

Contents in Brief

Contents	xiii
Preface	xli
Acknowledgments	xliii
Contributors	xlv

Part I

Overall Perspective

- 1 The Brain and Behavior 7
- 2 Genes and Behavior 26
- 3 Nerve Cells, Neural Circuitry, and Behavior 56
- 4 The Neuroanatomical Bases by Which Neural Circuits Mediate Behavior 73
- 5 The Computational Bases of Neural Circuits That Mediate Behavior 97
- 6 Imaging and Behavior 111

Part II

Cell and Molecular Biology of Cells of the Nervous System

- 7 The Cells of the Nervous System 133
- 8 Ion Channels 165
- 9 Membrane Potential and the Passive Electrical Properties of the Neuron 190
- 10 Propagated Signaling: The Action Potential 211

Part III

Synaptic Transmission

- 11 Overview of Synaptic Transmission 241

- 12 Directly Gated Transmission: The Nerve-Muscle Synapse 254
- 13 Synaptic Integration in the Central Nervous System 273
- 14 Modulation of Synaptic Transmission and Neuronal Excitability: Second Messengers 301
- 15 Transmitter Release 324
- 16 Neurotransmitters 358

Part IV

Perception

- 17 Sensory Coding 385
- 18 Receptors of the Somatosensory System 408
- 19 Touch 435
- 20 Pain 470
- 21 The Constructive Nature of Visual Processing 496
- 22 Low-Level Visual Processing: The Retina 521
- 23 Intermediate-Level Visual Processing and Visual Primitives 545
- 24 High-Level Visual Processing: From Vision to Cognition 564
- 25 Visual Processing for Attention and Action 582
- 26 Auditory Processing by the Cochlea 598
- 27 The Vestibular System 629
- 28 Auditory Processing by the Central Nervous System 651
- 29 Smell and Taste: The Chemical Senses 682

Part V

Movement

- 30 Principles of Sensorimotor Control 713
- 31 The Motor Unit and Muscle Action 737
- 32 Sensory-Motor Integration in the Spinal Cord 761
- 33 Locomotion 783
- 34 Voluntary Movement: Motor Cortices 815
- 35 The Control of Gaze 860
- 36 Posture 883
- 37 The Cerebellum 908
- 38 The Basal Ganglia 932
- 39 Brain–Machine Interfaces 953

Part VI

The Biology of Emotion, Motivation, and Homeostasis

- 40 The Brain Stem 981
- 41 The Hypothalamus: Autonomic, Hormonal, and Behavioral Control of Survival 1010
- 42 Emotion 1045
- 43 Motivation, Reward, and Addictive States 1065
- 44 Sleep and Wakefulness 1080

Part VII

Development and the Emergence of Behavior

- 45 Patterning the Nervous System 1107
- 46 Differentiation and Survival of Nerve Cells 1130
- 47 The Growth and Guidance of Axons 1156
- 48 Formation and Elimination of Synapses 1181

- 49 Experience and the Refinement of Synaptic Connections 1210
- 50 Repairing the Damaged Brain 1236
- 51 Sexual Differentiation of the Nervous System 1260

Part VIII

Learning, Memory, Language and Cognition

- 52 Learning and Memory 1291
- 53 Cellular Mechanisms of Implicit Memory Storage and the Biological Basis of Individuality 1312
- 54 The Hippocampus and the Neural Basis of Explicit Memory Storage 1339
- 55 Language 1370
- 56 Decision-Making and Consciousness 1392

Part IX

Diseases of the Nervous System

- 57 Diseases of the Peripheral Nerve and Motor Unit 1421
 - 58 Seizures and Epilepsy 1447
 - 59 Disorders of Conscious and Unconscious Mental Processes 1473
 - 60 Disorders of Thought and Volition in Schizophrenia 1488
 - 61 Disorders of Mood and Anxiety 1501
 - 62 Disorders Affecting Social Cognition: Autism Spectrum Disorder 1523
 - 63 Genetic Mechanisms in Neurodegenerative Diseases of the Nervous System 1544
 - 64 The Aging Brain 1561
- Index 1583

Contents

Preface xli
Acknowledgments xliii
Contributors xlv

Part I Overall Perspective

1 The Brain and Behavior 7

Eric R. Kandel, Michael N. Shadlen

Two Opposing Views Have Been Advanced on the Relationship Between Brain and Behavior 8

The Brain Has Distinct Functional Regions 10

The First Strong Evidence for Localization of Cognitive Abilities Came From Studies of Language Disorders 16

Mental Processes Are the Product of Interactions Between Elementary Processing Units in the Brain 21

Highlights 23

Selected Reading 23

References 24

2 Genes and Behavior 26

Matthew W. State, Cornelia I. Bargmann,
T. Conrad Gilliam

An Understanding of Molecular Genetics and Heritability Is Essential to the Study of Human Behavior 27

The Understanding of the Structure and Function of the Genome Is Evolving 27

Genes Are Arranged on Chromosomes 30

The Relationship Between Genotype and Phenotype Is Often Complex 31

Genes Are Conserved Through Evolution 32

Genetic Regulation of Behavior Can Be Studied in Animal Models 34

A Transcriptional Oscillator Regulates Circadian Rhythm in Flies, Mice, and Humans 34

Natural Variation in a Protein Kinase Regulates Activity in Flies and Honeybees 42

Neuropeptide Receptors Regulate the Social Behaviors of Several Species 44

Studies of Human Genetic Syndromes Have Provided Initial Insights Into the Underpinnings of Social Behavior 46

Brain Disorders in Humans Result From Interactions Between Genes and the Environment 46

Rare Neurodevelopmental Syndromes Provide Insights Into the Biology of Social Behavior, Perception, and Cognition 46

Psychiatric Disorders Involve Multigenic Traits 48

Advances in Autism Spectrum Disorder Genetics Highlight the Role of Rare and De Novo Mutations in Neurodevelopmental Disorders 48

Identification of Genes for Schizophrenia Highlights the Interplay of Rare and Common Risk Variants 49

Perspectives on the Genetic Bases of Neuropsychiatric Disorders 51

Highlights 51

Glossary 52

Selected Reading 53

References 53

3 Nerve Cells, Neural Circuitry, and Behavior 56

Michael N. Shadlen, Eric R. Kandel

The Nervous System Has Two Classes of Cells 57

Nerve Cells Are the Signaling Units of the Nervous System 57

Glial Cells Support Nerve Cells 61

Each Nerve Cell Is Part of a Circuit That Mediates Specific Behaviors 62

Signaling Is Organized in the Same Way in All Nerve Cells 64

The Input Component Produces Graded Local Signals 65

The Trigger Zone Makes the Decision to Generate an Action Potential 67

The Conductive Component Propagates an All-or-None Action Potential 67

The Output Component Releases Neurotransmitter 68

The Transformation of the Neural Signal From Sensory to Motor Is Illustrated by the Stretch-Reflex Pathway 68

Nerve Cells Differ Most at the Molecular Level 69

The Reflex Circuit Is a Starting Point for Understanding the Neural Architecture of Behavior 70

Neural Circuits Can Be Modified by Experience 71

Highlights 71

Selected Reading 72

References 72

4 The Neuroanatomical Bases by Which Neural Circuits Mediate Behavior. . . . 73

David G. Amaral

Local Circuits Carry Out Specific Neural Computations That Are Coordinated to Mediate Complex Behaviors 74

Sensory Information Circuits Are Illustrated in the Somatosensory System 74

Somatosensory Information From the Trunk and Limbs Is Conveyed to the Spinal Cord 76

The Primary Sensory Neurons of the Trunk and Limbs Are Clustered in the Dorsal Root Ganglia 79

