

Sensation & Perception

E. Bruce Goldstein • Fifth Edition



SENSATION AND PERCEPTION

FIFTH EDITION

E. BRUCE GOLDSTEIN

University of Pittsburgh



Brooks/Cole Publishing Company

ITP[®] An International Thomson Publishing Company

Pacific Grove • Albany • Belmont • Bonn • Boston • Cincinnati • Detroit • Johannesburg • London
Madrid • Melbourne • Mexico City • New York • Paris • Singapore • Tokyo • Toronto • Washington

Psychology Editor: *Marianne Taflinger*
Marketing Team: *Lauren Harp, Christine Davis*
Editorial Assistant: *Scott Brearton, Rachael Bruckman*
Production Coordinator: *Kirk Bomont*
Manuscript Editor: *Maryan Malone*
Permissions Editor: *Lillian Campobasso*
Cover Design: *Lisa Mirski Devenish, E. Kelly Shoemaker*

Interior Design: *Publications Development Company of Texas*
Interior Illustration: *Wayne Clark, Cyndie C. H. Wooley, Jon Clark*
Cover Image: *Damir Polić*
Art Editor: *Lisa Torri*
Typesetting: *Publications Development Company of Texas*
Printing and Binding: *R.R. Donnelley*

COPYRIGHT © 1999 by Brooks/Cole Publishing Company
A division of International Thomson Publishing Inc.

ITP The ITP logo is a registered trademark under license.

For more information, contact:

BROOKS/COLE PUBLISHING COMPANY
511 Forest Lodge Road
Pacific Grove, CA 93950
USA

International Thomson Publishing Europe
Berkshire House 168-173
High Holborn
London WC1V 7AA
England

Thomas Nelson Australia
102 Dodds Street
South Melbourne, 3205
Victoria, Australia

Nelson Canada
1120 Birchmount Road
Scarborough, Ontario
Canada M1K 5G4

International Thomson Editores
Seneca 53
Col. Polanco
11560 México, D. F., México

International Thomson Publishing GmbH
Königswinterer Strasse 418
53227 Bonn
Germany

International Thomson Publishing Asia
60 Albert Street
#15-10 Albert Complex
Singapore 189969

International Thomson Publishing Japan
Hirakawacho Kyowa Building, 3F
2-2-1 Hirakawacho
Chiyoda-ku, Tokyo 102
Japan

All rights reserved. No part of this work may be reproduced, stored in a retrieval system, or transcribed, in any form or by any means—electronic, mechanical, photocopying, recording, or otherwise—without the prior written permission of the publisher, Brooks/Cole Publishing Company, Pacific Grove, California 93950.

Printed in the United States of America

10 9 8 7 6 5 4

Library of Congress Cataloging-in-Publication Data

Goldstein, E. Bruce

Sensation and perception/E. Bruce Goldstein—5th ed.

p. cm.

Includes bibliographical references and index.

ISBN 0-534-34680-4 (alk. paper)

1. Senses and sensation. 2. Perception. I. Title

QP431.G64 1999

152.1—dc21

98-5846

CIP



PREFACE

When I was a graduate student at Brown University I studied chemical reactions that occur in the visual receptors. In my youthful enthusiasm, I thought that understanding these chemical reactions was the key to understanding perception. I was not totally wrong, because the chemical reactions that occur when molecules in the receptors absorb light are an essential first step in the perceptual process. However, as I continued my study of perception, I soon realized that the perceptual process extends far beyond molecules in the receptors, stretching into the visual cortex and—as research was just beginning to suggest at the time—even into cortical areas beyond the primary sensory receiving areas. I also became aware that perception cannot be understood by studying physiology alone. I learned that psychophysics—the study of the relationships between stimuli and perception—is central to our understanding of perception.

My appreciation for both the psychophysics and physiology of perception has been reflected in each edition of *Sensation and Perception*, beginning with the first edition, which was published in 1980. As I wrote the first edition and the revisions that followed, I have been motivated by a desire to tell the story of perceptual research in a way that transmits the excitement of this fascinating topic. In each successive edition, I have made changes to reflect new developments in the field and to respond to feedback I've received from instructors and students. In this, the fifth edition, I have made numerous changes in both content and presentation while keeping the characteristics that so many people have appreciated in the previous editions. The following summarizes some of

the features and changes in this fifth edition of *Sensation and Perception*.

