Contents

Series Editor's Foreword XIII Preface XV About the Authors XXI

- 1Color Vision and Self-Luminous Visual Technologies11.1Color Vision Features and the Optimization of Modern
Self-Luminous Visual Technologies2
- 1.1.1 From Photoreceptor Structure to Colorimetry 2
- 1.1.2 Spatial and Temporal Contrast Sensitivity 6
- 1.1.3 Color Appearance Perception 12
- 1.1.4 Color Difference Perception 15
- 1.1.5 Cognitive, Preferred, Harmonic, and Emotional Color 17
- 1.1.6 Interindividual Variability of Color Vision 18
- 1.2 Color Vision-Related Technological Features of Modern Self-Luminous (Nonprinting) Visual Technologies 18
- 1.3 Perceptual, Cognitive, and Emotional Features of the
 Visual System and the Corresponding Technological Challenge 20
 References 23
- 2 Colorimetric and Color Appearance-Based Characterization of Displays 25
- 2.1 Characterization Models and Visual Artifacts in General 25
- 2.1.1 Tone Curve Models and Phosphor Matrices 26
- 2.1.2 Measured Color Characteristics, sRGB, and Other Characterization Models 27
- 2.1.3 Additivity and Independence of the Color Channels 35
- 2.1.4 Multidimensional Phosphor Matrices and Other Methods 35
- 2.1.5 Spatial Uniformity and Spatial Independence 39
- 2.1.6 Viewing Direction Uniformity 45
- 2.1.7 Other Visual Artifacts 46
- 2.1.8 The Viewing Environment: Viewing Conditions and Modes 48

