

Subcortical Structures and Cognition

Leonard F. Koziol • Deborah Ely Budding

Subcortical Structures and Cognition

Implications for Neuropsychological
Assessment



Springer

Leonard F. Koziol
Park Ridge, IL, USA
LFKoziol@aol.com

Deborah Ely Budding
CA, USA
deborah.budding@gmail.com

ISBN 978-0-387-84866-2 e-ISBN 978-0-387-84868-6
DOI 10.1007/978-0-387-84868-6

Library of Congress Control Number: 2008940617

© Springer Science+Business Media, LLC 2009

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden. The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

springer.com

Dedication and Acknowledgments

I may not have gone where I intended to go, but I think I have ended up where I intended to be.

Douglas Adams

This book was made possible as a result of the extraordinary influence and support of many people. This manuscript is dedicated to these individuals. First, I thank Mark Moulthrop, Ph.D. I was extremely fortunate to have him as my clinical neuropsychology supervisor nearly 30 years ago. Mark taught me how to think about cognition and its measurement, and even more importantly, he taught me how to think about patients. I am forever grateful for his influences upon my thinking.

I also thank my patients. By this, I mean each and every clinical case I personally saw in consultation, as well as those cases presented to me by students for supervision. This is an extremely voluminous number of cases, an astonishing tally, but a little bit of every one of these patients is represented in this book, because this book is about understanding their problems. Without the experience I gained by evaluating the diagnostic issues presented by these patients, there would be little reason for this book. Thank you for allowing me to learn from you. I also thank my graduate and post-graduate students. Your questions compelled me to think, which allowed me to learn.

Several individuals provided practical assistance in completing the manuscript. Drs. Phillip Kent, Keith Kobes, Doug Callan, Adam Piccolino, Kevin Duffy, Dana Chidekel, Deborah Miora, Raymond List, Karin Suesser, and Diane Engelman all provided comments and literary assistance in reading through various versions of different chapters. Catherine Gottlieb, MLIS, provided invaluable editorial research and editorial research consulting. Becky Fong proved to be an exceptional illustrator. All of your contributions were critical to the completion of this manuscript. Thank you.

Special thanks goes to Deborah Budding. She did more than anyone could ever ask for in making this book a reality. It would be an understatement to say her ideas, her literature searches, her sharing and updating of citations, her constant availability, and her literary and editorial expertise were invaluable.

She was the inspirational and energizing catalyst that made this book possible. I was extremely fortunate to have the privilege of working with her.

I also thank Mark and Janel Blakely for the photographs of Kaitlyn. Those pictures in Chapter 4, Fig. 4 illustrates “reinforcement learning” in a way that could never be described in words. I greatly appreciate your contribution, which allows others to learn as I did. I also thank the Wambach family for their precious support. Finally, I thank my brother Don, who has never really known that he has always been an inspiration to me.

Thank you.

Leonard F. Koziol

First, I would like to give profound thanks to Len Koziol for sharing his knowledge, wisdom, and time with me. His generosity and trust have been awe-inspiring. He is a rare person of honor and integrity. I am also fortunate to have had a number of remarkable people as mentors, colleagues and sources of support over the years and during the writing of this book. My parents, grandparents, and sisters provided early inspiration in addition to ongoing opportunities for learning from experience. Barbara Counter, Ph.D. encouraged me to follow my instincts. Arnold Purisch, Ph.D. opened my eyes to the possibilities held within the world of neuropsychology and continues to serve as a valued mentor. Lorraine Gorlick, LCSW, Ph.D. has shared her tremendous patience, fortitude, and humor with me while demonstrating how it is possible to be still and still moving. Dana Chidekel, Ph.D. inspires and challenges me to keep moving, even when I don’t feel like it, and shared her editorial and writing prowess on a number of chapters. Deborah Miora, Ph.D., Jayme Jones, Ph.D., and Denise McDermott, M.D. have lent ongoing moral support—with accompanying appreciation for both work and play—in addition to direct assistance with this project. Cathy Gottlieb, MLIS lent both research and moral support and is listed in the dictionary under the definition of “friend.” Finally, my husband, Bill, who continues to inspire me, cook for me and make me laugh, and my stepdaughter, Alex and sons, Nicholas and Matthew—who have waited forever for me to be finished—have made all of this worthwhile. Thank you all. I am deeply grateful.

Deborah Ely Budding

Preface

A little revolution now and then is a good thing.

Thomas Jefferson

If everyone is thinking alike then somebody isn't thinking.

George S. Patton

Most clinical neuropsychologists are taught a cortico-centric model of cognition. From this viewpoint, the neocortex is considered to play the most important role in generating human thinking and behavior. This book departs from that view by additionally considering subcortical contributions to cognition. Our focus concerns subcortical structures that have traditionally been considered only as co-processors of movement. These structures contribute to cognition and emotion. We propose that the cortex, basal ganglia, and cerebellum operate in parallel to generate adaptive behaviors and we examine the role of neuropsychological testing and evaluation within this framework. We believe that this adds needed dimensionality for assessing complex behavioral systems.

This book was written for practicing neuropsychologists and for those in training. This book would be useful for both graduate and post-graduate students as well. Although we primarily had neuropsychologists in mind in writing this manuscript, we believe that the ideas described in this book are also useful for people in other related professions. Anyone working in a medically or health related profession who wants to learn more about how cognition and behavior are organized within the brain should be familiar with the content of this manuscript.

In writing this book, we made the assumption that the reader is already familiar, or in the process of becoming familiar, with all fundamental concepts of cortically based brain–behavior relationships. Anyone who is not familiar with this information should consult a traditional neuropsychology textbook.

Because the intended audience of this book is clinically based, its focus is very practical. We strive for the reader to acquire a practical understanding of cortical–subcortical functional relationships. This book was not geared toward people primarily involved in research. The book was not meant to include an exhaustive review of the literature. Instead, the book offers an integrated view

of cortical–subcortical functioning that we believe has practical clinical applicability. However, whether or not you fit the profile of our intended reader, we encourage you to read on and we hope that you find the information in this book useful if not inspiring.