Increased Clarity

One goal of this revision was to increase the clarity of the presentation. By listening to feedback from students and instructors who had used the fourth edition, and getting input from a student reviewer who flagged sections that were difficult, I was able to increase the readability of sections that students had found difficult in the last edition.

Cutting Edge Coverage

Another goal of this revision was to include new research. To this end, nearly 100 references to articles published in the last three years have been added. A few examples of cutting-edge topics that are new to this edition or are expanded from the last edition are the role of action in perception, the effects of brain damage on perception, modular processing of different perceptual qualities, the perception of ecologically valid stimuli, and the interplay between perception and attention.

“Bite-Sized” Chapters in a Logical Sequence

The chapters in this edition are shorter than in the fourth edition and the logical sequencing that has

been a feature of earlier editions has been refined. The first four chapters introduce the basic idea behind the study of perception and establish the basic physiological principles that are needed to understand the rest of the text. The next six chapters build on these basic principles and consider the following topics in visual perception: color vision (Chapter 5), the perceptual constancies (Chapter 6), object perception (Chapter 7), space perception (Chapter 8), size, illusions, and the ecological approach (Chapter 9), and movement perception (Chapter 10).

Chapters 6 and 9 are new, serving two purposes: (1) they introduce new material, and (2) they contain material that was in chapters that were too long in the fourth edition and so help to shorten these chapters. For example, material on color and lightness constancy that was originally in the color vision chapter is now in Chapter 6. Although there are a greater number of chapters, the book is shorter than before. Thus, the chapters in this edition are more “bite-sized,” and easier to digest.

Chapters 11 and 12, which cover basic mechanisms of hearing, represent a notable improvement in organization. The psychophysical and physiological approaches are no longer separated, as in previous editions, since these chapters are organized on the basis of perceptions rather than processes. Thus, Chapter 11 introduces the auditory system and focuses on pitch perception, and Chapter 12 focuses on auditory localization, loudness, and other auditory qualities.

The chapters on speech (Chapter 13), the cutaneous senses (Chapter 14), the chemical senses (Chapter 15), and clinical aspects of vision and hearing (Chapter 17) are updated versions of the corresponding chapters in the fourth edition, but the chapter on perceptual development (Chapter 16) is new. This chapter gathers together and integrates material from the *Developmental Dimensions* sections that appeared at the end of each chapter in the fourth edition. The result is a more coherent overview of perceptual development than was provided by the more piecemeal treatment in the previous edition.

Finally, the *Other Worlds of Perception* feature that appeared at the end of each chapter in the fourth

edition has been eliminated as a separate section, but much of the material from these sections, which described how animals perceive, has been integrated into the text.

Underlying Principles and Commonalties Across the Senses

Short sections called *Underlying Principles* that appear after Chapters 4, 10, and 16 emphasize that although each of the senses has its own unique qualities, there are basic principles that cut across all of the senses. The first section introduces eight principles based on the material in Chapters 1–4. The second section applies these principles to the material in Chapters 5–10 and adds three more principles. The third section applies all of the principles to the material in Chapters 11–16.

The idea that there are basic principles that hold across the senses is reinforced by a one-page section called *Across the Senses* that appears at the end of each chapter and which describes similar phenomena that occur across two or more senses. The topics in these sections are listed on page xviii.

Demonstrations

The *Demonstrations* have been a popular feature of previous editions, because they provide perceptual experiences that illustrate principles discussed in the text. The demonstrations are simple enough that students can easily do them and are integrated into the flow of the text so that they become part of the ongoing story. The demonstrations are listed on page xvii.

Thinking about the Material

A section called *Something to Consider* that appears at the end of each chapter discusses an especially important concept or a controversial issue, giving the student something open-ended to think about.

