Plasticity		138
5.6.1 Recovery from Brain Injury		139
5.6.2 Earlier Is Not Always Better for Recovery from Brain Injury		140
5.6.3 Multiple Windows of Plasticity across the Brain		140
5.7 Childhood Adversity		144
5.7.1 Brain Plasticity as a Double-Edged Sword		144
5.7.2 Risks Associated with Adverse Childhood Experiences		145
5.7.3 Dimensions of Childhood Adversity		147
Summary		147

Review Questions	148
Further Reading	148
References	149
6 Attention and Perception	155
6.1 Attention	156
6.1.1 Underpinnings of Arousal	156
6.1.2 Measuring Attention	157
6.2 Continuity from Pre- to Postnatal Perceptual Development	157
6.2.1 Little Statisticians	158
6.2.2 Timing Matters in How Environmental Structure Impacts the Developing Brain	159
6.3 Touch, Taste, Smell	160
6.4 Audition	161
6.4.1 Overview of the Primary Auditory Pathway	161
6.4.2 Converting Sound to Neural Energy	161
6.4.3 Early Hearing Abilities from the Pre- to Postnatal Period	165
6.4.4 Measurements Specific to Hearing Development	165
6.5 Vision	166
6.5.1 The Neural Basis for Vision	167
6.5.2 Visual Development: From Reflexive Looking to Visual Control	169
6.5.3 Segregation of Vision into Dorsal and Ventral Streams	170
6.5.4 Development of Advanced Visual Processing Capabilities	173
6.6 Higher-Level Vision	174
6.6.1 Face Recognition	174
6.6.2 Dedicated Brain Areas Are Further Tuned to Faces through Experience	175
6.6.3 Is It Expertise in Faces, or Configurations?	176
6.6.4 Effects of Face Deprivation	181
6.7 Multisensory Perception	184
6.7.1 The Emergence of Experience-Based Integrative Circuitry	184
6.7.2 Is It Multisensory Integration, or Convergence?	185
6.7.3 Novel Approach to Multisensory Research in Infants	186
Summary	189
Review Questions	189
Further Reading	190
References	190
7 Social Cognition	199
7.1 Early Social Cognition	199
7.1.1 The Developmental Onset of Imitation	200
7.1.2 Neuronal Mirroring System	201

	Contents	xi
7.1.3	Contingent Learning Is Social Learning	203
7.1.4	Mental Representations and Distinguishing between Social and Non-Social Objects	203
7.2	Faces and Eyes Are Social	204
7.2.1	The Importance of Eye Gaze	205
7.2.2	A Visual Pathway That Supports Social Perception	206
7.3	Representation of Self and Other	208
7.3.1	Goal-Directed Actions and Intentionality	208
7.3.2	False Beliefs and Theory of Mind	210
7.3.3	Understanding Others' Minds	211
7.4	Brain Basis for Mentalizing	212
7.4.1	Developmental Time Course of Mentalizing	213
7.4.2	Interpreting the Data	215
7.4.3	Changes in Neural Connectivity Support Mentalizing	215
7.5	Mentalizing Supports Learning	217
7.5.1	Social Referencing and Emotion Regulation	218
7.5.2	Brain Injury at Different Ages Highlights Developmental Basis for Social Abilities	219
7.6	Atypical Social Cognition	221
7.6.1	ASD Phenotype	221
7.6.2	Advances in ASD Diagnosis	222
7.6.3	Structural and Functional Indicators of the ASD Brain	224
7.6.4	Early Intervention	225
	Summary	228
	Review Questions	228
	Further Reading	229
	References	229
8	Language Learning and Social Interaction	239
8.1	How the Brain Supports Language and How Language Shapes the Brain	240
8.2	What Is Language?	240
8.2.1	Building Blocks of Language Comprehension and Production	241
8.2.2	Specificity and Universality	243
8.2.3	Localizing Language in the Adult Brain	243
8.2.4	Complex Processing: Beyond Localization of Language Function	246
8.3	Is the Infant Brain Primed for Language? Evidence from Phonetics and Phonology	248
8.3.1	Auditory Input Interacts with Developing Brain Structure	248
8.3.2	Increasing Sensitivity to Language Sound Specific Structure	249
8.3.3	Neural Correlates of Language Specific Perceptual Tuning	251
8.3.4	Hemispheric Asymmetries	253