The Terminals of Central Axons of Dorsal Root Ganglion Neurons in the Spinal Cord Produce a Map of the Body Surface 81

Each Somatic Submodality Is Processed in a Distinct Subsystem From the Periphery to the Brain 81

The Thalamus Is an Essential Link Between Sensory Receptors and the Cerebral Cortex 82

Sensory Information Processing Culminates in the Cerebral Cortex 84

Voluntary Movement Is Mediated by Direct Connections Between the Cortex and Spinal Cord 89

Modulatory Systems in the Brain Influence Motivation, Emotion, and Memory 89

The Peripheral Nervous System Is Anatomically Distinct From the Central Nervous System 92

Memory Is a Complex Behavior Mediated by Structures Distinct From Those That Carry Out Sensation or Movement 93

The Hippocampal System Is Interconnected With the Highest-Level Polysensory Cortical Regions 94

The Hippocampal Formation Comprises Several Different but Highly Integrated Circuits 94

The Hippocampal Formation Is Made Up Mainly of Unidirectional Connections 95

Highlights 95

Selected Reading 96

References 96

5 The Computational Bases of Neural Circuits That Mediate Behavior. 97

Larry F. Abbott, Attila Losonczy, Nathaniel B. Sawtell

Neural Firing Patterns Provide a Code for Information 98

Sensory Information Is Encoded by Neural Activity 98

Information Can Be Decoded From Neural Activity 99

Hippocampal Spatial Cognitive Maps Can Be Decoded to Infer Location 99

Neural Circuit Motifs Provide a Basic Logic for Information Processing 102

Visual Processing and Object Recognition Depend on a Hierarchy of Feed-Forward Representations 103

Diverse Neuronal Representations in the Cerebellum Provide a Basis for Learning 104

Recurrent Circuitry Underlies Sustained Activity and Integration 105

Learning and Memory Depend on Synaptic Plasticity 107

Dominant Patterns of Synaptic Input Can be Identified by Hebbian Plasticity 107

Synaptic Plasticity in the Cerebellum Plays a Key Role in Motor Learning 108

Highlights 110

Selected Reading 110

References 110

6 Imaging and Behavior 111

Daphna Shohamy, Nick Turk-Browne

Functional MRI Experiments Measure Neurovascular Activity 112

fMRI Depends on the Physics of Magnetic Resonance 112

fMRI Depends on the Biology of Neurovascular Coupling 115

Functional MRI Data Can Be Analyzed in Several Ways 115

- fMRI Data First Need to Be Prepared for Analysis by Following Preprocessing Steps 115
- fMRI Can Be Used to Localize Cognitive Functions to Specific Brain Regions 118
- fMRI Can Be Used to Decode What Information Is Represented in the Brain 118
- fMRI Can Be Used to Measure Correlated Activity Across Brain Networks 119

Functional MRI Studies Have Led to Fundamental Insights 120

- fMRI Studies in Humans Have Inspired Neurophysiological Studies in Animals 120
- fMRI Studies Have Challenged Theories From Cognitive Psychology and Systems Neuroscience 121
- fMRI Studies Have Tested Predictions From Animal Studies and Computational Models 122

Functional MRI Studies Require Careful Interpretation 122**Future Progress Depends on Technological and Conceptual Advances 123**

Highlights 125

Suggested Reading 126

References 126

Part II**Cell and Molecular Biology of Cells of the Nervous System****7 The Cells of the Nervous System. . . . 133**

Beth Stevens, Franck Polleux, Ben A. Barres

Neurons and Glia Share Many Structural and Molecular Characteristics 134**The Cytoskeleton Determines Cell Shape 139****Protein Particles and Organelles Are Actively Transported Along the Axon and Dendrites 142**

Fast Axonal Transport Carries Membranous Organelles 143

Slow Axonal Transport Carries Cytosolic Proteins and Elements of the Cytoskeleton 146

Proteins Are Made in Neurons as in Other Secretory Cells 147

Secretory and Membrane Proteins Are Synthesized and Modified in the Endoplasmic Reticulum 147

Secretory Proteins Are Modified in the Golgi Complex 149

Surface Membrane and Extracellular Substances Are Recycled in the Cell 150**Glial Cells Play Diverse Roles in Neural Function 151**

Glia Form the Insulating Sheaths for Axons 151

Astrocytes Support Synaptic Signaling 154

Microglia Have Diverse Functions in Health and Disease 159

Choroid Plexus and Ependymal Cells Produce Cerebrospinal Fluid 160

Highlights 162

Selected Reading 163

References 163

8 Ion Channels 165

John D. Koester, Bruce P. Bean

Ion Channels Are Proteins That Span the Cell Membrane 166**Ion Channels in All Cells Share Several Functional Characteristics 169**

Currents Through Single Ion Channels Can Be Recorded 169

The Flux of Ions Through a Channel Differs From Diffusion in Free Solution 171

The Opening and Closing of a Channel Involve Conformational Changes 172

The Structure of Ion Channels Is Inferred From Biophysical, Biochemical, and Molecular Biological Studies 174

Ion Channels Can Be Grouped Into Gene Families 177

X-Ray Crystallographic Analysis of Potassium Channel Structure Provides Insight Into Mechanisms of Channel Permeability and Selectivity 180

X-Ray Crystallographic Analysis of Voltage-Gated Potassium Channel Structures Provides Insight into Mechanisms of Channel Gating 182

The Structural Basis of the Selective Permeability of Chloride Channels Reveals a Close Relation Between Channels and Transporters 185

Highlights 187

Selected Reading 188

References 188

9 Membrane Potential and the Passive Electrical Properties of the Neuron 190

John D. Koester, Steven A. Siegelbaum

The Resting Membrane Potential Results From the Separation of Charge Across the Cell Membrane 191

The Resting Membrane Potential Is Determined by Nongated and Gated Ion Channels 191

Open Channels in Glial Cells Are Permeable to Potassium Only 193

Open Channels in Resting Nerve Cells Are Permeable to Three Ion Species 194

The Electrochemical Gradients of Sodium, Potassium, and Calcium Are Established by Active Transport of the Ions 195

Chloride Ions Are Also Actively Transported 198

The Balance of Ion Fluxes in the Resting Membrane Is Abolished During the Action Potential 198

The Contributions of Different Ions to the Resting Membrane Potential Can Be Quantified by the Goldman Equation 199

The Functional Properties of the Neuron Can Be Represented as an Electrical Equivalent Circuit 199

The Passive Electrical Properties of the Neuron Affect Electrical Signaling 201

Membrane Capacitance Slows the Time Course of Electrical Signals 203

Membrane and Cytoplasmic Resistance Affect the Efficiency of Signal Conduction 204

Large Axons Are More Easily Excited Than Small Axons 206

Passive Membrane Properties and Axon Diameter Affect the Velocity of Action Potential Propagation 207

Highlights 208

Selected Reading 209

References 210

10 Propagated Signaling: The Action Potential 211

Bruce P. Bean, John D. Koester

The Action Potential Is Generated by the Flow of Ions Through Voltage-Gated Channels 212

Sodium and Potassium Currents Through Voltage-Gated Channels Are Recorded With the Voltage Clamp 212

Voltage-Gated Sodium and Potassium Conductances Are Calculated From Their Currents 217

The Action Potential Can Be Reconstructed From the Properties of Sodium and Potassium Channels 219

The Mechanisms of Voltage Gating Have Been Inferred From Electrophysiological Measurements 220

Voltage-Gated Sodium Channels Select for Sodium on the Basis of Size, Charge, and Energy of Hydration of the Ion 222

Individual Neurons Have a Rich Variety of Voltage-Gated Channels That Expand Their Signaling Capabilities 224

