

Contents

| | |
|--|------|
| Introduction | xiii |
| Werner G. K. Backhaus, Reinhold Kliegl and John S. Werner | |

I. Color Vision in Art and Science

| | |
|--|----|
| 1. Aging through the Eyes of Monet John S. Werner | |
| 1.1 Introduction | 1 |
| 1.2 A Link between Sunlight and Aging . | 5 |
| 1.3 The Trivariance of Color Mixture: Maxwell and Helmholtz | 9 |
| 1.4 Monet's Early Impressionistic Style . | 12 |
| 1.4.1 Possible Influences of Turner and Goethe | 13 |
| 1.4.2 Possible Influences of Chevreul and Delacroix | 17 |
| 1.5 Monet's Years in Argenteuil and Vètheuil | 23 |
| 1.6 The Opponent Code for Color Appearance: Hering | 23 |
| 1.7 Monet's Response to Pointillism and Divisionism. | 27 |
| 1.8 Hay Stack and Cathedral Series. | 30 |
| 1.9 Monet Returns to London. | 33 |
| 1.10 Water Lilies and Cataracts. | 33 |
| 1.11 Summary | 38 |
| References | 39 |

II. Physiology and Neuroethology

| | |
|---|----|
| 2. Physiological and Psychophysical Simulations of Color Vision in Humans and Animals Werner G. K. Backhaus | |
| 2.1 Introduction | 45 |

| | | |
|-------|--|----|
| 2.1.1 | Phenomenology of Color Vision | 45 |
| 2.1.2 | Disciplines | 45 |
| 2.1.3 | Psychophysical Simulations | 46 |
| 2.1.4 | Physiological Simulations | 46 |
| 2.2 | Color Stimuli | 47 |
| 2.3 | Psychophysics of Color Vision | 48 |
| 2.3.1 | Psychophysical Judgments | 50 |
| 2.4 | Psychophysical Color Spaces | 51 |
| 2.4.1 | The Color Similarity (MDS) Space . . | 51 |
| 2.4.2 | The Elementary Color Space (Color Sensations Space) | 52 |
| 2.4.3 | The jnd Scale | 54 |
| 2.5 | Neurophysiology of Color Vision . . . | 54 |
| 2.5.1 | Humans and Other Vertebrates | 54 |
| 2.5.2 | Honeybees and Other Invertebrates . . | 56 |
| 2.6 | Physiological Color Spaces | 57 |
| 2.6.1 | Physical Description of the Color Stimulus | 57 |
| 2.6.2 | The Color Stimulus Space | 57 |
| 2.6.3 | The Photoreceptor Sensitivity (Light Absorption) Space (1st Physiological Color Space) | 60 |
| 2.6.4 | The Photoreceptor Excitation Space (2nd Physiological Color Space) | 61 |
| 2.6.5 | The Color-Opponent Coding Space (3rd Physiological Color Space) | 61 |
| 2.6.6 | Color Spaces and jnd Scales | 62 |
| 2.7 | Psychophysical and Physiological Simulations of Color Vision | 62 |
| 2.7.1 | The Psychophysical (MDS) Color Space in Honeybees | 62 |
| 2.7.2 | Neuronal Color-Coding and Color-Choice Behavior in Honeybees | 64 |
| 2.7.3 | Identification of the Physiological COC Space and the Psychophysical MDS Space | 65 |
| 2.8 | Conscious vs. Unconscious Judgments | 71 |