xii Contents

8.4	Language Engages the Infant Brain beyond the Language Network	257
8.4.1	Language Learning Is Contingent Learning	260
8.4.2	The Importance of Both Quantity and Quality in Speech Input	261
8.4.3	Bilingualism and Multilingualism	265
8.5	Is Language a “Special” Ability in the Human Toolkit?	265
8.6	Coda: Why Don’t Non-Human Primates Have Language?	266
	Summary	269
	Review Questions	269
	Further Reading	270
	References	270
9	Memory Systems	279
9.1	Memory as the Foundation for Learning	280
9.2	Memory Systems	281
9.2.1	Memory Classification	281
9.2.2	The Neural Basis of Distinct Memory Systems	283
9.3	Episodic Memory	286
9.3.1	Features of Episodic Memory	286
9.3.2	Is Episodic Memory a Uniquely Human Capacity?	287
9.3.3	The Medial Temporal Lobes	288
9.3.4	Episodic Memory Networks	293
9.4	Development of Memory Systems	294
9.4.1	Implicit Memory Development	294
9.4.2	Emergence of Episodic Memory	296
9.4.3	Improvements in Episodic Memory over Childhood	299
9.5	Development of the Medial Temporal Lobes	300
9.5.1	Structural Development	300
9.5.2	Mechanistic Accounts of Infantile “Amnesia”	301
9.5.3	Hippocampal Function in Early Childhood	301
9.5.4	Further Development of Hippocampal Function	304
9.5.5	Development of Episodic Memory Networks	305
	Summary	307
	Review Questions	307
	Further Reading	308
	References	308
10	Working Memory and Executive Functions	314
10.1	Early Theoretical Framework	317
10.1.1	Phonological WM	318
10.1.2	Visuospatial WM	319
10.1.3	The “Central Executive” (EFs)	319
10.2	Measuring WM Capacity	320

	Contents	xiii
10.3 WM Development		322
10.3.1 How WM Supports Learning		322
10.3.2 Age-Related Increases in WM Span		323
10.3.3 Age-Related Increases in Spatial WM Precision		324
10.4 Neural Basis of WM		325
10.4.1 Early Discoveries		325
10.4.2 Neuroimaging Studies in Adults		327
10.4.3 Neuromodulatory Influences on WM		328
10.4.4 Mechanisms of WM		329
10.5 Neural Changes That Support the Development of WM		330
10.5.1 Changes in WM Maintenance over Middle Childhood and Adolescence		330
10.5.2 Neural Basis of Early WM Development		334
10.5.3 Neurodevelopmental Improvements in WM with EF Demands		334
10.6 Developmental Changes in the Recruitment of Top-Down Control		338
Summary		340
Review Questions		341
Further Reading		341
References		342
11 Language and Literacy		349
11.1 Reading Paradox		350
11.1.1 Writing as a Cultural Invention That Has Enabled Reading		350
11.1.2 Co-invention of Writing and Reading		350
11.1.3 Shallow (Transparent) and Deep (Opaque) Orthographies Impact Reading Acquisition		352
11.2 Neuronal Specialization and the Creation of Reading-Specific Areas on the Brain		352
11.2.1 Visual Object Categories and the Visual Word Form Area (VWFA)		353
11.2.2 Language-Specific Tuning of the VWFA		353
11.2.3 Learning to Read “Creates” the VWFA		355
11.2.4 Alternative Perspectives on the VWFA		356
11.3 Brain Interconnectivity and Literacy		357
11.3.1 Interfacing the VWFA with the Rest of the Language System		358
11.3.2 Anatomy of Visual Reading Circuitry: Dorsal and Ventral Pathways		361
11.3.3 Improved Reading Proficiency Involves a Dorsal-to-Ventral Shift		363
11.4 Language Influences Reading; Reading Influences Language		363
11.4.1 The Importance of Both Quantity and Quality of Oral Language Exposure		364
11.4.2 Emergent Skills That Are Critical to the Acquisition of Reading		365
11.5 Subtypes and Sources of Poor Reading		367
11.5.1 Correlates with Socioeconomic Status		368
11.5.2 Developmental Dyslexia		369