The Diversity of Voltage-Gated Channel Types Is Generated by Several Genetic Mechanisms 225

Voltage-Gated Sodium Channels 225

Voltage-Gated Calcium Channels 227

Voltage-Gated Potassium Channels 227

Voltage-Gated Hyperpolarization-Activated Cyclic Nucleotide-Gated Channels 228

Gating of Ion Channels Can Be Controlled by Cytoplasmic Calcium 228

Excitability Properties Vary Between Types of Neurons 229

Excitability Properties Vary Between Regions of the Neuron 231

Neuronal Excitability Is Plastic 233

Highlights 233

Selected Reading 234

References 234

Part III

Synaptic Transmission

11 Overview of Synaptic Transmission 241

Steven A. Siegelbaum, Gerald D. Fischbach

Synapses Are Predominantly Electrical or Chemical 241

Electrical Synapses Provide Rapid Signal Transmission 242

Cells at an Electrical Synapse Are Connected by Gap-Junction Channels 244

Electrical Transmission Allows Rapid and Synchronous Firing of Interconnected Cells 247

Gap Junctions Have a Role in Glial Function and Disease 248

Chemical Synapses Can Amplify Signals 248

The Action of a Neurotransmitter Depends on the Properties of the Postsynaptic Receptor 249

Activation of Postsynaptic Receptors Gates Ion Channels Either Directly or Indirectly 250

Electrical and Chemical Synapses Can Coexist and Interact 251

Highlights 252

Selected Reading 252

References 253

12 Directly Gated Transmission: The Nerve-Muscle Synapse 254

Gerald D. Fischbach, Steven A. Siegelbaum

The Neuromuscular Junction Has Specialized Presynaptic and Postsynaptic Structures 255

The Postsynaptic Potential Results From a Local Change in Membrane Permeability 255

The Neurotransmitter Acetylcholine Is Released in Discrete Packets 260

Individual Acetylcholine Receptor-Channels Conduct All-or-None Currents 260

The Ion Channel at the End-Plate Is Permeable to Both Sodium and Potassium Ions 260

Four Factors Determine the End-Plate Current 262

The Acetylcholine Receptor-Channels Have Distinct Properties That Distinguish Them From the Voltage-Gated Channels That Generate the Muscle Action Potential 262

Transmitter Binding Produces a Series of State Changes in the Acetylcholine Receptor-Channel 263

The Low-Resolution Structure of the Acetylcholine Receptor Is Revealed by Molecular and Biophysical Studies 264

The High-Resolution Structure of the Acetylcholine Receptor-Channel Is Revealed by X-Ray Crystal Studies 267

Highlights 268

Postscript: The End-Plate Current Can Be Calculated From an Equivalent Circuit 269

Selected Reading 272

References 272

13 Synaptic Integration in the Central Nervous System. 273

Rafael Yuste, Steven A. Siegelbaum

Central Neurons Receive Excitatory and Inhibitory Inputs 274

Excitatory and Inhibitory Synapses Have Distinctive Ultrastructures and Target Different Neuronal Regions 274

Excitatory Synaptic Transmission Is Mediated by Ionotropic Glutamate Receptor-Channels Permeable to Cations 277

The Ionotropic Glutamate Receptors Are Encoded by a Large Gene Family 278

Glutamate Receptors Are Constructed From a Set of Structural Modules 279

NMDA and AMPA Receptors Are Organized by a Network of Proteins at the Postsynaptic Density 281

NMDA Receptors Have Unique Biophysical and Pharmacological Properties 283

The Properties of the NMDA Receptor Underlie Long-Term Synaptic Plasticity 284

NMDA Receptors Contribute to Neuropsychiatric Disease 284

Fast Inhibitory Synaptic Actions Are Mediated by Ionotropic GABA and Glycine Receptor-Channels Permeable to Chloride 287

Ionotropic Glutamate, GABA, and Glycine Receptors Are Transmembrane Proteins Encoded by Two Distinct Gene Families 287

Chloride Currents Through GABA_A and Glycine Receptor-Channels Normally Inhibit the Postsynaptic Cell 288

Some Synaptic Actions in the Central Nervous System Depend on Other Types of Ionotropic Receptors 291

Excitatory and Inhibitory Synaptic Actions Are Integrated by Neurons Into a Single Output 291

Synaptic Inputs Are Integrated at the Axon Initial Segment 292

Subclasses of GABAergic Neurons Target Distinct Regions of Their Postsynaptic Target Neurons to Produce Inhibitory Actions With Different Functions 293

Dendrites Are Electrically Excitable Structures That Can Amplify Synaptic Input 295

Highlights 298

Selected Reading 299

References 299

14 Modulation of Synaptic Transmission and Neuronal Excitability: Second Messengers. 301

Steven A. Siegelbaum, David E. Clapham, Eve Marder

The Cyclic AMP Pathway Is the Best Understood Second-Messenger Signaling Cascade Initiated by G Protein–Coupled Receptors 303

The Second-Messenger Pathways Initiated by G Protein–Coupled Receptors Share a Common Molecular Logic 305

A Family of G Proteins Activates Distinct Second-Messenger Pathways 305

Hydrolysis of Phospholipids by Phospholipase C Produces Two Important Second Messengers, IP_3 and Diacylglycerol 305

Receptor Tyrosine Kinases Compose the Second Major Family of Metabotropic Receptors 308

Several Classes of Metabolites Can Serve as Transcellular Messengers 309

Hydrolysis of Phospholipids by Phospholipase A_2 Liberates Arachidonic Acid to Produce Other Second Messengers 310

Endocannabinoids Are Transcellular Messengers That Inhibit Presynaptic Transmitter Release 310

The Gaseous Second Messenger Nitric Oxide Is a Transcellular Signal That Stimulates Cyclic GMP Synthesis 310

The Physiological Actions of Metabotropic Receptors Differ From Those of Ionotropic Receptors 312

Second-Messenger Cascades Can Increase or Decrease the Opening of Many Types of Ion Channels 312

G Proteins Can Modulate Ion Channels Directly 315

Cyclic AMP–Dependent Protein Phosphorylation Can Close Potassium Channels 317

Second Messengers Can Endow Synaptic Transmission with Long-Lasting Consequences 317

Modulators Can Influence Circuit Function by Altering Intrinsic Excitability or Synaptic Strength 317

Multiple Neuromodulators Can Converge Onto the Same Neuron and Ion Channels 320

Why So Many Modulators? 320

Highlights 321

Selected Reading 322

References 322

15 Transmitter Release 324

Steven A. Siegelbaum, Thomas C. Südhof, Richard W. Tsien

Transmitter Release Is Regulated by Depolarization of the Presynaptic Terminal 324

Release Is Triggered by Calcium Influx 327

The Relation Between Presynaptic Calcium Concentration and Release 329

Several Classes of Calcium Channels Mediate Transmitter Release 329

Transmitter Is Released in Quantal Units 332

Transmitter Is Stored and Released by Synaptic Vesicles 333

Synaptic Vesicles Discharge Transmitter by Exocytosis and Are Recycled by Endocytosis 337

Capacitance Measurements Provide Insight Into the Kinetics of Exocytosis and Endocytosis 338

Exocytosis Involves the Formation of a Temporary Fusion Pore 338

The Synaptic Vesicle Cycle Involves Several Steps 341

Exocytosis of Synaptic Vesicles Relies on a Highly Conserved Protein Machinery 343

The Synapsins Are Important for Vesicle Restraint and Mobilization 345

SNARE Proteins Catalyze Fusion of Vesicles With the Plasma Membrane 345

Calcium Binding to Synaptotagmin Triggers Transmitter Release 347

The Fusion Machinery Is Embedded in a Conserved Protein Scaffold at the Active Zone 347