The Illustration Program

The extensive illustration program for which this text is known has been continued in this edition. There are over 600 diagrams, drawings, graphs, and photographs in this edition, with over 150 of these illustrations being new to this edition. Old illustrations were pruned and new ones added to reflect advances in research since the last edition.

Color Essays

As in the fourth edition, the color illustrations are contained in three short “color essays,” which stand on their own but also illustrate phenomena described elsewhere in the text.

Study Questions

At the end of each chapter are study questions keyed to pages in the text. Beginning in Chapter 5, each set of questions begins with a special section designed to help students identify the “Underlying Principles” discussed in the chapter.

Glossary

As in the previous edition, all of the definitions of bold-faced terms are contained in a single glossary at the end of the book.

Help for the Instructor

A set of transparencies of some of the text’s illustrations and a test bank are available to instructors. The instructor’s manual contains a test bank and other material to help in teaching the course, including a chapter-by-chapter list correlating the interactions in the *Exploring Perception* CD-ROM (see below) with the book. The test bank, which is also available in

computerized form, includes over 600 questions, many of which were “class tested.”

Help for the Student

For the first time, a student’s study guide is now available. This study guide supplements the study questions that are included in the book, with chapter outlines, expanded discussion of key terms and concepts, and practice test questions.

Web Site Links

A way to supplement the material in this book is to check perception-related sites on the World Wide Web. To find these sites, access the Brooks/Cole homepage at www.brookscole.com.

Exploring Perception CD-ROM

Exploring Perception, a CD-ROM for Macintosh and IBM Windows, is an exciting new ancillary available from Brooks/Cole. This interactive CD-ROM, which was developed by Colin Ryan of James Cook University, North Queensland, Australia, gives students an opportunity to actively explore many of the concepts described in the text, including psychophysics, physiological principles, and perception of color, form, motion, and depth. In addition, instructors can use *Exploring Perception* to demonstrate key principles in class by using the “organizer” function, which allows them to sequence material in the CD to fit their lecture. For further information about *Exploring Perception*, instructors can contact their local Brooks/Cole representative or inquire via e-mail to info@brookscole.com.

A Message to the Student

Although much of this preface has been directed to instructors, I want to close by addressing a few words to the students who will be using this book. As you read

this book, you will see that it is a story about experiences that may initially seem simple, such as seeing a face or smelling a rose, but that turn out to be extremely complex. I hope that reading this book helps you appreciate both the complexity and the beauty of the mechanisms responsible for these experiences. I hope that as you gain an appreciation for the impressive advances that researchers have made toward understanding perception, you will also appreciate how much is still left to be discovered. But most important of all, I hope that reading this book will make you more aware of how perception affects you personally.

After all, perception is something you experience all the time, and the study of perception can enhance this experience. I've found that studying perception has made me more observant of my environment, and more appreciative of the miraculous processes that transform energy falling on receptors into the richness of experience. I hope reading this book has the same effect on you. If you have questions, comments, or other feedback about this book, I invite you to communicate with me via e-mail at bruceg+@pitt.edu.

E. Bruce Goldstein

ACKNOWLEDGMENTS

Although I have been writing textbooks for more than two decades, I am still impressed by the extent to which creating a textbook is a group effort. One person who has played an indispensable role in creation of this book is Marianne Taflinger, my editor, who I thank for pushing me to write this revision even though I initially resisted. Marianne also supported my efforts by obtaining excellent reviews, making valuable suggestions regarding ways to improve the book, and approving the creation of many new illustrations for this edition.

My special thanks go to Nancy Marcus Land and all of the people at Publications Development Company in Crockett, Texas, who, with grace, creativity and extreme professionalism, turned my manuscript into this book. I thank Pam Blackmon at PDC for coordinating all parts of the production, and Kirk Bomont, who handled production liaison at Brooks/Cole, for his continued support.

I also wish to thank Lisa Torri, who again was a joy to work with on the art program, Kelly Shoemaker for her work toward creation of the cover design, Christine Davis for creating the brochure extolling the book's merits, and Jennifer Wilkinson for being patient with me as I worked on the study guide and instructor's manual. In addition, I thank my friends in Pittsburgh, who have finally become used to the fact that I am always writing "the book," and I especially thank my wife, Barbara, who has persevered with love and understanding through numerous book projects.