xiv Contents

Summary	372
Review Questions	373
Further Reading	373
References	373
12 Numeracy	379
12.1 Number Systems	380
12.1.1 Number Sense	380
12.1.2 Cultural Construction of Symbolic Mathematics	381
12.1.3 Numerical Systems	382
12.2 Non-Symbolic Number	383
12.2.1 Mechanisms Underlying Non-Symbolic Number Representation	383
12.2.2 Evidence for Object Tracking	384
12.2.3 Evidence for Approximate Number	384
12.2.4 Origins of the Approximate Number System	385
12.3 Symbolic Number	386
12.3.1 A Brief Digression into Language Acquisition and Attentional Focus	386
12.3.2 Individuation and Counting	387
12.3.3 Counting Helps Focus Children on Number Rather than Other Attributes	388
12.4 Relationship between Non-Symbolic and Symbolic Number	389
12.4.1 The Brain Basis for Number	390
12.4.2 The Neuronal Code for Number	391
12.4.3 Number Representations and Brain Networks	394
12.4.4 How Numerical Symbols Acquire Their Meaning	396
12.4.5 Stepping Stones to Mathematical Competency	399
12.5 Arithmetic	400
12.5.1 The Arithmetic Network in Typically Developing Children	401
12.5.2 Difficulties with Number	404
12.5.3 Developmental Dyscalculia	405
12.5.4 Individual Differences in the Arithmetic Network	407
12.6 Math Education	407
12.6.1 Math Intervention	408
12.6.2 Effects of Math Intervention on the Developing Brain	408
Summary	409
Review Questions	410
Further Reading	410
References	410
13 Motivated Behavior and Self-Control	417
13.1 Drivers of Behavior	417
13.1.1 Approach, Avoidance, and Self-Control	418
13.1.2 Insights from Patients	420

	Contents	xv
13.1.3	PFC Injuries Incurred during Development	423
13.2	Self-Control	424
13.2.1	The Protracted Neurodevelopment of Self-Control	424
13.2.2	Measuring Self-Control	425
13.2.3	Delay of Gratification	426
13.2.4	Predicting Life Outcomes	427
13.3	Neural Basis of Self-Control and Its Development	428
13.3.1	Self-Control in a Neutral Context: Inhibiting Motor Responses	428
13.3.2	Neurodevelopment of Response Inhibition	429
13.4	Neural Basis of Self-Control in a Motivationally Salient Context: Resisting Temptation	432
13.4.1	Approaches to Studying Hot Self-Control	432
13.4.2	Neural Basis of Delay of Gratification	433
13.4.3	Reward-Based Decision-Making	435
13.4.4	Reward Sensitivity in Adolescence	436
13.5	Adolescent Decision-Making	437
13.5.1	The Transition to Adulthood	437
13.5.2	Social Influences on Adolescent Decision-Making	437
13.5.3	Positive and Negative Growth Trajectories	440
	Summary	443
	Review Questions	444
	Further Reading	444
	References	445
14	Key Themes and Future Directions	449
14.1	Overview	449
14.1.1	The Developmental Process Is Probabilistic	449
14.1.2	There Are No Genes “for” Psychological and Behavioral Traits	450
14.1.3	Variation in Neural Circuits Contributes to Individual Differences	451
14.2	Future Directions in Theoretical Approaches	451
14.2.1	Interactive Specialization as a Guiding Framework	451
14.2.2	Making Theory Explicit	452
14.2.3	Good Theory Forces Hard Questions	453
14.2.4	Levels of Structure Inform Levels of Analysis	454
14.3	Future Directions in Methodological Approaches	455
14.3.1	Scope of Investigations	455
14.3.2	The Importance of Formal Modeling	457
14.4	Societal Relevance	459
14.5	Public Health	460
14.5.1	Public Health Mandates	460
14.5.2	Pressing Public Health Issues	461

xvi	Contents	
	14.6 Communicating the Science	463
	14.6.1 DCN in the News	463
	14.6.2 Advising Policymakers and Practitioners	464
	14.6.3 Responsible Conduct and Dissemination of Research	465
	14.7 Wrapping Up	465
	References	466
	Index	470