Park Ridge, Illinois
Manhattan Beach, California

Leonard F. Koziol
Deborah Ely Budding

Contents

1 Introduction: Movement, Cognition, and the Vertically Organized Brain	1
A Case of Dementia?	3
Why Do We Have a Cortico-centric Bias?	5
Vertically Organized Brain Systems	6
A Theoretical and Historic Context	9
How to Do Things in a Changing Environment	11
When to Do Things—Intention Programs	13
Theories of Types of Behavioral Processing and the Frontostriatal System	14
Analogous Memory Systems	16
The Phylogenetic Perspective	17
Excitation Versus Inhibition	19
Adjustment of Motor “How”—The Changing Characteristics of Excitation and Inhibition.	20
Summary	22
References	23
2 The Basal Ganglia: Beyond the Motor System—From Movement to Thought	27
Anatomical Structures and Subdivisions of the Basal Ganglia	28
Basal Ganglia Circuitry	33
Specific Projections into the Striatum.	34
Direct and Indirect Pathways	36
The Subthalamic Pathway	37
The Striosomal Pathway.	38
Basal Ganglia–Subcortical Loops.	38
What Does the Cortico-striatal System Do?.	41
Three Selection Pathways—An Interim Summary.	42
Application of Motor Behavior to Cognition.	42
Examples of the Frontostriatal System in Operation	44
Sensitivity to Context: The Basal Ganglia in Learning	45

Higher-Order Cognition and Working Memory 46

How Does Working Memory Work? 50

Context and Higher-Order Control in Combination 54

The Basal Ganglia and Automatic Processing 55

Alternating Episodes of Automatic Versus Higher-Order
Control 57

An Integrated Cortical–Subcortical Model of Behavioral
Selection 58

The Striatum Learns and Mobilizes Procedures. 58

The Prefrontal Cortex Decides upon Behavior. 59

Pathology/Developmental Disorders 61

Summary 62

References 62

**3 Frontal–Subcortical Real Estate: Location, Location,
Location 69**

Divisions of the Frontal Cortex and the Anterior Circuits 70

The Dorsolateral Prefrontal Circuit (DLPFC). 71

Orbitofrontal Circuit (OFC). 75

The Medial Frontal Circuit (MFC)/Anterior Cingulate
Circuit 77

The Motor Circuits 79

Motor, Cognitive, Motivational, and Affective Analogues 80

Frontal System Syndromes. 82

Summary 90

References 90

**4 Learning and the Basal Ganglia: Benefiting from Action
and Reinforcement 95**

The Basal Ganglia and Learning 96

The Inferotemporal and Parietal Loops 100

Categorization and Classification. 101

Positive and Negative Reinforcement Learning 108

Summary 118

References 119

**5 The Cerebellum: Quality Control, Creativity, Intuition,
and Unconscious Working Memory 125**

Surface Anatomy of the Cerebellum. 126

Cortex and Cerebellum—Superficial Comparison
of Infrastructure 128

Infrastructure of the Cerebellum 129

The Cerebellum and Non-Motor Functions. 131

The Cerebellum in Procedural Learning. 133

The Cerebro-Cerebellar Circuit	134
The Cerebellum and the Principle of Lateral Crossed Control	137
The Olivo-Cerebellar System	137
Theories of Cerebellar Function	138
A Hybrid Model of Cerebellar Function	140
Three Brain Systems in Parallel	142
Dysmetria—What Does It Signify?	143
Working Memory, Expertise, Creativity, and Giftedness	145
Clinical Presentations	148
The Cerebellar Cognitive Affective Syndrome	149
The Posterior Fossa Syndrome	151
Agenesis of the Cerebellum	153
Very Pre-Term Infants	153
DSM-IV Behaviorally Defined Conditions	154
The Cerebellum as a Modulator	155
Dysmetria—Undershooting and Overshooting—An Important Paradigm	157
Summary	157
References	158
6 Automaticity and Higher-Order Control in Communication:	
A Brief Introduction to Language and Social Cognition.	167
Gesture, Communication, and Speech	169
The Declarative-Procedural Model of Language	171
Social Cognition—Automatic and Higher-Order Control Systems	174
Reflexive and Reflective Systems	177
Social Intuition, Social Skill, and Non-Verbal Communication	178
Implications of Dual-System Models for Social Cognition and Language	180
Summary	182
References	183
7 The Vertically Organized Brain in Clinical Psychiatric Disorders	187
Obsessive-Compulsive Disorder	191
Attention Deficit Hyperactivity Disorder	194
Schizophrenia	199
The Basal Ganglia in Schizophrenia	200
The Cerebellum in Schizophrenia	202
Mapping Anatomy and Symptomology	203

Other Clinical Disorders 205
 Autism Spectrum Disorder 205
 Mood Disorders 207
 Alzheimer’s Disease 207
 Summary 208
 References 209

8 Familiarity and Novelty—Evaluating the Frontostriatal System 219

The Frontostriatal System 221
 The Frontostriatal System in Operation 223
 Interpretation Paradigms 224
 Dynamically Changing Locus of Control 225
 Neuropsychological Testing and the Frontostriatal System 226
 Test Methodologies for Identifying the Integrity of the Frontostriatal System 228
 Verbal Fluency Tasks 232
 The Stroop Color Word Test 233
 Traditional “Frontal Lobe” Problem-Solving Tests 235
 Task Comparisons 243
 Continuous Performance and Go–No-Go Tasks 245
 Commonly Used Neuropsychological and Cognitive Tests: What Do They Measure? 249
 Summary 251
 References 252

9 Thought in Action: Procedural Learning, Processing Speed, and Automaticity 257

Processing Speed 259
 The Measurement of Processing Speed 260
 Processing Speed—A By-Product of Cognitive/Executive Control 262
 Practice Effect 263
 Types of Practice Effect 265
 Procedural Learning in Neuropsychological Evaluation 268
 The Wechsler Mazes 269
 Trailmaking Tests 270
 Perceptual–Motor Skill Learning 271
 Subcircuit Differentiation 272
 Motor Adaptation 273
 Summary 274
 References 274

10 The Basal Ganglia and Neuropsychological Testing 277

 Interpretation Paradigm 280

 Level of Performance 281

 Test Score Comparisons/Pattern Analysis 281

 Pathognomonic Signs 282

 Body-Side Comparisons 282

 Clinical Case Examples 283

 Case 1 283

 Case 2 293

 Case 3 298

 Case 4 304

 Case 5 310

 Summary 316

 References 317

11 The Cerebellum in Neuropsychological Testing 321

 Clinical Case Examples 322

 Case 1 322

 Case 2 330

 Case 3 337

 Case 4 347

 Summary 360

 References 360

12 The Integrated Brain: Implications for Neuropsychological Evaluation 363

 It's Not "All Cortex"- It's the Flexibility of Interaction 365

 Clinical Applications 368

 References 377

Index 381

Chapter 1

Introduction: Movement, Cognition, and the Vertically Organized Brain

Nature does nothing uselessly

Aristotle

How does the mind work? This question has puzzled philosophers, physicians, and artists for centuries. This question has led to remarkable discoveries, and in turn, further questions. Currently, technological advances appear to be outpacing our abilities to keep up with applying them. Yet the same questions continue to arise. Why do we keep losing our keys? Why do we have the same argument over and over again? Why do we hit a hole-in-one on the golf course one day and are lucky to bogey the same hole a week later? These kinds of questions are no less significant than questions regarding why societies fail to learn from history or individuals allow envy or greed to turn them away from important opportunities. Science has long attempted to answer these and other questions. Sometimes what we know can get in the way of discoveries yet to be made, exemplified by earlier assumptions about the “unimportant” prefrontal lobes or the “silent” right hemisphere. Nevertheless, discoveries continue and the neurosciences in turn continue to adapt to these discoveries along with their associated intended and unintended consequences.