| | | |
|-----------|---|-----|
| 2.8.1 | Color Sensations in Animals | 71 |
| 2.9 | Conclusions | 74 |
| | References | 75 |
| 3. | Receptors, Channels and Color in Primate Retina Barry B. Lee | |
| 3.1 | Introduction | 79 |
| 3.2 | Physiology and Anatomy in the Retina | 80 |
| 3.3 | Conclusions | 86 |
| | References | 87 |
| 4. | Chromatic Processing in the Lateral Geniculate Nucleus of the Common Marmoset (<i>Callithrix jacchus</i>) Jan Kremers, Eberhart Zrenner, Stefan Weiss and Sabine Meierkord | |
| 4.1 | Introduction | 89 |
| 4.2 | Spectral Responsivities | 91 |
| 4.3 | Responses of LGN Cells to Various Photoreceptor Contrasts | 93 |
| 4.4 | Selective Photoreceptor Stimulation in Human Observers | 95 |
| 4.5 | Summary | 98 |
| | References | 98 |
| 5. | Molecular Genetics and the Biological Basis of Color Vision Maureen Neitz and Jay Neitz | |
| 5.1 | Introduction | 101 |
| 5.2 | Background | 101 |
| 5.2.1 | Types of Congenital Color Vision Defects | 101 |
| 5.2.2 | Genome Organization and Inheritance Patterns of Color Vision Defects | 102 |
| 5.2.3 | Genes and Gene Expression | 103 |
| 5.3 | Spectral Tuning of M- and L-Cone Pigments | 104 |
| 5.4 | Color Vision Defects | 108 |
| 5.4.1 | What Distinguishes Normal from Anomalous Pigments? | 111 |
| 5.4.2 | What Distinguishes Photopigments Underlying Dichromacy from Normal Pigments? | 113 |

| | | |
|-----------|--|-----|
| 5.5 | Variation in Normal Color Vision . . . | 115 |
| 5.6 | What Can Visual Pigment Gene Expression Tell Us about the Architecture of the Retina? | 116 |
| | References | 117 |
| 6. | Source Analysis of Color-Evoked Potentials in a Realistic Head Model Confirmed by Functional MRI Walter Paulus, Renate Kolle, Jürgen Baudewig, Nora Freudenthaler, Mathias Kunkel, Michael Finkenstaedt and Hans-Heino Rustenbeck | |
| 6.1 | Introduction | 121 |
| 6.2 | Methods | 127 |
| 6.3 | Results | 128 |
| 6.4 | Discussion | 129 |
| 6.5 | Summary | 129 |
| | References | 129 |
| 7. | Wavelength Information Processing <i>versus</i> Color Perception: Evidence from Blindsight and Color-Blind Sight Petra Stoerig | |
| 7.1 | Introduction | 131 |
| 7.2 | Wavelength Information Processing . | 134 |
| 7.2.1 | Wavelength Information Processing in Cortical Blindness. | 134 |
| 7.2.2 | Wavelength Processing in Cortical Color Blindness. | 138 |
| 7.3 | Segregation of Wavelength and Intensity Information and Constancy. | 141 |
| 7.4 | Color Perception | 143 |
| | References | 145 |
| 8. | Color Vision in Lower Vertebrates Christa Neumeyer | |
| 8.1 | Introduction | 149 |
| 8.2 | Wavelength Discrimination in Lower Vertebrates | 150 |
| 8.2.1 | Goldfish | 150 |
| 8.2.2 | Turtles | 151 |
| 8.2.3 | Amphibia | 154 |
| 8.3 | Color Constancy and Color Contrast. | 155 |

| | | |
|-----------|---|-----|
| 8.4 | Color Vision and Other Visual Functions: Evidence for Parallel Processing of Visual Information . . . | 157 |
| 8.5 | Color Perception | 159 |
| 8.6 | Summary | 160 |
| | References | 161 |
| 9. | Color Vision: Ecology and Evolution in Making the Best of the Photic Environment | |
| | Peter G. Kevan and Werner G. K. Backhaus | |
| 9.1 | Introduction | 163 |
| 9.2 | Palaeontological Record | 164 |
| 9.3 | Daylight and Color Vision. | 165 |
| 9.4 | Colorimetry | 167 |
| 9.5 | Color Spaces. | 168 |
| 9.6 | Evolution of Floral Colors and Color Vision. | 171 |
| 9.7 | Color Patterns in Flowers | 175 |
| 9.8 | Trichromacy and Tetrachromacy | 177 |
| 9.9 | Conclusions | 178 |
| | References | 178 |