Preface

How do brains change from infancy through adolescence? How are they shaped by the interplay between different genotypes and environmental input? How do these brain changes manifest as changes in behavior? Our goal with this book is to introduce students to the field of Developmental Cognitive Neuroscience (DCN), the scientific interface between biological studies of the brain and behavioral studies of human development. Researchers in DCN study brain development and the corresponding cognitive, social, and emotional changes that take place beginning prenatally and continuing through childhood and adolescence. We study how a child's environment and experiences shape their developing brain.

Neuroscientific discoveries have been crucial to our understanding of psychological processes and their underlying brain basis. 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, behavioral psychologists have found new and better ways to look “under the hood” to understand the processes supporting developmental change, and neuroscientists have expanded their focus to include structural and functional mechanisms that help characterize human growth and development. Together, 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.

The DCN approach to research integrates measures of neural development and concomitant changes in cognitive, social, and affective processes in both typical and atypical populations. Critical to the melding of disciplines has been the application of a variety of techniques and technologies, including electrophysiology and functional neuroimaging, to the behavioral paradigms typically used in human development research. Together with insights from animal models, patient populations, and psychopharmacological and genetic assays, these approaches are providing a wider variety of data to help characterize developmental change. This book summarizes where the field currently stands, providing a much-needed integration of information from various and diverse methodological approaches, populations, and theoretical positions.

Motivation

What do we have to offer in writing a textbook on DCN? First, we teach courses about this field at both the undergraduate and graduate levels. Second, our complementary research interests span many of the topics covered in this book, as well as the full pediatric age range from infancy through adolescence. One of us (Bortfeld) focuses on language learning from infancy through early childhood and examines experience-dependent neural plasticity in the auditory system.

xviii Preface

The other (Bunge) has studied executive functions, various forms of memory, reasoning, environmental influences on the developing brain, and applications to education. Third, both of us use techniques that range from the behavioral to neurophysiological: Bortfeld uses looking time techniques in conjunction with functional near-infrared spectroscopy; Bunge uses cognitive measures, eye-tracking, and structural and functional magnetic resonance imaging. Thus, our collective experience as researchers covers a broad age range and many of the developmental changes therein. We also can offer our experience in teaching these concepts to students at universities with very different student populations: three different University of California campuses (Berkeley, Davis, and Merced), Stony Brook University, Texas A&M, Brown, University of Connecticut, and Stanford. Our lives and our understanding of how to teach have been meaningfully changed by our interactions with the students at these schools. The irony is not lost on us that it is perhaps we who have learned the most from interactions with those who came to us for instruction.

Why did we write this book? In teaching, we have been hard pressed to find an up-to-date textbook that approaches the complex progression of brain changes that co-occur with the emergence of human abilities in an easily tractable way. Teaching a course on DCN requires a wide range of field-specific framing, including review of anatomical detail from developmental neuroscience, behavioral methods from developmental psychology, and technological innovations from cognitive neuroscience. After many years of culling and revising reading lists to cover those topics and address those needs, we realized that we ourselves would benefit from a coherent presentation of them all together and in one place – and we thought perhaps others would as well.

Our Approach

Our goal has been to characterize how the developing brain supports and interacts with the emergence of a diverse range of abilities. We believe that you can't begin to understand these complex capabilities without understanding the biology underlying them. Students often think of psychology in categories – cognitive, social, clinical – in large part because courses are designed to fit into specific psychological subdomains. When developmental psychology is the focus of a course, we have found that students assume biological details will not be part of the discussion. This bias is further reinforced by the superficial dichotomy of development as being influenced by nature *or* nurture, a tired framework that has stymied deeper understanding of human development. Our aim is to focus on and celebrate the interdependence of psychology and biology – of mind and brain.