The problem of “mind” and “body” has endured endless discussions which we will not further belabor. Much difficulty has arisen in trying to conceptualize cognition in the context of emotion and behavior. Arbitrary separation of these things fails to address the inherent constant interplay between how we think, feel, and act. Leaders of countries, businesses, and families must regularly make decisions about what to do, and in relation to this must try to consider when and how to override emotion or instinct in favor of higher-order thought. Psychotherapy patients endeavor to learn from previous experiences and alter their ingrained “automatic” responses to situations that *feel* similar to earlier interactions but are not the same in reality. While emotional function is essential to all of this, cognition plays a central role.

Cognition, from a neuroscience perspective, has generally been considered almost exclusively in relation to neocortical function. Most of us have been trained to consider our ability to think as part of a cortical system that separates

us from our primate ancestors. This idea becomes perpetuated in advanced studies, as most clinicians in the cognitive neurosciences are taught a cortico-centric model of neuropsychology. In this model, the cortex is considered not only the seat of cognition, but also the center of higher-order control over behavior. We are taught that the evolutionary expansion of neo-cortex is generally what makes us unique thinkers, and it, therefore, makes intuitive sense to look to cortical functioning as the source of cognitive activity.

To support the unique role of cortex, researchers often point to evidence from brain pathology. For example, lesions of the cortex result in a variety of deficits in higher-order cognition (Lezak, 2004). This is usually manifested by instrumental disturbances in thinking that affect the language, visuospatial, executive-related, and memory domains. Similarly, there is a voluminous neuroimaging literature that demonstrates the recruitment of various cortical networks during cognitive activity. When subcortical structures are considered, these brain areas have generally been relegated to the role of engineering movement in tandem with key cortical structures. Thus, within this model, the basal ganglia and the cerebellum are considered primarily as co-processors of movement. Accordingly, disease affecting these regions results in kinetic disturbance.

Basal ganglia pathology is associated with either hyperkinetic or hypokinetic movement disorders typified respectively by Huntington's and Parkinson's diseases (Blumenfeld, 2002). These pathologies are characterized by the loss of voluntary control over movement. Therefore, a general symptom of these conditions concerns a loss of intentional control over movement. Cerebellar pathology is characterized by disorders of coordination, chief of which are the ataxic syndromes. The primary symptom of cerebellar pathology is dysmetria, in which the quality of movement is affected, as movements become erratic in amplitude and direction so that patients appear to lack coordination (Houk & Mugnaini, 2003). This compartmentalization of cognition and motor functions represents a succinct "package," offering clinicians a certain level of simplicity that nonetheless promotes a false sense of security in the understanding of brain-behavior relationships.

But what if that "package" is too simplistic? What if it is so neat that it essentially derails a more comprehensive and accurate understanding of integrated brain function? Within the constraints of this model, the similarly important role of the neocortex in non-cognitive functions is often overlooked or minimized. For example, many regions of the posterior cortices participate in somatosensory functions, and a substantial region of the frontal convexity participates in motor functioning. Therefore, certain regions of the neocortex are heavily involved in activities that in no way would be considered "purely" cognitive.

If the cortex plays a role in non-cognitive functioning, we must consider this influence in the opposite direction. Accordingly, considerable evidence has accumulated implicating the basal ganglia and the cerebellum in cognitive and emotional functioning (Bedard, Agid, Chouinard, Fahn, & Korczyn, 2003; Schmahmann, 1997). In Huntington's disease, which is characterized

by deterioration of the caudate nucleus, personality changes along with executive function decline are often the initial presenting signs of the disorder (Cummings, 1993). Patients with Parkinson's disease, which is characterized by deterioration of the substantia nigra, very commonly demonstrate cognitive deficits such as impairment in working memory and set shifting, cognitive slowing, and affective blunting as initial symptoms (Lichter, 1991). Patients with posterior and inferior involvement of the cerebellum present with cognitive pathology and emotional dysregulation instead of motor disturbance (Schmahmann, 2004). Therefore, the cortex participates in functions that are non-cognitive and subcortical regions participate in functions that are non-motor.

Understanding this interplay between structures has far-reaching implications. It challenges the primacy of a horizontal, cortico-centric model of brain organization. This traditional model focuses upon "left versus right" and "anterior versus posterior" organization as the main principles structuring cognition. The purpose of this book is to explore subcortical contributions to cognition and emotion. The book will present anatomical and functional evidence. We will then discuss the implications of these findings for neuropsychological assessment. A vertical dimension that includes cortical-subcortical relationships is essential for creating a more accurate view of brain function. This expanded perspective will assist clinical neuropsychologists in navigating through the complicated neural landscape, adding important dimensionality to our ability to "picture" human adaptive function through our assessments.

A Case of Dementia?

To illustrate how critical it is to understand vertical brain organization, it would be useful to consider the following example. This middle-aged patient arrived for differential diagnostic evaluation with few or any subjective complaints, believing he was to receive a disability evaluation (which was not the case). He could not explain why he was not working. He understood that he was brought by his family, but was unable to more specifically explain why they brought him. His family's primary complaints revolved around his moodiness and irritability, which were coupled with disinterest and relative apathy. His interpersonal presentation during the examination lacked initiative and spontaneity. Accompanying affect was flat. Nevertheless, he was fully cooperative. Consider the following test scores (Table 1.1).

Any clinician reviewing these test scores would justifiably conclude that this patient suffers from dementia. However, is this a case of cortical dementia? There are certainly elements of this profile of scores that suggest a cortical dementia, as the characteristics of anterograde amnesia and language difficulty seem so pronounced. One look at the limited amount of learning and storage

Table 1.1 48 year old male/12 years education

WASI FSIQ 84	CVLT	
VIQ 72	I.	1
PIQ 103	II.	2
WCST	III.	2
6 categories/104 cards	IV.	2
4 perseverative responses	V.	2
TOL	B	3
Total move 43/ss90	SDFR	0
Correct 4/ss100	SDCR	0/2int
Init. Tx 116"/ss124	LDFR	0
Exec. TX 540"/ss60	LDCR	1/3int
Tot Tx 656"/ss60	Rec	10/6FP(2 list B)
RV/2 off ss60		
TMT	WMS III/LM	
A 66"(30.7/8.8)	I	24/sc5
B 217"(64.4/18.3)	D	0
Sent Rep 36PR		
Token 6PR		
FAS 12/10PR		
An 8/10PR		

that occurs supports this assertion. A closer look at the data implies that problem solving is reasonably well preserved, although the patient works very slowly. One might hypothesize that posterior brain regions are deteriorated but anterior regions are significantly less affected. However, the pattern of relatively intact executive functioning coupled with dramatic slowing in execution of tasks combined with marked difficulties in memory and learning lead to a *possible* anatomical link to the anterior thalamus (Graff-Radford, Tranel, & Brandt, 1992). In truth, one cannot with certainty differentiate diagnoses or localize the source of pathology based on these data. In actuality, this patient had a hypothalamic tumor, far removed from primary cortical pathology. This tumor was impinging upon basal forebrain circuitry and ultimately required neurosurgical intervention. The lesson here is a simple one: By focusing only upon horizontal brain organization, a differential diagnostic conclusion cannot be reached beyond the obvious one of dementia. The obvious temptation would be to jump to *cortical* conclusions, which would be diagnostically misleading but understandable within a two-dimensional model.