Modulation of Transmitter Release Underlies Synaptic Plasticity 350

Activity-Dependent Changes in Intracellular Free Calcium Can Produce Long-Lasting Changes in Release 351

Axo-axonic Synapses on Presynaptic Terminals Regulate Transmitter Release 351

Highlights 354

Selected Reading 356

References 356

16 Neurotransmitters. 358

Jonathan A. Javitch, David Sulzer

A Chemical Messenger Must Meet Four Criteria to Be Considered a Neurotransmitter 358

Only a Few Small-Molecule Substances Act as Transmitters 360

- Acetylcholine 360
- Biogenic Amine Transmitters 361
- Amino Acid Transmitters 364
- ATP and Adenosine 364

Small-Molecule Transmitters Are Actively Taken Up Into Vesicles 364

Many Neuroactive Peptides Serve as Transmitters 367

Peptides and Small-Molecule Transmitters Differ in Several Ways 370

Peptides and Small-Molecule Transmitters Can Be Co-released 370

Removal of Transmitter From the Synaptic Cleft Terminates Synaptic Transmission 371

Highlights 376

Selected Reading 377

References 378

Part IV

Perception

17 Sensory Coding 385

Esther P. Gardner, Daniel Gardner

Psychophysics Relates Sensations to the Physical Properties of Stimuli 387

- Psychophysics Quantifies the Perception of Stimulus Properties 387

Stimuli Are Represented in the Nervous System by the Firing Patterns of Neurons 388

- Sensory Receptors Respond to Specific Classes of Stimulus Energy 390
- Multiple Subclasses of Sensory Receptors Are Found in Each Sense Organ 393
- Receptor Population Codes Transmit Sensory Information to the Brain 395
- Sequences of Action Potentials Signal the Temporal Dynamics of Stimuli 396
- The Receptive Fields of Sensory Neurons Provide Spatial Information About Stimulus Location 397

Central Nervous System Circuits Refine Sensory Information 398

- The Receptor Surface Is Represented Topographically in the Early Stages of Each Sensory System 400

Sensory Information Is Processed in Parallel Pathways in the Cerebral Cortex 402

Feedback Pathways From the Brain Regulate Sensory Coding Mechanisms 403

Top-Down Learning Mechanisms Influence Sensory Processing 404

Highlights 405

Selected Reading 406

References 406

18 Receptors of the Somatosensory System 408

Esther P. Gardner

Dorsal Root Ganglion Neurons Are the Primary Sensory Receptor Cells of the Somatosensory System 409

Peripheral Somatosensory Nerve Fibers Conduct Action Potentials at Different Rates 410

A Variety of Specialized Receptors Are Employed by the Somatosensory System 414

Mechanoreceptors Mediate Touch and Proprioception 414

Specialized End Organs Contribute to Mechanosensation 416

Proprioceptors Measure Muscle Activity and Joint Positions 421

Thermal Receptors Detect Changes in Skin Temperature 422

Nociceptors Mediate Pain 424

Itch Is a Distinctive Cutaneous Sensation 425

Visceral Sensations Represent the Status of Internal Organs 426

Action Potential Codes Transmit Somatosensory Information to the Brain 426

Sensory Ganglia Provide a Snapshot of Population Responses to Somatic Stimuli 427

Somatosensory Information Enters the Central Nervous System Via Spinal or Cranial Nerves 427

Highlights 432

Selected Reading 433

References 433

19 Touch 435

Esther P. Gardner

Active and Passive Touch Have Distinct Goals 436

The Hand Has Four Types of Mechanoreceptors 437

A Cell's Receptive Field Defines Its Zone of Tactile Sensitivity	438
Two-Point Discrimination Tests Measure Tactile Acuity	439
Slowly Adapting Fibers Detect Object Pressure and Form	444
Rapidly Adapting Fibers Detect Motion and Vibration	446
Both Slowly and Rapidly Adapting Fibers Are Important for Grip Control	446
Tactile Information Is Processed in the Central Touch System	450
Spinal, Brain Stem, and Thalamic Circuits Segregate Touch and Proprioception	450
The Somatosensory Cortex Is Organized Into Functionally Specialized Columns	452
Cortical Columns Are Organized Somatotopically	454
The Receptive Fields of Cortical Neurons Integrate Information From Neighboring Receptors	457
Touch Information Becomes Increasingly Abstract in Successive Central Synapses	460
Cognitive Touch Is Mediated by Neurons in the Secondary Somatosensory Cortex	460
Active Touch Engages Sensorimotor Circuits in the Posterior Parietal Cortex	463
Lesions in Somatosensory Areas of the Brain Produce Specific Tactile Deficits	464
Highlights	466
Selected Reading	467
References	467
20 Pain	470
Allan I. Basbaum	
Noxious Insults Activate Thermal, Mechanical, and Polymodal Nociceptors	471
Signals From Nociceptors Are Conveyed to Neurons in the Dorsal Horn of the Spinal Cord	474
Hyperalgesia Has Both Peripheral and Central Origins	476
Four Major Ascending Pathways Convey Nociceptive Information From the Spinal Cord to the Brain	484
Several Thalamic Nuclei Relay Nociceptive Information to the Cerebral Cortex	484
The Perception of Pain Arises From and Can Be Controlled by Cortical Mechanisms	485
Anterior Cingulate and Insular Cortex Are Associated With the Perception of Pain	485
Pain Perception Is Regulated by a Balance of Activity in Nociceptive and Nonnociceptive Afferent Fibers	488
Electrical Stimulation of the Brain Produces Analgesia	488
Opioid Peptides Contribute to Endogenous Pain Control	489
Endogenous Opioid Peptides and Their Receptors Are Distributed in Pain-Modulatory Systems	489
Morphine Controls Pain by Activating Opioid Receptors	490
Tolerance to and Dependence on Opioids Are Distinct Phenomena	493
Highlights	493
Selected Reading	494
References	494
21 The Constructive Nature of Visual Processing	496
Charles D. Gilbert, Aniruddha Das	
Visual Perception Is a Constructive Process	496
Visual Processing Is Mediated by the Geniculostriate Pathway	499
Form, Color, Motion, and Depth Are Processed in Discrete Areas of the Cerebral Cortex	502
The Receptive Fields of Neurons at Successive Relays in the Visual Pathway Provide Clues to How the Brain Analyzes Visual Form	506
The Visual Cortex Is Organized Into Columns of Specialized Neurons	508
Intrinsic Cortical Circuits Transform Neural Information	512
Visual Information Is Represented by a Variety of Neural Codes	517
Highlights	518
Selected Reading	519
References	519
22 Low-Level Visual Processing: The Retina	521
Markus Meister, Marc Tessier-Lavigne	
The Photoreceptor Layer Samples the Visual Image	522
Ocular Optics Limit the Quality of the Retinal Image	522
There Are Two Types of Photoreceptors: Rods and Cones	524

Phototransduction Links the Absorption of a Photon to a Change in Membrane Conductance 526

- Light Activates Pigment Molecules in the Photoreceptors 528
- Excited Rhodopsin Activates a Phosphodiesterase Through the G Protein Transducin 529
- Multiple Mechanisms Shut Off the Cascade 530
- Defects in Phototransduction Cause Disease 530

Ganglion Cells Transmit Neural Images to the Brain 530

- The Two Major Types of Ganglion Cells Are ON Cells and OFF Cells 530
- Many Ganglion Cells Respond Strongly to Edges in the Image 531
- The Output of Ganglion Cells Emphasizes Temporal Changes in Stimuli 531
- Retinal Output Emphasizes Moving Objects 531
- Several Ganglion Cell Types Project to the Brain Through Parallel Pathways 531