For the most part, we cover research in humans from the vantage point of developmental psychology, cognitive neuroscience, and the intersection of these two fields. However, we do occasionally feature cellular and systems neuroscience research on laboratory animals that has provided important insights on a given topic. We also provide a high-level overview of genetics and epigenetics, but do not cover other areas of molecular neurobiology. As molecular, cellular, and systems neuroscience are large fields of research unto themselves, we cannot do them justice here. But in touching on these areas, we hope to spark students' curiosity about them.

To be clear, we also emphasize that understanding only the biology won't get us very far. That is, we believe that studying the biology of the brain is not an end in itself: DCN needs always to be informed and motivated by questions about actual behavior. Further, we don't

think of behavior as being divided into the biological and the cognitive/social/emotional. The complex manifestation of the latter comes about through the mechanisms and developmental trajectories of the former. These aspects of behavior are intertwined in complex, interdependent ways. Our aim here is to explore how this comes to be.

We operate on the premise that a firm grasp of cognitive and brain changes in typically developing children is essential for understanding what goes awry in neurodevelopmental disorders that affect social, motoric, linguistic, and/or cognitive development. Most importantly, we think this understanding is essential for predicting the onset of a disorder in an individual child and providing insights relevant for early detection and treatment. Because there is so much ground to cover with regards to typical development, we cannot provide comprehensive coverage of these disorders, of which there are many. However, we do highlight several disorders in association with specific topics. When we teach this course, we encourage students who are interested in clinical psychology, neuropsychology, or medicine to pick a specific disorder to investigate for a class presentation or final paper.

The field of DCN is increasingly of interest not only in the clinical realm, but also in fields as far-flung as public health, education, the law, and more. Every day, policymakers, practitioners, and the public seek out information about the developing brain, and news headlines abound. We believe that a solid foundation in DCN is important for parsing these headlines, and for making informed decisions at both the personal and societal levels. We endeavor to provide a balanced discussion of a few hot-button issues and list many others in the concluding chapter. In our classes, we invite students who are interested in the broader societal implications of DCN to pick one of the issues highlighted in Chapter 14 for a presentation or final paper.

Organization

The book includes fourteen chapters, representing the arc of information necessary to understanding how someone progresses from a tiny cluster of cells to a sentient being. Thus, we devote the first four chapters to laying the groundwork for emerging human abilities. Chapter 2 provides an overview of the core methods used to examine development, including functional neuroimaging (fMRI/MEG), electrophysiology (EEG/ERP), functional near-infrared spectroscopy (fNIRS), and transcranial magnetic stimulation, as well as other basic neuroscience approaches based on cellular and animal models. Chapter 3 serves as a primer on genetics and epigenetics, while Chapter 4 summarizes the biological processes that underpin the emergence of a human from conception to birth and beyond, while also providing cursory orientation to the major divisions of the brain, and an introduction to the different cell types. Chapter 5 focuses on brain plasticity, providing a more nuanced examination of how nature and nurture interact continually to influence development. Chapters 6–8 provide foundational information about the emergence of basic processes – perception, attention, social awareness, and early language acquisition – that are necessary for a person to function in the world. Chapters 9–10 then focus on various forms of memory, and how we leverage memory in the service of goal-directed behavior, while Chapters 11–12 focus on the culturally constructed, educationally relevant skills of literacy and numeracy. Chapter 13 examines key drivers of behavior and the capacity for self-control.

xx Preface

Finally, we conclude with a chapter looking towards the future, anticipating new directions, including methods, in which the field is moving. This textbook is not intended to be a comprehensive treatment of all of DCN. For example, it does not provide extensive coverage of motor development and learning, social cognition in late childhood and adolescence, or computational research, all of which are exciting areas of research. Nonetheless, this book introduces students to DCN and a wide array of topics of active investigation in the field.

Pedagogical Features

Our approach is to tell a story about how research on a particular subtopic arrived at where it currently is. This necessarily includes having to make difficult decisions about what to include and what to leave out to ensure the story is a coherent one. We think we have achieved this, and have added several features to help students extract the bones of each story. These include:

- Learning objectives
- Chapter summaries
- Review questions
- Further readings, including influential empirical papers and reviews

We have also included in each chapter a “Scientist Spotlight”: there are excerpts from an interview with a researcher whose focus of study relates to one of the topics under discussion in the text. The purpose of these spotlights is to personalize the science by providing the origin story of leading figures in the field. Each chapter also contains a box that provides a deeper dive into the details of an issue that is relevant to the main text.