Most cognitive test interpretation in clinical neuropsychology has emphasized the horizontal organization of the brain, specifically, lateralized brain-behavior relationships. In most right-handed people, it is believed that the left hemisphere subserves language functions and that the right hemisphere mediates visuospatial functions. Neuropsychological testing approaches clinical evaluation by attempting to ascertain differences in functioning across this lateralized gradient. Additional attention is placed upon the anterior-posterior

dimension (throughout this book, we define posterior cortices as the occipital, parietal, and temporal lobes, since these lobes lie posterior to the central sulcus; we define anterior brain regions as the frontal lobes and the basal forebrain region). This concerns an evaluation of the anterior-mediated executive domain and an assessment of the posterior-mediated perceptual domains. Therefore, traditional test interpretation is characterized by inferring left versus right hemispheric differences in functioning and frontal versus temporal–parietal–occipital lobe differences in functioning. Clinical neuropsychology has become adept at evaluation within this horizontally organized model of brain–behavior relationships. However, this is an oversimplified model that neglects the vertical organization of the brain. The model does not take into account that subcortical pathology can generate presentations that mimic cortical involvement, and in this way, this model can even distort the clinical picture.

This book describes the vertical organization of brain–behavior relationships and considers methodologies for evaluating these processes. Our main goal is to present an updated and more integrated view of brain–behavior relationships by examining the contributions of both cortical and subcortical brain regions. In this way, we can move from a two-dimensional to a three-dimensional depiction of brain function and in doing so better understand and describe human adaptation as a dynamic process.

Why Do We Have a Cortico-centric Bias?

When the neurosciences were in their infancy, techniques for studying functional neuroanatomy were limited. Many inferences about brain–behavior relationships were made only from behavioral observations of patients with documented cortical brain damage and from laboratory and imaging techniques that were primitive by today’s standards. Our knowledge of brain structure was incomplete. The development of neuropsychological testing was rooted in the assumptions of this cortico-centric model. Brain function is dependent upon structure. Patients with brain pathology were tested on cognitive tasks, and the test results were correlated with the site of the cortical lesion. Patients with subcortical pathology demonstrated disturbances in movement. When these movement problems were accompanied by cognitive deficits, it was assumed that the cognitive impairment was a manifestation of cortical deafferentation. The cognitive deficit that was observed was presumed to be the result of disconnecting cortical regions from the rest of the brain.

However, over the past 20–25 years, the development of experimental and diagnostic techniques has allowed for notable revisions in our understanding of functional neuroanatomy. Imaging techniques such as CT scans, PET studies, and fMRI investigations, and physiological techniques such as cell recording and neuronal tracing studies have significantly expanded our understanding of

neuronal structures, their connective patterns, and about how structure relates to function. Additionally, advances in computer science have allowed for greater ability to model the functioning of complex neural systems (Afraimovich, Zhigulin, & Rabinovich, 2004; Basar & Guntekin, 2007; Freeman, 2008; Izhikevich, 2007).

Segregated neuronal connections between associative and paralimbic regions of the neocortex and the basal ganglia and discrete circuitries between these same areas of the neocortex and the cerebellum have been identified. Multiple, parallel, segregated circuits between the cortex and basal ganglia and between the cortex and cerebellum provide the anatomic substrate for supporting not only motor, but also cognitive and emotional function (Middleton & Strick, 2000). Since the brain operates on a “need-to-know” basis (Kolb & Whishaw, 2008), and because function is related to structure, the most obvious and compelling conclusion is that cortical–subcortical connections support a range of highly specialized behavioral functions, including those related to cognition and emotion.

Vertically Organized Brain Systems

There are two vertically organized re-entrant brain systems that interface the cortex and the descending systems. These are the cortico-basal ganglia system and the cerebro-cerebellar system. They are termed re-entrant systems because their circuitries form a “loop”—the circuit re-enters a region near its point of origin. The circuits originate in the cerebral cortex. After passing through the various subcortical structures within each respective system, the circuit re-enters the cortex and terminates very near the same region in which the circuit originated. Therefore, a general feature of these circuits comprises a *cortical–subcortical–cortical* loop of interaction. Within the nervous system, loops of interaction of this type are considered to have a modulatory function. In these two systems, the cortical inputs are always excitatory. Outputs from these subcortical regions are largely inhibitory. This means that these subcortical circuits are regulating or modulating—and thus changing—the nature of input received from various cortical domains. Therefore, *these subcortical regions play an important role in deciding what information is or is not returned to the cerebral cortex* (Andreasen & Pierson, 2008). This “looped” architecture represents an organizational system central to brain–behavior relationships, and therefore, in a broader context, these circuitries are central to neuropsychology.

The prototypical cortico-basal ganglia circuit features an anatomy that is preserved throughout the system of all the circuits that have been identified (Alexander, DeLong, & Strick, 1986). The prototypical circuits can be grouped into seven general categories, as will be discussed in Chapters 2–4 (Middleton & Strick, 2001). However, it has also been argued that there are as many circuits as

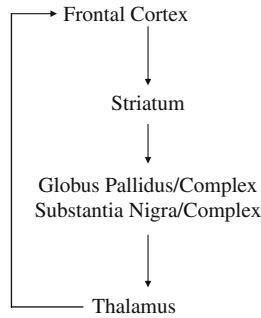


Fig. 1.1 Simplified version of frontal-subcortical circuit

there are specialized functions (Divac & Oberg, 1992). Each circuit is composed of the same number of structures. These structures include the cortex, the striatum, the globus pallidus, the substantia nigra, and the thalamus. Literature has referred to this circuitry as the “cortico-striatal-pallidal-thalamic loop” (see Fig. 1.1).

Each segregated, parallel circuit originates in a specific, circumscribed cortical region. For example, the dorsolateral prefrontal circuit projects specifically to the dorsolateral region of the head of the caudate nucleus, the orbitofrontal circuit projects to the ventral region of the caudate nucleus, the anterior cingulate cortical region projects to the nucleus accumbens, and the auditory and visual association areas of the cortex project to specific regions within the body and the tail of the caudate nucleus (Middleton & Strick, 2001).