A Network of Interneurons Shapes the Retinal Output 536

- Parallel Pathways Originate in Bipolar Cells 536
- Spatial Filtering Is Accomplished by Lateral Inhibition 536
- Temporal Filtering Occurs in Synapses and Feedback Circuits 537
- Color Vision Begins in Cone-Selective Circuits 538
- Congenital Color Blindness Takes Several Forms 538
- Rod and Cone Circuits Merge in the Inner Retina 540

The Retina's Sensitivity Adapts to Changes in Illumination 540

- Light Adaptation Is Apparent in Retinal Processing and Visual Perception 540
- Multiple Gain Controls Occur Within the Retina 541
- Light Adaptation Alters Spatial Processing 543

Highlights 543

Selected Reading 543

References 544

23 Intermediate-Level Visual Processing and Visual Primitives..... 545

Charles D. Gilbert

Internal Models of Object Geometry Help the Brain Analyze Shapes 547

Depth Perception Helps Segregate Objects From Background 550

Local Movement Cues Define Object Trajectory and Shape 554

Context Determines the Perception of Visual Stimuli 555

- Brightness and Color Perception Depend on Context 555
- Receptive-Field Properties Depend on Context 558

Cortical Connections, Functional Architecture, and Perception Are Intimately Related 558

- Perceptual Learning Requires Plasticity in Cortical Connections 559
- Visual Search Relies on the Cortical Representation of Visual Attributes and Shapes 559
- Cognitive Processes Influence Visual Perception 560

Highlights 562

Selected Reading 563

References 563

24 High-Level Visual Processing: From Vision to Cognition 564

Thomas D. Albright, Winrich A. Freiwald

High-Level Visual Processing Is Concerned With Object Recognition 564

The Inferior Temporal Cortex Is the Primary Center for Object Recognition 565

- Clinical Evidence Identifies the Inferior Temporal Cortex as Essential for Object Recognition 566
- Neurons in the Inferior Temporal Cortex Encode Complex Visual Stimuli and Are Organized in Functionally Specialized Columns 568
- The Primate Brain Contains Dedicated Systems for Face Processing 569
- The Inferior Temporal Cortex Is Part of a Network of Cortical Areas Involved in Object Recognition 570

Object Recognition Relies on Perceptual Constancy 571

Categorical Perception of Objects Simplifies Behavior 572

Visual Memory Is a Component of High-Level Visual Processing 573

- Implicit Visual Learning Leads to Changes in the Selectivity of Neuronal Responses 573
- The Visual System Interacts With Working Memory and Long-Term Memory Systems 573

Associative Recall of Visual Memories Depends on Top-Down Activation of the Cortical Neurons That Process Visual Stimuli 578

Highlights 579

Selected Reading 580

References 580

25 Visual Processing for Attention and Action 582

Michael E. Goldberg, Robert H. Wurtz

The Brain Compensates for Eye Movements to Create a Stable Representation of the Visual World 582

Motor Commands for Saccades Are Copied to the Visual System 582

Oculomotor Proprioception Can Contribute to Spatially Accurate Perception and Behavior 587

Visual Scrutiny Is Driven by Attention and Arousal Circuits 588

The Parietal Cortex Provides Visual Information to the Motor System 592

Highlights 595

Selected Reading 596

References 596

26 Auditory Processing by the Cochlea 598

Pascal Martin, Geoffrey A. Manley

The Ear Has Three Functional Parts 599

Hearing Commences With the Capture of Sound Energy by the Ear 600

The Hydrodynamic and Mechanical Apparatus of the Cochlea Delivers Mechanical Stimuli to the Receptor Cells 603

The Basilar Membrane Is a Mechanical Analyzer of Sound Frequency 603

The Organ of Corti Is the Site of Mechano-electrical Transduction in the Cochlea 604

Hair Cells Transform Mechanical Energy Into Neural Signals 606

Deflection of the Hair Bundle Initiates Mechano-electrical Transduction 606

Mechanical Force Directly Opens Transduction Channels 609

Direct Mechano-electrical Transduction Is Rapid 610

Deafness Genes Provide Components of the Mechanotransduction Machinery 611

Dynamic Feedback Mechanisms Determine the Sensitivity of the Hair Cells 613

Hair Cells Are Tuned to Specific Stimulus Frequencies 613

Hair Cells Adapt to Sustained Stimulation 614

Sound Energy Is Mechanically Amplified in the Cochlea 616

Cochlear Amplification Distorts Acoustic Inputs 618

The Hopf Bifurcation Provides a General Principle for Sound Detection 618

Hair Cells Use Specialized Ribbon Synapses 618

Auditory Information Flows Initially Through the Cochlear Nerve 621

Bipolar Neurons in the Spiral Ganglion Innervate Cochlear Hair Cells 621

Cochlear Nerve Fibers Encode Stimulus Frequency and Level 622

Sensorineural Hearing Loss Is Common but Is Amenable to Treatment 624

Highlights 626

Selected Reading 626

References 627

27 The Vestibular System 629

J. David Dickman, Dora Angelaki

The Vestibular Labyrinth in the Inner Ear Contains Five Receptor Organs 631

Hair Cells Transduce Acceleration Stimuli Into Receptor Potentials 631

The Semicircular Canals Sense Head Rotation 632

The Otolith Organs Sense Linear Accelerations 634

Central Vestibular Nuclei Integrate Vestibular, Visual, Proprioceptive, and Motor Signals 636

The Vestibular Commissural System Communicates Bilateral Information 636

Combined Semicircular Canal and Otolith Signals Improve Inertial Sensing and Decrease Ambiguity of Translation Versus Tilt 638

Vestibular Signals Are a Critical Component of Head Movement Control 639

Vestibulo-Ocular Reflexes Stabilize the Eyes When the Head Moves 639

The Rotational Vestibulo-Ocular Reflex Compensates for Head Rotation 640

The Translational Vestibulo-Ocular Reflex Compensates for Linear Motion and Head Tilts 642

Vestibulo-Ocular Reflexes Are Supplemented by Optokinetic Responses 643

The Cerebellum Adjusts the Vestibulo-Ocular Reflex 643

The Thalamus and Cortex Use Vestibular Signals for Spatial Memory and Cognitive and Perceptual Functions 645

Vestibular Information Is Present in the Thalamus 645

Vestibular Information Is Widespread in the Cortex 645

Vestibular Signals Are Essential for Spatial Orientation and Spatial Navigation 646

Clinical Syndromes Elucidate Normal Vestibular Function 647

Caloric Irrigation as a Vestibular Diagnostic Tool 647

Bilateral Vestibular Hypofunction Interferes With Normal Vision 647

Highlights 648

Selected Reading 649

References 649

28 Auditory Processing by the Central Nervous System. 651

Donata Oertel, Xiaoqin Wang

Sounds Convey Multiple Types of Information to Hearing Animals 652

The Neural Representation of Sound in Central Pathways Begins in the Cochlear Nuclei 652

The Cochlear Nerve Delivers Acoustic Information in Parallel Pathways to the Tonotopically Organized Cochlear Nuclei 655

The Ventral Cochlear Nucleus Extracts Temporal and Spectral Information About Sounds 655

The Dorsal Cochlear Nucleus Integrates Acoustic With Somatosensory Information in Making Use of Spectral Cues for Localizing Sounds 656

The Superior Olivary Complex in Mammals Contains Separate Circuits for Detecting Interaural Time and Intensity Differences 657

The Medial Superior Olive Generates a Map of Interaural Time Differences 657

The Lateral Superior Olive Detects Interaural Intensity Differences 659

The Superior Olivary Complex Provides Feedback to the Cochlea 662

Ventral and Dorsal Nuclei of the Lateral Lemniscus Shape Responses in the Inferior Colliculus With Inhibition 663