Thanks also to the following people who kindly provided new photographs for this edition: Velma Dobson, Kerry Green, Kelly Kaye, David Pisoni, Edmund Rolls, and Daniel Simons. Finally, I thank the following reviewers and colleagues who provided

valuable feedback about the fourth edition and the manuscript for this edition:

Frank M. Bagrash
California State University, Fullerton

William P. Banks
Pomona College

Michael Biderman
University of Tennessee-Chattanooga

Bruce Bridgeman
University of California, Santa Cruz

Patrick Cavanagh
Harvard University

James C. Craig
Indiana University

W. Jay Dowling
University of Texas at Dallas

Susan E. Dutch
Westfield State College

Bradley Gibson
University of Notre Dame

Norma Graham
Columbia University

Donald Greenfield
Eye Institute of New Jersey

Timothy S. Klitz
University of Minnesota-Twin Cities

Harry Lawless
Cornell University

W. Trammell Neill
SUNY-Albany

Catherine Palmer
University of Pittsburgh

David B. Pisoni
Indiana University

Dennis Proffitt
University of Virginia

Lawrence D. Rosenblum
University of California at Riverside

Colin Ryan
James Cook University

H. A. Sedgwick
State University of New York

Kenneth R. Short
Creighton University

Steven M. Specht
Lebanon Valley College

Leslie Tolbert
University of Arizona

Robert G. Vautin
Wheaton College

William Yost
Loyola University of Chicago

CONTENTS

1

INTRODUCTION TO PERCEPTION

The Perceptual Process	2
<i>Distal Stimulus</i>	2
<i>Proximal Stimulus</i>	3
<i>Transduction</i>	3
<i>Neural Processing</i>	3
<i>Perception</i>	4
<i>Recognition</i>	4
<i>Action</i>	5
Studying the Perceptual Process	6
The Behavioral Approach: Linking Stimulation and Perception	7
<i>The Phenomenological Method: Describing What Is Perceived</i>	7
<i>The Classical Psychophysical Methods: Measuring Thresholds</i>	8
<i>Magnitude Estimation: Measuring Magnitude above Threshold</i>	12
The Physiological Approach: Linking Stimulation and Neural Firing	13
<i>The Physiological Approach: Early History</i>	13
<i>Neurons and Electrical Signals</i>	14
<i>Recording Electrical Signals in Neurons</i>	15
<i>Basic Properties of Action Potentials</i>	17
<i>Chemical and Electrical Events at the Synapse</i>	19
<i>Basic Structure of the Brain</i>	19

The Approach in This Book	21
<i>Achieving a Balance between Behavior and Physiology</i>	21
<i>Answering Questions and Learning to Ask Them</i>	22
<i>Filling in the Details and Learning Basic Principles</i>	22
Why Do We Study Perception?	23
Something to Consider: The Complexity of Perception	25
Study Questions	27

2

RECEPTORS AND NEURAL PROCESSING

Introducing the Visual System: Transforming Objects into Electricity	29
<i>The Visual Stimulus: Visible Light Structured by the World</i>	30
<i>Overall Structure of the Visual System</i>	31
<i>Is the Eye Like a Camera?</i>	33
<i>Adjusting Focus by Changing the Shape of the Lens</i>	35
<i>The Rod and Cone Receptors: Shape and Distribution</i>	36
<i>The Rod and Cone Receptors: Transducing Light into Electricity</i>	39
Duplicity Theory: Different Receptors for Different Perceptions	42
<i>Dark Adaptation of the Rods and Cones</i>	42
<i>Spectral Sensitivity of the Rods and Cones</i>	46

Neural Processing: Analysis and Transformation of Electrical Signals 49

Neural Circuits: The Basis of Processing 49

Neural Processing in the Retina: Introduction to Receptive Fields 51

Neural Processing in the Retina: Seeing Dim Lights, Fine Details, and Brightness 54