Therefore, the basal ganglia receive input from nearly all cortical regions. This has important implications which will be discussed in subsequent sections of this book. Similarly segregated anatomic arrangements are upheld and respected in the globus pallidus and thalamus, while a progressive spatial restriction and compaction occur as these circuits project deep into the basal forebrain region. This spatial compaction has significant implications for the understanding of developmental and “psychological” disorders in particular, as will be discussed in Chapters 3 and 7. Not surprisingly, traditional models of neuropsychological test interpretation have encountered difficulty “explaining” these disorders along lateralized and anterior–posterior gradients.

This general review of the circuitry presents two key points. First, since these circuits originate in associative and paralimbic regions of cerebral cortex, this provides compelling neuroanatomic evidence that the basal ganglia contribute to functions outside the motor domain. Second, because the basal ganglia are anatomically connected to nearly all regions of neocortex, the basal ganglia are in a powerful position to exert influence over a very wide range of functions, including the modulation of perception, cognition, affect, and action (Middleton, 2003).

The second vertically organized brain system is defined by cerebro-cerebellar circuitry (Schmahmann & Pandya, 1997). This re-entrant system demonstrates anatomic and conceptual similarities with the cortico-basal ganglia system. The cerebro-cerebellar circuit originates in the neocortex. Specific regions of the frontal, temporal, parietal, and paralimbic areas of the cerebral hemispheres are all represented as points of origin. Each circuit is again composed of the same cerebellar structures. Cortical regions send segregated projections to their preferred sites of the highly specialized pontine nuclei in the brain stem. Through the mossy fiber input system, specialized projections arrive at specific zones or lobules of the cerebellar cortex (see Chapter 5). The fiber system of the cerebellar cortex projects to specialized regions of the deep cerebellar nuclei, and from there, back to thalamus and on to cortex to a region where the specialized circuit originated (see Fig. 1.2).

The cerebellum, which is actually composed of more neurons than can be found in the remainder of the central nervous system, represents an extremely compact yet powerful computational mechanism (Houk & Mugnaini, 2003). Once again, relying on the anatomic principle that circuitries in the nervous system are established and organized around a “need-to-know” functional basis, these segregated circuits must be contributing to, or perhaps more to the point, modulating, the functions subserved by the regions of origin of the circuits (Middleton & Strick, 2000). This principle can readily be understood by examining the organization of sensory and motor cortices, which is beyond the scope of this book. Comprehensive reviews are provided by Kolb and Wishaw (2008) and M. Banich (2004). As is true for the basal ganglia, the cerebellum is also in a position to exert powerful computational or modulatory influence over all domains of behavior.

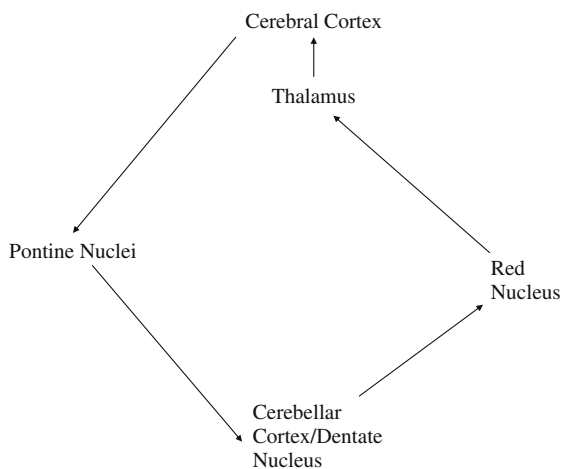


Fig. 1.2 Simplified version of cerebro-cerebellar circuit

To be sure, the neocortex, the basal ganglia, and the cerebellum are all complex brain regions. As might be suggested even by only a cursory description of the circuitries summarized above, understanding these systems is a challenging, daunting task. However, complex systems can often be made more intelligible and understandable when we know something about their history. Theory, evolution, and phylogeny, thus provide the background and clues for understanding the purposes and organization of these brain regions and systems.

A Theoretical and Historic Context

We begin with a deceptively simple question: What is the purpose of the organism? The simplest answer is in the following: The purpose of the organism is to survive. How does the organism survive? In short, the organism survives through interaction with the environment. Therefore, the brain must be organized in a way that allows for successful interaction with and adaptation to the environment. In order to interact and adapt successfully, six criteria must necessarily be met. Three of these criteria have to do with sensory processing, and three of these criteria have to do with motor functioning. The nervous system of the complex organism must have the following minimal characteristics:

1. Capacity for object recognition functions
2. Capacity for object location functions
3. Capacity to detect movement
4. The ability to know what to do
5. The ability to know how to do it (or to know how to act)
6. The ability to know when to act

First, the brain needs to “know” what objects exist in the environment. In other words, the brain needs to have information about the objects that are out there in the world. In the terminology of sensory systems, this information is called *object identification* or *object recognition*. However, being able to accurately identify objects is not enough. Without knowledge of where these objects are, any attempt at interaction for survival is impossible. To interact adaptively, the brain needs information about where these objects are located. Therefore, the brain evolved a system of spatial coordinates to identify objects in space. This function is termed *object location*. Object recognition and location are so important that nature allows for storage of this sensory information to persist over time through the medial temporal lobe memory system. Knowing about objects and where they are located is important, but being able to *remember* information about these objects provides even greater adaptive advantage. In fact, it can even be argued that this type of learning and memory is unsupervised, representing the “default condition” of the cortex (Doya, 1999).

Unfortunately, objects in the environment might not be stationary, and moving objects might threaten an organism's survival. From a survival standpoint, it might be necessary to track a moving target. In this regard, sensory systems also need to include the ability to detect movement, which is the third element of sensory organization. Sensory systems are in fact biologically organized in this fashion in order to perceive identity and location, and to detect movement (Ungerleider & Haxby, 1994; Ungerleider & Mishkin, 1982).

For instance, in most vertebrates and certainly in non-human and human primates, sensory systems and subsystems are coordinated to fulfill and accommodate these sensory tasks of perceiving identity, location, and motion. Ventral regions of the sensory or posterior cortices typically subserve object identification or recognition functions. Dorsally organized information-processing streams subserve object location functions. Tucked inside the superior temporal lobe sulcus is a visual information-processing pathway that is specialized for the detection of movement (Banich, 2004).

Very considerable amounts of cortical tissue are dedicated to these object recognition, location, and detection of motion functions. Therefore, it is clear that the organism evolved to have access to appropriate sensory information in order to make necessary decisions about potential behavior. This sensory information often includes cognitive components. The basal ganglia and cerebellum have access to this information through the respective re-entrant circuitries. The functional neuroanatomy of these circuitries will be discussed in Chapters 2–5. These re-entrant circuitries ensure that the entire brain has access to the same sensory and motor information.