III. Psychology and Philosophy

| | | |
|------------|---|-----|
| 10. | The Perception of Blackness: An Historical and Contemporary Review | |
| | Vicki J. Volbrecht and Reinhold Kliegl | |
| 10.1 | Introduction | 187 |
| 10.2 | The Phenomenology of Blackness. . . | 187 |
| 10.2.1 | Helmholtz: Trichromatic Theory of Color Vision | 189 |
| 10.2.2 | Hering: Opponent-Process Theory of Color Vision | 189 |
| 10.2.3 | Criticism and Other Theories | 191 |
| 10.3 | Historical Review | 194 |
| 10.3.1 | Induction Experiments | 194 |
| 10.3.2 | Blackness-Induction Experiments . . . | 195 |
| 10.4 | Physiological Mechanisms | 201 |
| 10.5 | Conclusion | 202 |
| | References | 202 |

| | | |
|------------|--|-----|
| 11. | Basic Color Terms and Basic Color Categories | 207 |
| | Clyde L. Hardin | |
| | Discussion and Summary | 215 |
| | References | 216 |
| 12. | Color Perception: From Grassman Codes to a Dual Code for Object and Illumination Colors | |
| | Rainer Mausfeld | |
| 12.1 | Introduction | 219 |
| 12.2 | Elementaristic vs. Ecological Perspectives in Color Research | 220 |
| 12.3 | Attributes of Color | 222 |
| 12.4 | Early Color Coding and the Elementaristic Approach | 224 |
| 12.4.1 | Newton and Helmholtz's Approach to Color Perception | 224 |
| 12.4.2 | The Young-Helmholtz Theory and Grassmann's Laws. | 225 |
| 12.4.3 | Opponent-Color Theory | 226 |
| 12.4.4 | Relating Psychophysical and Neurophysiological Color Codes. | 228 |
| 12.4.5 | Elementary Color Codes Accounting for Variations in Spatial and Temporal Context. | 231 |
| 12.5 | Ecological and Computational Perspectives | 236 |
| 12.5.1 | The Problem of Approximate Color Constancy from a Computational Point of View | 238 |
| 12.5.2 | Qualitative Observations on the Dialectic Relationship of Illumination and Object Color. | 240 |
| 12.6 | Center-Surround Configurations as Minimal Stimuli for Triggering a Dual Code for 'Object Colors' and 'Illumination Colors' | 242 |
| 12.6.1 | Laminar Segmentation and a Dual Code for 'Object Color' and 'Illumination Color' | 243 |
| 12.6.2 | Segregation of 'Object Color' and 'Illumination Color' in Minimal Seurat-type Configurations | 245 |
| | References | 248 |

| | | |
|------------|--|-----|
| 13. | Color Contrast Gain Control | |
| | Michael D’Zmura | |
| 13.1 | Introduction | 251 |
| 13.1.1 | What is Contrast Gain Control? | 251 |
| 13.1.2 | Selectivity for Spatial Frequency, Orientation and Color | 252 |
| 13.1.3 | Feed-Forward, Matrix-Multiplicative Circuitry | 253 |
| 13.1.4 | Spatial Pooling of Contrast | 254 |
| 13.2 | Model Components. | 254 |
| 13.3 | Color Image Processing | 256 |
| 13.3.1 | Channel Responses | 256 |
| 13.3.2 | Channel Contrasts. | 257 |
| 13.3.3 | Channel Interaction. | 261 |
| 13.3.4 | Channel Gains | 261 |
| 13.3.5 | Multichannel Contrast Gain Control . | 263 |
| 13.4 | Discussion | 264 |
| 13.5 | Summary | 265 |
| | References | 265 |
| 14. | Binocular Brightness Combination: A Mechanism for Combining Two Sources of Rather Similar Information | |
| | Hans Irtel | |
| 14.1 | Intensity Invariance of Binocular Brightness. | 267 |
| 14.2 | Methods | 269 |
| 14.3 | Results | 270 |
| 14.4 | Discussion | 271 |
| 14.5 | Summary | 273 |
| | References | 273 |
| 15. | Inferences about Infant Color Vision | |
| | Kenneth Knoblauch, Michelle L. Bieber and John S. Werner | |
| 15.1 | Introduction | 275 |
| 15.2 | Inferences from Luminosity | 275 |
| 15.3 | Inferences from Silent Substitution . . | 277 |
| 15.4 | Inferences about Rod Intrusion | 278 |
| 15.5 | Inferences about M- and L-Cones . . . | 279 |
| 15.6 | Summary | 281 |
| | References | 281 |