VII

VIII Contents

2.1.9	Application of CIELAB, CIELUV, and CIECAM02 to Self-Luminous Displays 49
2.2	Characterization Models and Visual Artifacts of the Different
2.2.1	Modern Applications of the Different Display Technologies 52
2.2.1	Special Characterization Models of the Different Displays 53
2221	CRT 53
2222	PDP 55
2.2.2.2	Various I CD Technologies and Their Viewing Direction Uniformity 60
2.2.2.3	Head-Mounted Displays and Head-Up Displays 67
2225	Projectors Including DMD and ICD 68
2226	OLEDs 71
2.2.2.0	Display Light Source Technologies 72
2.3	Projector Light Sources 73
2.3.1	Backlight Sources 75
233	Color Filters Local Dimming and High Dynamic Range Imaging 79
2.3.3	Color Appearance of Large Viewing Angle Displays 81
2.1	Color Appearance Differences between Small and Large Color
2.1.1	Stimuli 81
2.4.1.1	Color Appearance of an Immersive Color Stimulus on a PDP 82
2.4.1.2	Xiao et al.'s Experiment on the Appearance of a Self-Luminous
	50° Color Stimulus on an LCD 87
212	Mathematical Modeling of the Color Size Effect 87
2.4.2	Mathematical Modeling of the Color Size Effect - 87
2.4.2	References 91
3	References 91 Ergonomic, Memory-Based, and Preference-Based Enhancement
3	References 91 Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays 97
3.1	References 91 Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays 97 Ergonomic Guidelines for Displays 97
3 3.1 3.2	References 91 Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays 97 Ergonomic Guidelines for Displays 97 Objectives of Color Image Reproduction 105
3 3.1 3.2 3.3	References 91 Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays 97 Ergonomic Guidelines for Displays 97 Objectives of Color Image Reproduction 105 Ergonomic Design of Color Displays: Optimal Use of
3 3.1 3.2 3.3	References91Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast 107
3 3.1 3.2 3.3 3.3.1	References91Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction105Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast107Principles of Ergonomic Color Design107
3 3.1 3.2 3.3 3.3.1 3.3.2	References91Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction105Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast107Principles of Ergonomic Color Design107Legibility, Conspicuity, and Visual Search108
3 3 .1 3 .2 3 .3 3 .3.1 3 .3.2 3 .3.2 3 .3.3	References91Ergonomic, Memory-Based, and Preference-Based Enhancementof Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction105Ergonomic Design of Color Displays: Optimal Use ofChromaticity Contrast107Principles of Ergonomic Color Design107Legibility, Conspicuity, and Visual Search108Chromaticity Contrast for Optimal Search Performance111
3 3 .1 3 .2 3 .3 3 .3.1 3 .3.2 3 .3.3 3 .3.4	References91Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction105Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast107Principles of Ergonomic Color Design107Legibility, Conspicuity, and Visual Search108Chromaticity Contrast for Optimal Search Performance111Chromaticity and Luminance Contrast Preference123
3 .1 3.2 3.3 3.3.1 3.3.2 3.3.1 3.3.2 3.3.3 3.3.4 3.4	References91Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction105Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast107Principles of Ergonomic Color Design107Legibility, Conspicuity, and Visual Search108Chromaticity Contrast for Optimal Search Performance111Chromaticity and Luminance Contrast Preference123Long-Term Memory Colors, Intercultural Differences, and
3 3.1 3.2 3.3 3.3.1 3.3.2 3.3.2 3.3.3 3.3.4 3.4	References91Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction105Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast107Principles of Ergonomic Color Design107Legibility, Conspicuity, and Visual Search108Chromaticity Contrast for Optimal Search Performance111Chromaticity and Luminance Contrast Preference123Long-Term Memory Colors, Intercultural Differences, and Their Use to Evaluate and Improve Color Image Quality134
3 3 .1 3 .2 3 .3 3 .3.1 3 .3.2 3 .3.2 3 .3.3 3 .3.4 3 .4 3 .4.1	References91Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction105Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast107Principles of Ergonomic Color Design107Legibility, Conspicuity, and Visual Search108Chromaticity Contrast for Optimal Search Performance111Chromaticity and Luminance Contrast Preference123Long-Term Memory Colors, Intercultural Differences, and134Long-Term Memory Colors for Familiar Objects135
3 3 .1 3 .2 3 .3 3 .3.1 3 .3.2 3 .3.3 3 .3.4 3 .4 3 .4.1 3 .4.2	References91Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction105Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast107Principles of Ergonomic Color Design107Legibility, Conspicuity, and Visual Search108Chromaticity Contrast for Optimal Search Performance111Chromaticity and Luminance Contrast Preference123Long-Term Memory Colors, Intercultural Differences, and134Their Use to Evaluate and Improve Color Image Quality134Long-Term Memory Colors for Familiar Objects135Intercultural Differences of Long-Term Memory Colors139