Afferent Auditory Pathways Converge in the Inferior Colliculus 664

Sound Location Information From the Inferior Colliculus Creates a Spatial Map of Sound in the Superior Colliculus 665

The Inferior Colliculus Transmits Auditory Information to the Cerebral Cortex 665

Stimulus Selectivity Progressively Increases Along the Ascending Pathway 665

The Auditory Cortex Maps Numerous Aspects of Sound 668

A Second Sound-Localization Pathway From the Inferior Colliculus Involves the Cerebral Cortex in Gaze Control 669

Auditory Circuits in the Cerebral Cortex Are Segregated Into Separate Processing Streams 670

The Cerebral Cortex Modulates Sensory Processing in Subcortical Auditory Areas 670

The Cerebral Cortex Forms Complex Sound Representations 671

The Auditory Cortex Uses Temporal and Rate Codes to Represent Time-Varying Sounds 671

Primates Have Specialized Cortical Neurons That Encode Pitch and Harmonics 673

Insectivorous Bats Have Cortical Areas Specialized for Behaviorally Relevant Features of Sound 675

The Auditory Cortex Is Involved in Processing Vocal Feedback During Speaking 677

Highlights 679

Selected Reading 680

References 680

29 Smell and Taste: The Chemical Senses 682

Linda Buck, Kristin Scott, Charles Zuker

A Large Family of Olfactory Receptors Initiate the Sense of Smell 683

Mammals Share a Large Family of Odorant Receptors 684

Different Combinations of Receptors Encode Different Odorants 685

Olfactory Information Is Transformed Along the Pathway to the Brain 686

Odorants Are Encoded in the Nose by Dispersed Neurons 686

Sensory Inputs in the Olfactory Bulb Are Arranged by Receptor Type 687

The Olfactory Bulb Transmits Information to the Olfactory Cortex	688
Output From the Olfactory Cortex Reaches Higher Cortical and Limbic Areas	690
Olfactory Acuity Varies in Humans	691
Odors Elicit Characteristic Innate Behaviors	691
Pheromones Are Detected in Two Olfactory Structures	691
Invertebrate Olfactory Systems Can Be Used to Study Odor Coding and Behavior	691
Olfactory Cues Elicit Stereotyped Behaviors and Physiological Responses in the Nematode	694
Strategies for Olfaction Have Evolved Rapidly	695
The Gustatory System Controls the Sense of Taste	696
Taste Has Five Submodalities That Reflect Essential Dietary Requirements	696
Tastant Detection Occurs in Taste Buds	696
Each Taste Modality Is Detected by Distinct Sensory Receptors and Cells	698
Gustatory Information Is Relayed From the Periphery to the Gustatory Cortex	702
Perception of Flavor Depends on Gustatory, Olfactory, and Somatosensory Inputs	702
Insects Have Modality-Specific Taste Cells That Drive Innate Behaviors	702
Highlights	703
Selected Reading	704
References	705
Part V	
Movement	
<hr/>	
30 Principles of Sensorimotor Control	713
Daniel M. Wolpert, Amy J. Bastian	
The Control of Movement Poses Challenges for the Nervous System	714
Actions Can Be Controlled Voluntarily, Rhythmically, or Reflexively	715
Motor Commands Arise Through a Hierarchy of Sensorimotor Processes	715
Motor Signals Are Subject to Feedforward and Feedback Control	716
Feedforward Control Is Required for Rapid Movements	716
Feedback Control Uses Sensory Signals to Correct Movements	719
Estimation of the Body's Current State Relies on Sensory and Motor Signals	719
Prediction Can Compensate for Sensorimotor Delays	723
Sensory Processing Can Differ for Action and Perception	724
Motor Plans Translate Tasks Into Purposeful Movement	725
Stereotypical Patterns Are Employed in Many Movements	725
Motor Planning Can Be Optimal at Reducing Costs	726
Optimal Feedback Control Corrects for Errors in a Task-Dependent Manner	728
Multiple Processes Contribute to Motor Learning	729
Error-Based Learning Involves Adapting Internal Sensorimotor Models	730
Skill Learning Relies on Multiple Processes for Success	732
Sensorimotor Representations Constrain Learning	734
Highlights	735
Selected Reading	735
References	735
31 The Motor Unit and Muscle Action	737
Roger M. Enoka	
The Motor Unit Is the Elementary Unit of Motor Control	737
A Motor Unit Consists of a Motor Neuron and Multiple Muscle Fibers	737
The Properties of Motor Units Vary	739
Physical Activity Can Alter Motor Unit Properties	742
Muscle Force Is Controlled by the Recruitment and Discharge Rate of Motor Units	742
The Input–Output Properties of Motor Neurons Are Modified by Input From the Brain Stem	745
Muscle Force Depends on the Structure of Muscle	745
The Sarcomere Is the Basic Organizational Unit of Contractile Proteins	745

Noncontractile Elements Provide Essential Structural Support 747

Contractile Force Depends on Muscle Fiber Activation, Length, and Velocity 747

Muscle Torque Depends on Musculoskeletal Geometry 750

Different Movements Require Different Activation Strategies 754

Contraction Velocity Can Vary in Magnitude and Direction 754

Movements Involve the Coordination of Many Muscles 755

Muscle Work Depends on the Pattern of Activation 758

Highlights 758

Selected Reading 759

References 759

32 Sensory-Motor Integration in the Spinal Cord 761

Jens Bo Nielsen, Thomas M. Jessell

Reflex Pathways in the Spinal Cord Produce Coordinated Patterns of Muscle Contraction 762

The Stretch Reflex Acts to Resist the Lengthening of a Muscle 762

Neuronal Networks in the Spinal Cord Contribute to the Coordination of Reflex Responses 762

The Stretch Reflex Involves a Monosynaptic Pathway 762

Gamma Motor Neurons Adjust the Sensitivity of Muscle Spindles 766

The Stretch Reflex Also Involves Polysynaptic Pathways 767

Golgi Tendon Organs Provide Force-Sensitive Feedback to the Spinal Cord 769

Cutaneous Reflexes Produce Complex Movements That Serve Protective and Postural Functions 770

Convergence of Sensory Inputs on Interneurons Increases the Flexibility of Reflex Contributions to Movement 772

Sensory Feedback and Descending Motor Commands Interact at Common Spinal Neurons to Produce Voluntary Movements 773

Muscle Spindle Sensory Afferent Activity Reinforces Central Commands for Movements Through the Ia Monosynaptic Reflex Pathway 773

Modulation of Ia inhibitory Interneurons and Renshaw Cells by Descending Inputs Coordinate Muscle Activity at Joints 775

Transmission in Reflex Pathways May Be Facilitated or Inhibited by Descending Motor Commands 776

Descending Inputs Modulate Sensory Input to the Spinal Cord by Changing the Synaptic Efficiency of Primary Sensory Fibers 777

Part of the Descending Command for Voluntary Movements Is Conveyed Through Spinal Interneurons 778

Propriospinal Neurons in the C3–C4 Segments Mediate Part of the Corticospinal Command for Movement of the Upper Limb 778

Neurons in Spinal Reflex Pathways Are Activated Prior to Movement 779

Proprioceptive Reflexes Play an Important Role in Regulating Both Voluntary and Automatic Movements 779

Spinal Reflex Pathways Undergo Long-Term Changes 779

Damage to the Central Nervous System Produces Characteristic Alterations in Reflex Responses 780

Interruption of Descending Pathways to the Spinal Cord Frequently Produces Spasticity 780