Similarly, since humans confront choices regarding where to place attention, there must be a selection or gating mechanism to facilitate decisions about these choices. Over the course of evolution, sensory and cognitive systems increased or expanded. We became capable of analyzing object identification and location information within different specialized sensory modalities. We retained the capacity to respond to orienting stimuli for the purpose of survival, but we also developed the ability to withhold that response when necessary and to selectively attend to different aspects of a complex environment and to solve the problems posed by novel aspects of the environment. Therefore, there are potentially conflicting or incompatible sensory inputs and motor outputs that must be prioritized and selected on the basis of the well-being of the whole organism (Redgrave, Prescott, & Gurney, 1999). Subsequent sections and chapters will demonstrate that the modulatory properties of cortical–subcortical circuits include mechanisms for the selection of attention and action.

Once the brain determines “what” and “where” things are, it must now determine what to do about it. The nervous system needs three types of motor programs to act in relation to this information. These motor programs consist of knowing what action to perform (*what to do*), knowing how to perform the action (*how to do it*), and knowing when to perform the action (*when to do it*). In other words, the action patterns of the organism that interact with the environment need to include multiple different aspects of praxic and intention programs.

Knowing what to do might sound like an obvious function, but this actually poses an interesting organizational problem for a system structured on a need-to-know basis. The brain is organized to digest information as needed. However, not all types of input are the same. For example, certain aspects of the environment are very predictable. In this case, a fixed, routine, automatic response would be highly advantageous (Toates, 2006). In fact, a programmed response that always works would be of obvious immediate survival value since people would immediately “know” what to do, rapidly and effectively every time. However, as we know, the environment isn’t so straightforward. While it certainly has recurring elements and themes, it is not always predictable and from a survival standpoint, it cannot be trusted. Specifically, the brain must understand how to deal with novelty. Novelty makes it impossible to preprogram responses that would meet the characteristics of all situations. Under unfamiliar conditions, an organism that possesses only preprogrammed responses would not survive because it could not adapt to circumstances for which it had no response.

This suggests that the brain would need two separate systems for “knowing” what to do. First, the organism needs a stimulus-based system that is composed of those actions and behaviors the organism relies upon routinely to ensure its survival. Second, the organism needs a system that allows it to program new behaviors when it has no preprogrammed behavior to meet novel environmental requirements (Fuster, 1997). In other words, the organism needs a dual-layered model of behavioral control (Toates, 2005). The organism needs a “habit” or procedural system to interact with stimuli that present routinely, as well as a “thinking” or problem-solving system that can adapt to unfamiliar circumstances. These two systems are subserved by the basal ganglia and the frontal cortices respectively. Nature has actually fused these two systems to ensure maximum adaptability. The neuroanatomic product is known as the frontostriatal system. The frontostriatal system allows the organism to decide what to do. This system programs and selects behaviors. However, before discussing the flexibility of this system, let’s turn our attention to examining the “how” programs of the brain.

How to Do Things in a Changing Environment

Having decided what to do, we need to next know how to do it. Since all behaviors are dynamic, action requires appropriate amplification or adjustment during different phases of task execution. For example, even a seemingly simple behavior such as reaching for an object requires appropriate force of movement during the initial, middle, and termination phases of the task, with changing vectors of speed, distance, precision, and inhibition as the dynamic behavior unfolds. Similarly, even a routine behavior performed on a repetitive basis might need to be adjusted against the background of an environment presenting with slightly different characteristics.

Take the example of a basketball player or quarterback throwing a ball. The success of this pass depends in part on how far the other player is from the player throwing the ball, and whether they are moving or stationary, guarded or unguarded. These types of variables would influence either undershooting or overshooting of the target. Thus, the player needs not only to estimate how far to throw the ball but must intuitively adjust for the direction, rate, and surrounding circumstances of the receiver. Throwing the ball is not enough. The throw needs to be adjusted to fit the characteristics of the given circumstances. Knowing how to throw the ball includes the appropriate refinement of behavior according to the variables of rate, rhythm, and force. In this regard, the cerebellum appears to play a key role in regulating this behavior. It serves the function of knowing how to perform an action by adjusting behavioral output, accomplishing this task by regulating neural signals through loops of interaction with various regions of the cortex (Hallett & Grafman, 1997). Thus, patients with ataxia and patients with intention tremor can be characterized as demonstrating disturbances in this very general type of behavioral adjustment insofar as such symptoms can be understood in relation to problems controlling appropriate amplification (Houk & Mugnaini, 2003).

How would this type of issue appear in a cognitive or in an emotional system? Loss of appropriate coordination of thinking represents a cardinal symptom of thought disorder. This symptom has actually been referred to as cognitive dysmetria, and has been directly linked to cerebellar circuitry (Andreasen, Paradiso, & O'Leary, 1998; Andreasen et al., 1999; Crespo-Facorro et al., 1999; Volz, Gaser, & Sauer, 2000). The marked circumstantiality of thought seen in certain patient populations can readily be recognized as a type of cognitive "overshooting" or "undershooting" (Schmahmann, Weilburg, & Sherman, 2007). A less dramatic example of this lack of coordination in thought would look like the inability to "make the point" of conversation. Circumstantiality can be viewed as a cognitive analogue of the ataxia or the intention tremor occurring with cerebellar motor pathology. Within an emotional circuit, this type of problem would look like an inability to regulate affect. For example, experimental studies have demonstrated that stimulating various regions of cerebellar vermis to different degrees results in either "under" or "over" expressions of affect (Schmahmann, 2000). Affective blunting and/or exaggeration would be an analogous manifestation of a disrupted "limbic" cerebellar circuit (Schmahmann et al., 2007). For example, a "temper outburst" can be considered an instance of emotional expression featuring inappropriate amplification or force. The ataxia and frequent emotional lability of humans under the influence of alcohol—as well as the characteristics of individuals at risk for abuse of this substance—speaks to important aspects of cerebellar function (Deshmukh, Rosenbloom, Pfefferbaum, & Sullivan, 2002; Fitzpatrick, Jackson, & Crowe, 2008).

When to Do Things—Intention Programs

Finally, knowing what to do and how to do it are essential but not sufficient for successful adaptation. The organism also needs to know when to act, the third general feature of motor programming. Acting too soon or too late can defeat the purpose of adaptation. Persisting with behavior versus stopping a behavior prematurely is an essential component in interacting with the environment. Take our football quarterback. If he waits too long or throws too soon on a timed pass, it will be incomplete. Knowing when to act can make the difference between a touchdown and an interception.

Similarly, when engaging in and completing a complex activity, the organism often needs to switch from one behavior to another. Therefore, we need intention programs that allow us to appropriately initiate and inhibit behaviors, as well as switching mechanisms that allow for ongoing translation of sensory input into appropriate motor “when” actions. This requires us to be able to gate attentional and response selections. Again, subcortical structures, and particularly the basal ganglia, are critical to these processes.