Why Is Rod Vision More Sensitive Than Cone Vision? 54

Why Can We See Finer Details with Cone Vision Than with Rod Vision? 55

Neural Processing and the Perception of Brightness 57

A Neural Circuit for Mach Bands 61

Retinal Circuits: What They Can and Cannot Explain 62

Something to Consider: The Difference between Physical and Perceptual 64

Across the Senses: Sensing Environmental Energy by Humans and Animals 66

Study Questions 68

3

VISUAL PROCESSING: THE LATERAL GENICULATE NUCLEUS AND STRIATE CORTEX

The Lateral Geniculate Nucleus: Organization on the Way to the Cortex 72

Information Flow in the Lateral Geniculate Nucleus 73

Organization by Left and Right Eyes and Retinal Location 73

Organization by Magno and Parvo Layers 74

The Striate Cortex: Response to Bars, Edges, and Orientation 75

Receptive Fields of Neurons in the Striate Cortex 77

Psychophysical Evidence for Orientation Detectors: Selective Adaptation to Orientation 79

The Striate Cortex: Response to Spatial Frequency 82

What Is Spatial Frequency? 82

Cortical Neurons as Spatial Frequency Detectors 84

Psychophysical Evidence for Spatial Frequency Detectors: Selective Adaptation to Spatial Frequency 85

The Striate Cortex: Organization into Columns 88

Location Columns and Retinal Maps 88

Orientation Columns 90

Ocular Dominance Columns 91

Sensory Coding: Making Sense of the Neural Information 93

Specificity Coding 94

Distributed Coding 95

Something to Consider: Representing Bill 96

Across the Senses: Maps and Columns 98

Study Questions 100

4

HIGHER-LEVEL VISUAL PROCESSING

Visual Processing Streams 104

Streams for Perceiving What and Where 104

Streams for What and How 107

Modularity Demonstrated by Specialized Neural Responding 109

<i>Medial Temporal Cortex (MT): A Module for Movement</i>	110	<i>Trichromatic Theory: Color Matching</i>	138
<i>Inferotemporal Cortex (IT): A Module for Form</i>	110	<i>Opponent-Process Theory: Phenomenological Observations</i>	139
Modularity Demonstrated by the Effects of Cortical Damage in Humans	115	Physiological Research on Color Vision	141
<i>Blindsight: Pointing to Something That Can't Be "Seen"</i>	115	<i>Trichromatic Theory: Cone Pigments</i>	142
<i>Visual Agnosia: Seeing without Recognizing</i>	116	<i>Opponent-Process Theory: Neural Responding</i>	144
<i>Prosopagnosia: The Inability to Recognize Faces</i>	117	Color Deficiency	148
Visual Attention: Visual and Neural Selectivity	118	<i>Monochromatism</i>	149
<i>The Selectivity of Attention</i>	118	<i>Dichromatism</i>	149
<i>Visual Attention and Neural Responding</i>	119	<i>Physiological Mechanisms</i>	150
The Binding Problem: Combining Information from Different Areas	120	Something to Consider: Colorless Wavelengths and Private Experiences	150
Something to Consider: Determining That Neural Responding Is Related to Perception	122	<i>Are Wavelengths Colored?</i>	151
Across the Senses: Neurons That Respond to Vision and Touch	124	<i>Perception as a Private Experience</i>	152
Study Questions	126	Across the Senses: How Color Affects Taste and Smell	153
• UNDERLYING PRINCIPLES: CHAPTERS 1–4	128	Study Questions	154

5

PERCEIVING COLOR

Some Basic Properties of Color	132
<i>Functions of Color Perception</i>	132
<i>Describing Color Experience</i>	133
<i>What Are the Basic Colors?</i>	134
<i>Color and Wavelength</i>	136
Behavioral Research: Discovery of the Sensory Code for Color	138