Lesion of the Spinal Cord in Humans Leads to a Period of Spinal Shock Followed by Hyperreflexia 780

Highlights 781

Selected Reading 781

References 781

33 Locomotion 783

Trevor Drew, Ole Kiehn

Locomotion Requires the Production of a Precise and Coordinated Pattern of Muscle Activation 786

The Motor Pattern of Stepping Is Organized at the Spinal Level 790

The Spinal Circuits Responsible for Locomotion Can Be Modified by Experience 792

Spinal Locomotor Networks Are Organized Into Rhythm- and Pattern-Generation Circuits 792

Somatosensory Inputs From Moving Limbs Modulate Locomotion 795

Proprioception Regulates the Timing and Amplitude of Stepping 795

Mechanoreceptors in the Skin Allow Stepping to Adjust to Unexpected Obstacles 798

Supraspinal Structures Are Responsible for Initiation and Adaptive Control of Stepping 799

Midbrain Nuclei Initiate and Maintain Locomotion and Control Speed 800

Midbrain Nuclei That Initiate Locomotion Project to Brain Stem Neurons 800

The Brain Stem Nuclei Regulate Posture During Locomotion 802

Visually Guided Locomotion Involves the Motor Cortex 804

Planning of Locomotion Involves the Posterior Parietal Cortex 806

The Cerebellum Regulates the Timing and Intensity of Descending Signals 806

The Basal Ganglia Modify Cortical and Brain Stem Circuits 807

Computational Neuroscience Provides Insights Into Locomotor Circuits 809

Neuronal Control of Human Locomotion Is Similar to That of Quadrupeds 809

Highlights 811

Suggested Reading 812

References 812

34 Voluntary Movement: Motor Cortices 815

Stephen H. Scott, John F. Kalaska

Voluntary Movement Is the Physical Manifestation of an Intention to Act 816

Theoretical Frameworks Help Interpret Behavior and the Neural Basis of Voluntary Control 816

Many Frontal and Parietal Cortical Regions Are Involved in Voluntary Control 818

Descending Motor Commands Are Principally Transmitted by the Corticospinal Tract 819

Imposing a Delay Period Before the Onset of Movement Isolates the Neural Activity Associated With Planning From That Associated With Executing the Action 821

Parietal Cortex Provides Information About the World and the Body for State Estimation to Plan and Execute Motor Actions 823

The Parietal Cortex Links Sensory Information to Motor Actions 824

Body Position and Motion Are Represented in Several Areas of Posterior Parietal Cortex 824

Spatial Goals Are Represented in Several Areas of Posterior Parietal Cortex 825

Internally Generated Feedback May Influence Parietal Cortex Activity 827

Premotor Cortex Supports Motor Selection and Planning 828

Medial Premotor Cortex Is Involved in the Contextual Control of Voluntary Actions 829

Dorsal Premotor Cortex Is Involved in Planning Sensory-Guided Movement of the Arm 831

Dorsal Premotor Cortex Is Involved in Applying Rules (Associations) That Govern Behavior 833

Ventral Premotor Cortex Is Involved in Planning Motor Actions of the Hand 835

Premotor Cortex May Contribute to Perceptual Decisions That Guide Motor Actions 835

Several Cortical Motor Areas Are Active When the Motor Actions of Others Are Being Observed 837

Many Aspects of Voluntary Control Are Distributed Across Parietal and Premotor Cortex 840

The Primary Motor Cortex Plays an Important Role in Motor Execution 841

The Primary Motor Cortex Includes a Detailed Map of the Motor Periphery 841

Some Neurons in the Primary Motor Cortex Project Directly to Spinal Motor Neurons 841

Activity in the Primary Motor Cortex Reflects Many Spatial and Temporal Features of Motor Output 844

Primary Motor Cortical Activity Also Reflects Higher-Order Features of Movement 851

Sensory Feedback Is Transmitted Rapidly to the Primary Motor Cortex and Other Cortical Regions 852

The Primary Motor Cortex Is Dynamic and Adaptable 852

Highlights 856

Selected Reading 858

References 858

35 The Control of Gaze 860

Michael E. Goldberg, Mark F. Walker

The Eye Is Moved by the Six Extraocular Muscles 860

Eye Movements Rotate the Eye in the Orbit 860

The Six Extraocular Muscles Form Three Agonist–Antagonist Pairs 862

Movements of the Two Eyes Are Coordinated 862

The Extraocular Muscles Are Controlled by Three Cranial Nerves 862

Six Neuronal Control Systems Keep the Eyes on Target 866

An Active Fixation System Holds the Fovea on a Stationary Target 866

The Saccadic System Points the Fovea Toward Objects of Interest 866

The Motor Circuits for Saccades Lie in the Brain Stem 868

Horizontal Saccades Are Generated in the Pontine Reticular Formation 868

Vertical Saccades Are Generated in the Mesencephalic Reticular Formation 870

Brain Stem Lesions Result in Characteristic Deficits in Eye Movements 870

Saccades Are Controlled by the Cerebral Cortex Through the Superior Colliculus 871

The Superior Colliculus Integrates Visual and Motor Information into Oculomotor Signals for the Brain Stem 871

The Rostral Superior Colliculus Facilitates Visual Fixation 873

The Basal Ganglia and Two Regions of Cerebral Cortex Control the Superior Colliculus 873

The Control of Saccades Can Be Modified by Experience 877

Some Rapid Gaze Shifts Require Coordinated Head and Eye Movements 877

The Smooth-Pursuit System Keeps Moving Targets on the Fovea 878

The Vergence System Aligns the Eyes to Look at Targets at Different Depths 879

Highlights 880

Selected Reading 881

References 881

36 Posture..... 883

Fay B. Horak, Gammon M. Earhart

Equilibrium and Orientation Underlie Posture Control 884

Postural Equilibrium Controls the Body's Center of Mass 884

Postural Orientation Anticipates Disturbances to Balance 886

Postural Responses and Anticipatory Postural Adjustments Use Stereotyped Strategies and Synergies 886

Automatic Postural Responses Compensate for Sudden Disturbances 887

Anticipatory Postural Adjustments Compensate for Voluntary Movement 892

Posture Control Is Integrated With Locomotion 894

Somatosensory, Vestibular, and Visual Information Must Be Integrated and Interpreted to Maintain Posture 894

Somatosensory Signals Are Important for Timing and Direction of Automatic Postural Responses 894

Vestibular Information Is Important for Balance on Unstable Surfaces and During Head Movements 895

Visual Inputs Provide the Postural System With Orientation and Motion Information 897

Information From a Single Sensory Modality Can Be Ambiguous 897

The Postural Control System Uses a Body Schema That Incorporates Internal Models for Balance 898

Control of Posture Is Task Dependent 900

Task Requirements Determine the Role of Each Sensory System in Postural Equilibrium and Orientation 900

Control of Posture Is Distributed in the Nervous System 900

Spinal Cord Circuits Are Sufficient for Maintaining Antigravity Support but Not Balance 900

The Brain Stem and Cerebellum Integrate Sensory Signals for Posture 901

The Spinocerebellum and Basal Ganglia Are Important in Adaptation of Posture 902

Cerebral Cortex Centers Contribute to Postural Control 905

Highlights 906

Suggested Reading 906

References 906

37 The Cerebellum..... 908

Amy J. Bastian, Stephen G. Lisberger

Damage of the Cerebellum Causes Distinctive Symptoms and Signs 909

Damage Results in Characteristic Abnormalities of Movement and Posture 909

Damage Affects Specific Sensory and Cognitive Abilities 909

The Cerebellum Indirectly Controls Movement Through Other Brain Structures 911

The Cerebellum Is a Large Subcortical Brain Structure 911

The Cerebellum Connects With the Cerebral Cortex Through Recurrent Loops 911

Different Movements Are Controlled by
Functional Longitudinal Zones 911

**The Cerebellar Cortex Comprises Repeating Functional
Units Having the Same
Basic Microcircuit 918**

The Cerebellar Cortex Is Organized Into Three
Functionally Specialized Layers 918