Patients with movement disorders essentially demonstrate disturbances in intentionality. For example, Huntington’s and Parkinson’s diseases, which are manifestations of basal ganglia pathology, are considered disorders of voluntary movement (Blumenfeld, 2002). Huntington’s disease is characterized by the release of fragments of purposeful movements. Parkinson’s disease is characterized by difficulties in initiating movements, perseveration in terms of difficulty in switching from one movement to another, and difficulties in stopping movements. These basal ganglia disorders are associated with deficits in knowing when to start a movement, when not to start a movement, when to persist with a movement, and when to stop a movement. These functions comprise the brain’s four intention programs. Disorders such as Huntington’s and Parkinson’s diseases disrupt the brain’s intention programs. Therefore, the basal ganglia play an important role in governing intentions. Chapter 2 will explore the role of the basal ganglia in linking volition with automatic behavior so that the resultant behavioral output becomes biologically adaptive.

Again, it is useful to consider examples of how disturbance in intention would present pathology outside the motor domain. Cognitive distractibility, or the inability to refrain from responding to an idea or an external stimulus, is an example of disordered intention. Take the familiar example of someone who starts with the intention of studying for a test or completing an assignment and then becomes distracted by an extraneous influence such as surfing the web. This demonstrates a deficit in adequately linking volition with less relevant automatic or “stimulus-based” responding. At the behavioral level, this common form of distractibility actually reveals a deficit in behavioral persistence. The individual who interrupts others or the student who blurts out statements and questions is demonstrating deficits in knowing when to start or when not

to start behaviors. These problems with inhibitory control over interpersonal “pragmatics” can be understood as deficits in intention programs. Similarly, at the affective/interpersonal level, the child who exhibits “separation anxiety” is demonstrating an inappropriate affective persistence, a deficit in knowing when to persist with or when to stop a behavior, in other words, a perseveration. We believe that cognitive and affective regulations comprise *extensions of motor control systems* so that it becomes critical to recognize and understand these behavioral analogues. We will make use of these types of analogies throughout the book.

Theories of Types of Behavioral Processing and the Frontostriatal System

Most behavioral processing can be categorized according to two general types (Toates, 2006, 2005). These types of behavioral control comprise stimulus-based processing and higher-order control respectively. Stimulus-based control is composed of reflexes (which will not be discussed in detail in this book), habits, skills, and procedures. In short, these are the behaviors that the organism employs on a routine basis in order to ensure its survival in a predictable environment. The stimulus, which is either external or internal, triggers the appropriate response, and this response is adaptive, meeting the requirements of the circumstances, so that the behavior has survival value.

Stimulus-based control has obvious advantages. It allows the organism to exploit or take advantage of the predictable features of the environment. It allows for a high speed of reaction. It avoids the necessity of programming a behavior every time similar circumstances are confronted because the organism already “knows” what to do (For additional review, see Toates, 2006). Stimulus-based processing also has serious disadvantages. It affords the organism little spontaneity because a stimulus must be present to evoke the response. It ties the organism to the immediate, to the here-and-now. In its purest sense, it does not allow the organism the capacity to generate or synthesize new behavior under novel conditions. Therefore, the organism cannot function or adapt successfully under ambiguous or novel circumstances. In unfamiliar situations, stimulus-based control simply does not work.

The second type of behavioral processing is higher-order control. In short, higher-order processing comes into play when stimulus-based control does not work. Managing novelty and ambiguity requires the organism to refrain from responding in the here-and-now, and instead, requires the organism to solve problems. Successful problem solving requires *determining the context for stimulus-based control*. As an example, consider the instructions to the Wisconsin Card Sorting Test (Heaton, Chelune, Talley, Kay, & Curtis, 1993). In order to perform this task, the subject is asked to sort cards in the absence of provided categories. The categories are determined through informing the subject whether his or her choice is “right” or “wrong” after each and every card is

sorted. Therefore, the task for the subject is to take these ambiguous circumstances and develop the context for stimulus-based control, which in this case comprises the color, form, and number characteristics of the cards. The problem is solved by discovering the stimulus-based properties governing the task. We believe that *all problem-solving and higher-order control can be understood as breaking a problem situation down into stimulus-based characteristics* (Richer & Chouinard, 2003; Toates, 2006). In this way, higher-order control provides the organism autonomy by allowing for the programming of goal-directed behavior (this will be discussed in Chapter 8). Higher-order control features the enormous advantage of allowing adaptation to an environment that is ambiguous, novel, or unfamiliar. However, higher-order control also presents a significant drawback. *This system functions slowly, which is a disadvantage for adaptation.*

Therefore, one system of behavioral control is fast but not very smart. This is the stimulus-based control system. It always has the proper, adaptive response for the “right” stimulus, but it has no ability to do anything different (Toates, 2005). It works quickly under the “right” stimulus circumstances, but when confronted with novel stimuli, it is inflexible and cannot figure out what to do. Actually, this system can be slowly trained for the acquisition of skills and habits. After learning what to do, it “remembers.” This instrumental behavioral system is robust but not very flexible. Conversely, the higher-order control system is very smart but often too slow in its adaptation. It can take a long time to figure out what to do. For example, this system evaluates new circumstances in the present. It thinks about what it knows when it devises a plan of action. It thinks into the future to anticipate outcomes to decide if the behavior under consideration will work. When implementing a new behavior, it monitors and evaluates progress, taking the results of that assessment to further modify the behavior according to circumstances. Therefore, it has great flexibility. However, this is a slow, time-consuming course of adaptation.

During the course of evolutionary and phylogenetic development, there must have been considerable adaptive pressure to retain a system that was fast and accurate. Understandably, fast and accurate behavior increases survival opportunity since it exploits the features of the environment we can count on while conserving resources. There also must have been evolutionary pressure to develop a system that was smart and flexible. Nature did not respond to the pressures of adaptation by choosing between these two systems (Trimmer, Houston, Marshall et al., 2008). Instead, nature’s reply to adaptive pressures was to “have it both ways” by developing the frontostriatal system. This dual-layered control system is adaptive for several reasons.

This frontostriatal system has three important characteristics. First, *both ways of responding co-exist as a biologically economical system.* This means that operating in tandem, stimulus-based control can operate when it is advantageous to do so, and higher-order control can become operational when automatic processing does not work. Second, *both systems interact with each other.*

This means that the operations of both systems can shift back and forth, from one system to another, as environmental circumstances change, with frequent, alternating episodes of automatic behaviors and modifications through higher-order control when this becomes necessary. The systems operate independently, yet in a complimentary fashion. This dual-layered model of behavioral control allows for the greatest flexibility in adaptation (Toates, 2005). Most situations actually require alternating episodes of automatic responding and higher-order control. Therefore, this system conserves adaptive resources. Third, *the frontostriatal system allows the organism to benefit from experience*. This is an exceedingly important bonus. Solutions to novel problems can be practised and automated, so that these “new” solutions take on stimulus-based characteristics for future application (Kinsbourne, 1993; Miller & Wallis, 2003).