6

PERCEPTUAL CONSTANCY

Color Constancy	158
<i>Chromatic Adaptation</i>	159
<i>The Effect of the Surroundings</i>	160
<i>Memory Color</i>	161
<i>Physiological Mechanisms</i>	161
Lightness Constancy	162
<i>Intensity Relationships: The Ratio Principle</i>	162
<i>Interpretation of Illumination</i>	164
<i>Shadows</i>	165
<i>The Physiology of Lightness Constancy</i>	167
Shape Constancy	167
Introduction to Size Constancy	168

Something to Consider: Knowledge and Constancy	169
Across the Senses: Olfactory Constancy	171
Study Questions	172

7

PERCEIVING OBJECTS

Organizing the Environment: Perceptual Organization	176
<i>The Beginnings of Gestalt Psychology</i>	178
<i>The Laws of Perceptual Organization</i>	181
<i>Aren't the Gestalt Laws Just Statements of the Obvious?</i>	185
<i>Figure and Ground</i>	186
<i>Evaluation of the Gestalt Approach</i>	189
Neural Processing: The Firing of Feature Detectors	191
<i>The Neural Code for Objects</i>	191
<i>The Neural Code for Biologically Meaningful Objects</i>	193
Perceptual Processing: The Alphabet of Object Perception	194
<i>The Feature Integration Approach</i>	195
<i>The Computational Approach</i>	199
Recognizing Objects: Determining What Things Are	202
<i>The Recognition by Components Approach</i>	203
Knowledge, Experience, and Processing	205
<i>The Likelihood Principle and Hypothesis Testing</i>	205
<i>Examples of Top-Down Processing</i>	206
<i>Evolution, Experience, and Neural Processing</i>	207
Something to Consider: Comparing the Ways of Explaining Object Perception	208

Across the Senses: Shape Perception Through Vision and Touch	209
Study Questions	211

8

PERCEIVING VISUAL SPACE

The Cue Approach	215
Oculomotor Cues	216
<i>Convergence and Accommodation</i>	216
Pictorial Cues	217
<i>Occlusion</i>	217
<i>Relative Height</i>	217
<i>Relative Size</i>	218
<i>Familiar Size</i>	218
<i>Atmospheric Perspective</i>	219
<i>Linear Perspective</i>	220
<i>Texture Gradient</i>	221
Movement-Produced Cues	221
<i>Motion Parallax</i>	221
<i>Deletion and Accretion</i>	222
Binocular Disparity and Stereopsis	222
<i>Two Eyes: Two Viewpoints</i>	223
<i>Corresponding Retinal Points</i>	226
<i>Random-Dot Stereogram</i>	229
<i>The Correspondence Problem</i>	229
Binocular Vision: Physiology and Development	231
<i>Disparity Information in the Brain</i>	231
<i>Sensitive Periods in the Development of Binocular Vision</i>	233
Depth Information across Species	238
Something to Consider: How Do Bats Experience Space?	240
Across the Senses: Visual and Auditory Space	242
Study Questions	243

9

SIZE, ILLUSIONS, AND ECOLOGICAL ASPECTS OF PERCEPTION

- The Information for Perceiving Size 246
 Size Constancy and Depth Perception 247
- Visual Illusions 250
 The Müller-Lyer Illusion 251
 The Ponzo Illusion 254
 The Ames Room 254
 The Moon Illusion 256
 *Illusory Perception, Veridical Perception, and
 Conditions in the Environment* 258
- The Ecology of Perception 258
 Evolutionary Aspects of Perception 258
 *J. J. Gibson's Ecological Approach
 to Perception* 260
 The Physiology of Ecological Perception 266
- Something to Consider: Laboratory Research
and Ecological Validity 267
- Across the Senses: Visual and
Haptic Illusions 268
- Study Questions 270

10

PERCEIVING MOVEMENT

- The Information Provided by Movement 274
- Studying Movement Perception 276
- Detecting Movement: Neural Firing and
Environmental Information 281
 *Directionally Selective Neurons in
 Movement Perception* 281
 *A Neural Mechanism for
 Directional Selectivity* 281

- Neural Firing and Judging the Direction
of Movement* 283
*Corollary Discharge Theory: Taking Eye
Movements into Account* 284
*Environmental Information for
Movement Perception* 288