The Climbing-Fiber and Mossy-Fiber Afferent Systems
Encode and Process Information Differently 918

The Cerebellar Microcircuit Architecture
Suggests a Canonical Computation 920

**The Cerebellum Is Hypothesized to Perform Several
General Computational Functions 922**

The Cerebellum Contributes to Feedforward
Sensorimotor Control 922

The Cerebellum Incorporates an Internal Model of
the Motor Apparatus 922

The Cerebellum Integrates Sensory Inputs and Corollary
Discharge 923

The Cerebellum Contributes to Timing Control 923

**The Cerebellum Participates in Motor
Skill Learning 923**

Climbing-Fiber Activity Changes the Synaptic Efficacy
of Parallel Fibers 924

The Cerebellum Is Necessary for Motor Learning in
Several Different Movement Systems 925

Learning Occurs at Several Sites in the Cerebellum 928

Highlights 929

Selected Reading 929

References 930

38 The Basal Ganglia 932

Peter Redgrave, Rui M. Costa

**The Basal Ganglia Network Consists of Three Principal
Input Nuclei, Two Main Output Nuclei, and One Intrinsic
Nucleus 934**

The Striatum, Subthalamic Nucleus, and Substantia
Nigra Pars Compacta/Ventral Tegmental Area Are the
Three Principal Input Nuclei of the Basal Ganglia 934

The Substantia Nigra Pars Reticulata and the Internal
Globus Pallidus Are the Two Principal Output Nuclei of
the Basal Ganglia 935

The External Globus Pallidus Is Mostly an Intrinsic
Structure of the Basal Ganglia 935

**The Internal Circuitry of the Basal Ganglia Regulates
How the Components Interact 935**

The Traditional Model of the Basal Ganglia Emphasizes
Direct and Indirect Pathways 935

Detailed Anatomical Analyses Reveal a More Complex
Organization 936

**Basal Ganglia Connections With External Structures Are
Characterized by Reentrant Loops 937**

Inputs Define Functional Territories in the
Basal Ganglia 937

Output Neurons Project to the External
Structures That Provide Input 937

Reentrant Loops Are a Cardinal Principle
of Basal Ganglia Circuitry 937

**Physiological Signals Provide Further Clues
to Function in the Basal Ganglia 939**

The Striatum and Subthalamic Nucleus Receive Signals
Mainly from the Cerebral Cortex,
Thalamus, and Ventral Midbrain 939

Ventral Midbrain Dopamine Neurons Receive
Input From External Structures and Other
Basal Ganglia Nuclei 939

Disinhibition Is the Final Expression of Basal Ganglia
Output 940

**Throughout Vertebrate Evolution, the Basal Ganglia Have
Been Highly Conserved 940**

**Action Selection Is a Recurring Theme in Basal Ganglia
Research 941**

All Vertebrates Face the Challenge of Choosing
One Behavior From Several Competing
Options 941

Selection Is Required for Motivational, Affective,
Cognitive, and Sensorimotor Processing 941

The Neural Architecture of the Basal Ganglia Is
Configured to Make Selections 942

Intrinsic Mechanisms in the Basal Ganglia
Promote Selection 943

Selection Function of the Basal Ganglia
Questioned 943

**Reinforcement Learning Is an Inherent Property of a
Selection Architecture 944**

Intrinsic Reinforcement Is Mediated by Phasic
Dopamine Signaling Within the Basal
Ganglia Nuclei 944

Extrinsic Reinforcement Could Bias Selection by
Operating in Afferent Structures 946

**Behavioral Selection in the Basal Ganglia Is Under
Goal-Directed and Habitual Control 946**

**Diseases of the Basal Ganglia May Involve Disorders of
Selection 947**

- A Selection Mechanism Is Likely to Be Vulnerable to Several Potential Malfunctions 947
- Parkinson Disease Can Be Viewed in Part as a Failure to Select Sensorimotor Options 948
- Huntington Disease May Reflect a Functional Imbalance Between the Direct and Indirect Pathways 948
- Schizophrenia May Be Associated With a General Failure to Suppress Nonselected Options 948
- Attention Deficit Hyperactivity Disorder and Tourette Syndrome May Also Be Characterized by Intrusions of Nonselected Options 949
- Obsessive-Compulsive Disorder Reflects the Presence of Pathologically Dominant Options 949
- Addictions Are Associated With Disorders of Reinforcement Mechanisms and Habitual Goals 949

Highlights 950

Suggested Reading 951

References 951

39 Brain–Machine Interfaces 953

Krishna V. Shenoy, Byron M. Yu

BMIs Measure and Modulate Neural Activity to Help Restore Lost Capabilities 954

- Cochlear Implants and Retinal Prostheses Can Restore Lost Sensory Capabilities 954
- Motor and Communication BMIs Can Restore Lost Motor Capabilities 954
- Pathological Neural Activity Can Be Regulated by Deep Brain Stimulation and Antiseizure BMIs 956
- Replacement Part BMIs Can Restore Lost Brain Processing Capabilities 956
- Measuring and Modulating Neural Activity Rely on Advanced Neurotechnology 956

BMIs Leverage the Activity of Many Neurons to Decode Movements 958

- Decoding Algorithms Estimate Intended Movements From Neural Activity 960
- Discrete Decoders Estimate Movement Goals 961
- Continuous Decoders Estimate Moment-by-Moment Details of Movements 961

Increases in Performance and Capabilities of Motor and Communication BMIs Enable Clinical Translation 962

- Subjects Can Type Messages Using Communication BMIs 964
- Subjects Can Reach and Grasp Objects Using BMI-Directed Prosthetic Arms 965

- Subjects Can Reach and Grasp Objects Using BMI-Directed Stimulation of Paralyzed Arms 965

Subjects Can Use Sensory Feedback Delivered by Cortical Stimulation During BMI Control 967

BMIs Can Be Used to Advance Basic Neuroscience 968

BMIs Raise New Neuroethics Considerations 970

Highlights 971

Selected Reading 972

References 972

Part VI

The Biology of Emotion, Motivation, and Homeostasis

40 The Brain Stem 981

Clifford B. Saper, Joel K. Elmquist

The Cranial Nerves Are Homologous to the Spinal Nerves 982

- Cranial Nerves Mediate the Sensory and Motor Functions of the Face and Head and the Autonomic Functions of the Body 982

- Cranial Nerves Leave the Skull in Groups and Often Are Injured Together 985

The Organization of the Cranial Nerve Nuclei Follows the Same Basic Plan as the Sensory and Motor Areas of the Spinal Cord 986

- Embryonic Cranial Nerve Nuclei Have a Segmental Organization 987

- Adult Cranial Nerve Nuclei Have a Columnar Organization 987

- The Organization of the Brain Stem Differs From the Spinal Cord in Three Important Ways 992

Neuronal Ensembles in the Brain Stem Reticular Formation Coordinate Reflexes and Simple Behaviors Necessary for Homeostasis and Survival 992

- Cranial Nerve Reflexes Involve Mono- and Polysynaptic Brain Stem Relays 992

- Pattern Generators Coordinate More Complex Stereotypic Behaviors 994

- Control of Breathing Provides an Example of How Pattern Generators Are Integrated Into More Complex Behaviors 994

Monoaminergic Neurons in the Brain Stem Modulate Sensory, Motor, Autonomic, and Behavioral Functions 998