The procedural learning and memory system lies at the heart of automatic responding. This system allows for programming behaviors to meet the demands of a variety of changing environments. In this regard, a key to understanding how subcortical regions contribute to cognition concerns their relationship to the frontal lobes, and the ways in which they work together to acquire new behavioral patterns. These interactions will be explored in Chapters 2, 4, 8, and 9. Understanding the relationships between these systems provides an essential tool for understanding how cortical–subcortical interactions embody the essential underpinning of cognition.

Analogous Memory Systems

As previously indicated, the ability to remember information about objects would confer a decisive adaptive advantage. Nature provided for this function through the medial temporal lobe memory system (Squire, Stark, & Clark, 2004). This system allows *perceptual* experience to persist. This is important because in a problem-solving situation, the organism has a range of sensory experience to draw upon while attempting to break down a novel situation into stimulus-based characteristics. In fact, this memory system is so important that its functioning is routinely assessed during the course of a cognitive evaluation.

The frontostriatal system includes a habit or procedural memory system that allows the organism to benefit from the experience of its *activity*. It is an instrumental behavioral system that learns by doing. In essence, problem-solving actions and behaviors are retained because these behaviors can be useful for future adaptation. This is one of the functions that allows the organism to adapt to a new environment. Remembering what to do is important when features of a novel environment have now become familiar. However, the procedural memory system, which is essential for adaptation, is routinely overlooked in a cortico-centric model of neuropsychology that neglects the vertical organization of the brain. Simply put, clinical neuropsychology has not yet developed the “habit” of

considering procedural learning and memory, despite the fact that this system's automatic, stimulus-based responding provides an essential feature of adaptive functioning, as well as an important underpinning to the behaviors that often bring individuals to clinical attention. In fact, procedural learning is so important that nature has provided two subdivisions of procedural learning, namely, the cortico-striatal and the cortico-cerebellar procedural learning systems. The former system governs the acquisition of habits, and the latter system mediates response to environmental changes or perturbations (Doyon & Ungerleider, 2002). Most, if not all, behavior requires a combination of these systems, as will be discussed in Chapters 4, 5, and 9.

The Phylogenetic Perspective

The forebrain components of the basal ganglia are well conserved across vertebrates, and all tetrapod vertebrates share a common pattern of basal ganglia organization (Smeets, Marin, & Gonzalez, 2000). The striatum, which is the largest single structure in the basal ganglia, is present in all vertebrates. The striatum is always a sensory input structure. It always receives dopaminergic connections from the midbrain (Strieter, 2005). This is important since the basal ganglia appear to operate within the paradigm of reward-driven association learning mediated by dopamine (Joel & Weiner, 2000). All vertebrates have a nucleus accumbens, a globus pallidus, and a subthalamic nucleus (Marin, Smeets, & Gonzalez, 1998). These are the phylogenetically oldest regions of the basal ganglia, and their structure and function were retained over millions of years of evolutionary development. Therefore, the fundamental scheme of basal ganglia organization evolved with or before vertebrates and was retained thereafter because it had adaptive value (Striedter, 2005; Marin et al., 1998).

We believe this scheme was retained because these regions fundamentally support the integration of motivation with sensory input and motor output, along with a mechanism for intention programs. Motivation is provided by the nucleus accumbens, and sensory input is gated through the striatum. The ventral pallidum is tonically active and ready to "release" behavior by decreasing inhibition on the thalamus, while the subthalamic nucleus regulates the overall tone or neural output of the pallidum (Utter & Basso, 2008). These functions will be discussed in Chapters 2–4. The nucleus accumbens is a phylogenetically old reward center. It is composed of two regions, specifically, a shell and a core (Heimer, Van Hoesen, Trimble, & Zahm, 2008). The shell of the nucleus accumbens is a center of consummatory reward. The core of the nucleus accumbens projects to the ventral pallidum, a primary movement center. This implies that movement, and the subsequent development of procedures or habitual ways of responding that depend upon movement, evolved from motivational systems (Aboitiz, Morales, & Montiel, 2003; Brauth & Kitt, 1980; Parent, 1997). The subthalamic nucleus has been

demonstrated to adjust the magnitude of inhibitory pallidal output, and, therefore, serves as a type of thermostat in regulating motor output (Mink, 2003). Neurotransmitter organization and connectivity within these brain regions is also essentially the same within all vertebrates along the phylogenetic scale (Medina & Reiner, 1995).

In vertebrates, the caudate nucleus, the putamen, and the nucleus accumbens together are referred to as the striatum. In phylogenetically lower vertebrates, such as rodents, the caudate and putamen are one single structure referred to as the caudoputamen or the caudate-putamen suggesting this was the evolutionary origin of these structures. The fibers of the internal capsule course through this unit in rodents (Streidter, 2005). In all primates, the caudate and putamen are clearly separated by the internal capsule, although they remain connected by “cellular bridges.” This implies that the caudate and the putamen were derived from each other and that these regions separated or split apart from each other as phylogeny required increasing specialization. In this regard, the isocortex appears to have derived from the dorsal pallidum (Aboitiz et al., 2003).

In primates, the anterior caudate receives projections from prefrontal and orbitofrontal regions, while the body and tail of the caudate receive projections from temporal and parietal regions. The putamen receives input from motor, premotor, supplementary motor, and frontal eye field regions (Rolls & Johnstone, 1992). The caudate and putamen may have derived from the nucleus accumbens region. It is generally accepted that the caudate and putamen separated from each other during the course of evolution as a result and manifestation of increasing sensory and motoric specialization. The caudate became more specialized for sensory functions, and the putamen became more specialized for motoric functions.

It is interesting to compare these developments against the background of cortical changes. The neocortex dramatically increased in size and complexity throughout evolutionary history. Importantly, the basal ganglia kept pace (Divac & Oberg, 1992). These various regions of the basal ganglia not only became larger, but certain regions of the basal ganglia developed separately and took on increasing specialization. The case cannot be made that the basal ganglia enlarged simply because the cortex “got bigger.” Instead, structural evolutionary changes in the basal ganglia are correlated with increasing functional or behavioral specialization. As neocortex became more specialized, the basal ganglia became more specialized. The changes are not global or generic. Instead, the developments are very specific. In contrast, the growth of the diencephalon was very modest, while the olfactory tubercle is actually smaller in human primates (Divac & Oberg, 1992). Therefore, over the course of evolution, some structures enlarged, other structures remained proportionately the same, and other structures regressed.

How might these differences be understood? In primates, with increasing associative sensory capacities and increasing specialization of movement, cortico-cortical connections became more important than the growth of