- The Effect of Context on
Movement Perception 289
 A Framework Effect 289
 A Sequence Effect 290
 *Movement of the Human Form: Violating the
 Shortest-Path Constraint* 290
- Movement Creates Structure 292
 *The Kinetic Depth Effect: Movement Creates
 Form Perception* 292
 *Biological Motion: Movement Creates
 Perceptual Grouping* 293
- Optic Flow: Information from Action 295
 Negotiating the Environment 295
 Judging Time to Impact 297
 Maintaining Balance 298
- Something to Consider: The Interactive Nature
of Motion Perception 299
- Across the Senses: Apparent Movement on
the Skin 301
- Study Questions 303
- **UNDERLYING PRINCIPLES:
CHAPTERS 5–10** 305

11

SOUND, THE AUDITORY SYSTEM, AND PITCH PERCEPTION

- The Functions of Hearing 310
- Sound as a Physical Stimulus: Pressure Changes
in the Air 311

PERCEIVING LOUDNESS,
TIMBRE, AND THE
AUDITORY SCENE

- The Sound Stimulus Produced by a Loudspeaker* 312
Specifying the Amplitude of a Sound Stimulus 313
Specifying the Frequency of a Sound Stimulus 314
- Sound as a Perceptual Response:
 The Experience of Hearing 317
 Loudness 317
 Pitch 317
 Timbre 318
- Auditory System: Structure and Function 318
 The Outer Ear 318
 The Middle Ear 319
 The Inner Ear 321
 The Auditory Pathways 325
- The Place Code for Pitch: Traveling Waves, Tuning Curves, and Maps 325
 Helmholtz' Resonance Theory 327
 Békésy's Discovery: The Basilar Membrane Vibrates in a Traveling Wave 327
 Physiological Evidence for Place Coding 329
 Psychophysical Evidence for Place Coding 330
 The Outer Hair Cells: Electromechanical Amplifiers 333
 The Cochlea as a Frequency Analyzer 334
 Representation of Frequencies in the Auditory Cortex 335
- The Timing Code for Pitch 335
- Periodicity Pitch: Pitch Perception without the Fundamental 338
- Neural Response to Complex Stimuli 340
- Parallel Pathways in the Auditory System 341
- Something to Consider: Are Frequencies Really High Pitched or Low Pitched? 341
- Across the Senses: Cross-Modality Experience: Bright Tones and Colored Words 343
- Study Questions 345
- Sensitivity and Loudness: Exquisite Sensitivity, but Frequency Matters 350
 The Audibility Curve 351
 Loudness, Sound Pressure, and Frequency 352
 Equal Loudness Curves 353
 Physiological Aspects of Loudness 353
- Sound Quality: What a Stimulus Sounds Like 354
 Timbre 355
 Direct and Indirect Sound 356
 The Precedence Effect 357
- Auditory Scene Analysis: Identifying Sound Sources 358
 Principles of Auditory Grouping 359
- Auditory Localization: Determining Where Sound Sources Are Located 364
 Interaural Differences 365
 Pinnae Cues 367
 Distance Cues 368
 The Physiological Basis of Localization 369
 The Barn Owl's Topographic Map of Space 371
- A Practical Application: Sound as Information for the Visually Impaired 372
 Using Echoes to Locate Objects 373
 Personal Guidance System Based on Binaural Cues 374
- The Ecology of Auditory Perception: Two Kinds of Listening 375
- Something to Consider: Recognizing Sounds 376
- Across the Senses: Blindness Leads to Improved Hearing and Cortical Changes 377
- Study Questions 379