Full citations for all references mentioned in the text are provided at the end of each chapter. Key terms are bolded and defined in each chapter, with more detailed definitions provided in an accompanying glossary; additional terms are italicized and defined in the text. Finally, we provide online resources to support instructors and students, including lecture slides and a test bank of additional questions.

Teaching with This Book

This book is intended for advanced undergraduates and early-stage graduate students who want to get into the meat of research on the brain basis for developmental change in behavior. It is ideally suited for a semester-long course (usually 14–16 weeks), but specific chapters can be selected in support of shorter course terms.

The book presupposes a high school-level biology background and an introductory psychology course. Before embarking on this journey through DCN, students should have a rough sense of the different parts of the brain and their functions. Instructors whose students have no background in neuroscience are encouraged to give an introductory lecture on gross neuroanatomy. However, students need not know neuroanatomy in depth from the outset of the course, as we introduce each brain region or network as it becomes relevant to a particular topic.

We have presented our interpretation of the story that has emerged from the body of DCN literature. We encourage instructors to add to that story with their own data points and interpretations, their own experiences, and when possible, current headlines that address the issues raised by recent findings. We include references to the original peer-reviewed scientific articles from which the data were sourced so that instructors can pursue more detailed information about any given study.

The book is designed to stand alone; a single chapter is sufficiently rich to serve as the assigned reading for one week’s worth of lectures – or even two weeks, depending on the desired depth of coverage. For those wishing to take a deep dive on select topics rather than covering the entire textbook, each chapter lists empirical papers that can serve as the basis for discussion sections or student presentations. In whatever way an instructor approaches this course, we hope the excitement we experience as researchers in the field comes through in our writing.

Ultimately, our goal is for the book to help students think deeply and critically about human development, so that they can evaluate studies and formulate questions that are addressable through the methods and techniques of DCN. The mind–brain relationship has been the focus of inquiry for as long as humans have been thinking about thinking, and we happen to be passionate about understanding how the developing brain gives rise to the developing mind. Our hope is that we have adequately conveyed this passion, that it helps ignite similar excitement in students, and that it proves sufficiently intriguing to motivate many to enter this growing and continually developing field and join us in our search for the brain basis of human behavior.



Acknowledgments

We thank the many people who contributed to this book and associated materials. Jesse Gomez and Vaidehi Natu, Stephen Lomber, Tomás Ryan, and Ted Satterthwaite contributed text boxes providing a deeper dive into specific topics. Daniel Levitin provided extensive feedback on the full draft of the book, and unnamed experts solicited by Cambridge University Press each reviewed several chapters. Trainees in our labs and classes provided detailed input on specific chapters, along with helpful information and references; these include Haider Ali Bhatti, Monica Ellwood-Lowe, Aedan Enriquez, Lindsay Fleming, Elena Galeano Keiner, Leana King, Pradyumna Lanka, Elena Leib, Willa Voorhies, and the students in Heather's undergraduate course. Professor Janet Werker at the University of British Columbia provided extensive feedback on many chapters, incorporating comments from students in a graduate course: Erica Dharmawan, Denitza Dramkin, Raechel Drew, Jessica Flores de la Parra, Faith Jabs, Vivian Qi, Eloise West, and Francis Yuen. Additionally, Marta Bunge provided high-level input on several chapters. Graduate students Vinitha Rangarajan and Enitan Marcelle, along with research assistants Marisol Duran, Aedan Enriquez, and Dorsa Javaheri, assisted with figures and figure permissions. Mark Johnson, Michael Meaney, Damien Fair, Terry Jernigan, Takao Hensch, Janet Werker, Sally Rogers, Ghislaine Dehaine-Lambertz, Simona Ghetti, Beatriz Luna, Fumiko Hoeft, Daniel Ansari, and Eveline Crone participated in interviews for the scientist spotlight in each chapter, and Madison Lacanlale and Jaquelyn Borcea edited the videos of the interviews for online distribution.