3 3 .1 3 .2 3 .3 3 .3.1 3 .3.2 3 .3.3 3 .3.4 3 .4.1 3 .4.2 3 .4.3	References91Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction105Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast107Principles of Ergonomic Color Design107Legibility, Conspicuity, and Visual Search108Chromaticity Contrast for Optimal Search Performance111Chromaticity and Luminance Contrast Preference123Long-Term Memory Colors, Intercultural Differences, and114Intercultural Differences of Long-Term Memory Colors139Increasing Color Quality by Memory Colors141
3 3 3 .1 3 .2 3 .3 3 .3.1 3 .3.2 3 .3.3 3 .3.4 3 .4 3 .4.1 3 .4.2 3 .4.3 3 .5	References91Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction105Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast107Principles of Ergonomic Color Design107Legibility, Conspicuity, and Visual Search108Chromaticity Contrast for Optimal Search Performance111Chromaticity and Luminance Contrast Preference123Long-Term Memory Colors, Intercultural Differences, and114Their Use to Evaluate and Improve Color Image Quality134Long-Term Memory Colors for Familiar Objects135Intercultural Differences of Long-Term Memory Colors141Color Image Preference for White Point, Local Contrast,
3 3.1 3.2 3.3 3.3.1 3.3.2 3.3.3 3.3.4 3.4 3.4.1 3.4.2 3.4.3 3.5	References91Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays97Ergonomic Guidelines for Displays97Objectives of Color Image Reproduction105Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast107Principles of Ergonomic Color Design107Legibility, Conspicuity, and Visual Search108Chromaticity Contrast for Optimal Search Performance111Chromaticity and Luminance Contrast Preference123Long-Term Memory Colors, Intercultural Differences, and114Their Use to Evaluate and Improve Color Image Quality134Long-Term Memory Colors for Familiar Objects135Intercultural Differences of Long-Term Memory Colors141Color Image Preference for White Point, Local Contrast, Global Contrast, Hue, and Chroma142
3 3 .1 3 .2 3 .3 3 .3.1 3 .3.2 3 .3.3 3 .3.4 3 .4.1 3 .4.2 3 .4.3 3 .5 3 .5.1	References 91 Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays 97 Ergonomic Guidelines for Displays 97 Objectives of Color Image Reproduction 105 Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast 107 Principles of Ergonomic Color Design 107 Legibility, Conspicuity, and Visual Search 108 Chromaticity Contrast for Optimal Search Performance 111 Chromaticity and Luminance Contrast Preference 123 Long-Term Memory Colors, Intercultural Differences, and Their Use to Evaluate and Improve Color Image Quality 134 Long-Term Memory Colors for Familiar Objects 135 Intercultural Differences of Long-Term Memory Colors 139 Increasing Color Quality by Memory Colors 141 Color Image Preference for White Point, Local Contrast, Global Contrast, Hue, and Chroma 142 Apparatus and Method to Obtain a Color Image Preference Data Set 143
3 3 .1 3 .2 3 .3 3 .3.1 3 .3.2 3 .3.3 3 .3.4 3 .4 3 .4.1 3 .4.2 3 .4.3 3 .5 3 .5.1 3 .5.2	 References 91 Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays 97 Ergonomic Guidelines for Displays 97 Objectives of Color Image Reproduction 105 Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast 107 Principles of Ergonomic Color Design 107 Legibility, Conspicuity, and Visual Search 108 Chromaticity Contrast for Optimal Search Performance 111 Chromaticity and Luminance Contrast Preference 123 Long-Term Memory Colors, Intercultural Differences, and Their Use to Evaluate and Improve Color Image Quality 134 Long-Term Memory Colors for Familiar Objects 135 Intercultural Differences of Long-Term Memory Colors 139 Increasing Color Quality by Memory Colors 141 Color Image Preference for White Point, Local Contrast, Global Contrast, Hue, and Chroma 142 Apparatus and Method to Obtain a Color Image Preference Data Set 143 Image Transforms of Color Image Preference 144
3 3 3 .1 3 .2 3 .3 3 .3.1 3 .3.2 3 .3.3 3 .3.4 3 .4.1 3 .4.2 3 .4.3 3 .5 3 .5.1 3 .5.2 3 .5.3	References 91 Ergonomic, Memory-Based, and Preference-Based Enhancement of Color Displays 97 Ergonomic Guidelines for Displays 97 Objectives of Color Image Reproduction 105 Ergonomic Design of Color Displays: Optimal Use of Chromaticity Contrast 107 Principles of Ergonomic Color Design 107 Legibility, Conspicuity, and Visual Search 108 Chromaticity Contrast for Optimal Search Performance 111 Chromaticity and Luminance Contrast Preference 123 Long-Term Memory Colors, Intercultural Differences, and Their Use to Evaluate and Improve Color Image Quality 134 Long-Term Memory Colors for Familiar Objects 135 Intercultural Differences of Long-Term Memory Colors 139 Increasing Color Quality by Memory Colors 141 Color Image Preference for White Point, Local Contrast, Global Contrast, Hue, and Chroma 142 Apparatus and Method to Obtain a Color Image Preference Data Set 143 Image Transforms of Color Image Preference 144 Preferred White Point 144