SPEECH PERCEPTION

- The Speech Stimulus 382
Phonemes: Sounds and Meanings 382
The Acoustic Signal: Patterns of Pressure Changes 383
- Problems Posed by the Speech Stimulus 384
The Segmentation Problem 384
The Variability Problem 385
- Stimulus Dimensions of Speech Perception 388
The Search for Invariant Acoustic Cues: Matching Physical Energy and Phonemes 389
Categorical Perception: An Example of Constancy in Speech Perception 390
The Multimodal Nature of Speech Perception: Information from Hearing and Vision 391
- Cognitive Dimensions of Speech Perception 392
Meaning and Segmentation 392
Meaning and Phoneme Perception 393
Meaning and Word Perception 395
Speaker Characteristics 396
- The Physiology of Speech Perception 397
Neural Responses to Speech and Complex Sounds 397
Localization of Function 398
- Something to Consider: Is Speech “Special”? 399
- Across the Senses: Tadoma: “Hearing” with Touch 401
- Study Questions 402

THE CUTANEOUS SENSES

- Anatomy of the Somatosensory System 407
The Skin and Its Receptors 407
Central Structures 409
- The Psychophysics and Physiology of Tactile Perception 410
Psychophysical Channels for Tactile Perception 410
Four Neural Channels for Tactile Perception 411
Thermoreceptors: The Neural Response to Temperature 415
- Neural Processing of Tactile Stimuli 416
Measuring Tactile Acuity: The Two-Point Threshold 416
Receptive Fields and Tactile Acuity 416
Maps of the Body on the Cortex: The Magnification Factor 418
Changing the Maps on the Brain: Plasticity of the Somatosensory Cortex 419
Neurons That Respond to Specialized Stimuli 420
- Active Touch 422
Using Active Touch to Identify Objects 423
Haptic Perception: Tactile Perception of Three-Dimensional Objects 424
- Pain Perception: Neural Firing and Cognitive Influences 426
Neural Responding and Pain Perception 426
Culture, Experience, and Pain Perception 427
Gate Control Theory 428
Endorphins 429
- Something to Consider: Do All People Experience Pain in the Same Way? 431
- Across the Senses: Picture Perception by Touch 433
- Study Questions 435

15

THE CHEMICAL SENSES

- Olfaction: Uses and Facts 440
- The Olfactory System 443
 - The Olfactory Mucosa* 443
 - Receptor Proteins, Receptor Neurons, and Glomeruli* 444
- Odor: Stimulus and Quality 446
- The Neural Code for Odor Molecules 447
 - Coding at the Level of the Receptor Neurons* 448
 - Coding in the Olfactory Bulb and Olfactory Cortex* 448
- The Perception of Flavor 450
- Factors Influencing Food Preferences 452
 - Internal State* 453
 - Past Experiences* 453
 - Conditioned Flavor Aversion* 453
 - Specific Hungers* 454
- The Taste System 454
 - The Tongue and Transduction* 454
 - Central Destinations of Taste Signals* 456
- Taste Quality 457
 - The Four Basic Taste Qualities* 457
 - The Genetics of Taste Experience* 457
- The Neural Code for Taste Quality 459
 - Distributed Coding* 459
 - Specificity Coding* 459
- Something to Consider: Sensing Chemicals in the Environment 462
- Across the Senses: Chemesthesis: A Somatosensory Component in the Nose and Mouth 463
- Study Questions 465

16

PERCEPTUAL DEVELOPMENT

- Measuring Infant Perception 470
 - Problems in Measuring Infant Perception* 470
 - Preferential Looking* 471
 - Habituation* 471
- Infant Perceptual Capacities: Vision 473
 - Acuity and Contrast* 473
 - Perceiving Objects* 477
 - Perceiving Color* 481
 - Perceiving Depth* 484
 - Perceiving Movement* 487
- Infant Perceptual Capacities: Hearing and the Chemical Senses 488
 - Hearing* 488
 - Speech Perception* 490
 - Olfaction and Taste* 493
- Mechanisms of Perceptual Development: Experience or Biological Programming? 495
 - The Effects of Selective Rearing* 496
 - The Development of Myopia* 498
- Something to Consider: The Rapid Unfolding of Perception 500
- Across the Senses: Intermodal Perception in Infants 502
- Study Questions 504
- **UNDERLYING PRINCIPLES: CHAPTERS 11–16** 507

17

CLINICAL ASPECTS OF VISION AND HEARING

Visual Impairment

- How Can Vision Become Impaired? 516