IV. Color Metrics and Application

16. Dichromacy –

The Simplest Type of Color Vision

Horst Scheibner

| | | |
|-------|---|-----|
| 16.1 | Introduction: An Initial Overview . . . | 285 |
| 16.2 | The Trichromatic Instrumental Color Space ${}^3V_{BGR}$ | 286 |
| 16.3 | Measuring the Deutanopic Missing Color and Reducing Trichromacy to Deutanopia. | 287 |
| 16.4 | The Transition from the Instrumental Trichromatic Space to the Instrumental Deutanopic Space . . . | 290 |
| 16.5 | The Transformation from the Trichromatic Instrumental Color Space to the Deutanopic Opponent-Color Space | 291 |
| 16.6 | The Role of the Fundamental Color Space | 294 |
| 16.7 | Construction of the Fundamental Color Spaces ${}^3V_{PTD}$ and ${}^2V_{PT}$ and the Deutanopic Opponent-Color Channels. | 295 |
| 16.8 | A Synopsis of Deutanopia | 298 |
| 16.9 | A Synopsis of Dichromacy | 299 |
| 16.10 | A Lattice-Theoretical Classification of Dichromacy and Other Color Deficiencies | 301 |
| 16.11 | Concluding Remarks. | 301 |
| 16.12 | Summary | 302 |
| | References | 302 |

17. Current CIE Work to Achieve Physiologically-Correct Color Metrics

János Schanda

| | | |
|--------|---|-----|
| 17.1 | Introduction | 307 |
| 17.2 | Cone Excitation Spectra | 308 |
| 17.2.1 | Choice of the Color-Matching Functions | 308 |
| 17.2.2 | Deriving L-, M-, S-Cone Excitation Spectra from Color-Matching Data . . | 309 |
| 17.2.3 | Intra-Ocular Screening | 310 |
| 17.2.4 | Derivation of the Fundamental Response Curves. | 311 |

| | | |
|--------|------------------------------------|-----|
| 17.3 | Further Aspects | 314 |
| 17.3.1 | Rod Intrusion | 314 |
| 17.3.2 | Color Appearance | 315 |
| 17.3.3 | Color Management Studies | 315 |
| 17.4 | Summary | 316 |
| | References | 316 |

**18. Use of Computer Graphics in
PostScript for Color Didactics**

Klaus Richter

| | | |
|------|---|-----|
| 18.1 | Introduction | 319 |
| 18.2 | Multiplicity of Colors | 321 |
| 18.3 | Color Solid, Basic Colors and Color Attributes | 322 |
| 18.4 | Spectrum and 3-Dimensional Color Values | 324 |

| | | |
|---|---|------------|
| 18.5 | Color Measurement, Mixture and Contrast | 325 |
| 18.6 | Colors: Equally Spaced and Thresholds | 327 |
| 18.7 | Opponent Achromatic Color Vision. . | 328 |
| 18.8 | Sensitivity, Saturation and Chromaticity. | 329 |
| 18.9 | Summary | 332 |
| | References | 332 |
| List of Contributors | | 333 |
| Index | | 337 |