3.5.4 Preferred Local Contrast 147

- 3.5.5 Preferred Global Contrast 147
- 3.5.6 Preferred Hue and Chroma 150
- 3.6 Age-Dependent Method for Preference-Based Color Image Enhancement with Color Image Descriptors 151 References 156
- 4 Color Management and Image Quality Improvement for Cinema Film and TV Production 161
- 4.1 Workflow in Cinema Film and TV Production Today Components and Systems 161
- 4.1.1 Workflow 161
- 4.1.2 Structure of Color Management in Today's Cinema and TV Technology 164
- 4.1.3 Color Management Solutions 165
- 4.2 Components of the Cinema Production Chain 166
- 4.2.1 Camera Technology in Overview 166
- 4.2.2 Postproduction Systems 174
- 4.2.3 CIELAB and CIEDE 2000 Color Difference Formulas Under the Viewing Conditions of TV and Cinema Production 176
- 4.2.3.1 Procedure of the Visual Experiment 178
- 4.2.3.2 Experimental Results 181
- 4.2.4 Applications of the CIECAM02 Color Appearance Model in the Digital Image Processing System for Motion Picture Films 184
- 4.3 Color Gamut Differences 191
- 4.4 Exploiting the Spatial–Temporal Characteristics of Color Vision for Digital TV, Cinema, and Camera Development 195
- 4.4.1 Spatial and Temporal Characteristics in TV and Cinema Production 195
- 4.4.2 Optimization of the Resolution of Digital Motion Picture Cameras 199
- 4.4.3 Perceptual and Image Quality Aspects of Compressed Motion Pictures 205
- 4.4.3.1 Necessity of Motion Picture Compression 205
- 4.4.3.2 Methods of Image Quality Evaluation 205
- 4.4.3.3 The Image Quality Experiment 207
- 4.4.4 Perception-Oriented Development of Watermarking Algorithms for the Protection of Digital Motion Picture Films 214
- 4.4.4.1 Motivation and Aims of Watermarking Development 214
- 4.4.4.2 Requirements for Watermarking Technology 216
- 4.4.4.3 Experiment to Test Watermark Implementations 217
- 4.5 Optimum Spectral Power Distributions for Cinematographic Light Sources and Their Color Rendering Properties 223
- 4.6 Visually Evoked Emotions in Color Motion Pictures 229
- 4.6.1 Technical Parameters, Psychological Factors, and Visually Evoked Emotions 229
- 4.6.2 Emotional Clusters: Modeling Emotional Strength 231 References 233

X Contents

5	Pixel Architectures for Displays of Three- and Multi-Color Primaries	237
5.1	Displays to Obtain a Large Color Camut 238	
511	Target Color Sets 240	
5.1.1	Factors of Optimization 244	
5121	Color Camut Volume 244	
5121	Quantization Efficiency 244	
5122	Number of Color Primaries 245	
512.5	White Point 245	
512.4	Technological Constraints 246	
5126	P/W Ratio 247	
512.0	Roundness 249	
512.7	RCB Tone Scales and Display Black Point 250	
5.1.2.0	Large-Gamut Primary Colors and Their Gamut in Color	
5.2	Appearance Space 250	
5.2.1	Optimum Color Primaries 251	
5.2.2	Optimum Color Gamuts in Color Appearance Space 252	
5.3	Optimization Principles of Subpixel Architectures for	
	Multi-Primary Color Displays 257	
5.3.1	The Color Fringe Artifact 258	
5.3.2	Optimization Principles 259	
5.3.2.1	Minimum Color Fringe Artifact 259	
5.3.2.2	Modulation Transfer Function 260	
5.3.2.3	Isotropy 260	
5.3.2.4	Luminance Resolution 261	
5.3.2.5	High Aperture Ratio 261	
5.4	Three- and Multi-Primary Subpixel Architectures and Color	
	Image Rendering Methods 262	
5.4.1	Three-Primary Architectures 262	
5.4.2	Multi-Primary Architectures 264	
5.4.3	Color Image Rendering Methods 268	
	Acknowledgment 270	
	References 271	
c	Increasing the Color Quality of Indeen Light Seconds 272	
U 6 1	Introduction to Color Pondoring and Color Ouelity 273	
0.1	Ortigization for Indeen Light Courses to Dravide a Visual	
0.2	Environment of High Color Pendering 276	
621	Vigual Color Fidelity Experimenta 276	
622	Color Pendering Prediction Methods 202	
0.2.2	Deficite of the Current Color Pendering Index 202	
0.2.2.1	Denotes of the Current Color Rendering Index 282	
0.2.2.2	Optimization of Indoor Light Sources to Describe Color	
0.5	Harmony in the Visual Environment 286	
6.3.1	Visual Color Harmony Experiments 287	
3.3.1	, issue color furthering Experiments 20/	

Contents XI

- 6.3.2 Szab et al.'s Mathematical Model to Predict Color Harmony 287
- 6.3.3 A Computational Method to Predict Color Harmony Rendering 289
- 6.4 Principal Components of Light Source Color Quality 293
- 6.4.1 Factors Influencing Color Quality 293
- 6.4.2 Experimental Method to Assess the Properties of Color Quality 296
- 6.4.3 Modeling Color Quality: Four-Factor Model 302
- 6.4.4 Principal Components of Color Quality for Three Indoor Light Sources 303
- 6.5 Assessment of Complex Indoor Scenes Under Different Light Sources 304
- 6.5.1 Psychological Relationship between Color Difference Scales and Color Rendering Scales 305
- 6.5.2 Brightness in Complex Indoor Scenes in Association with Color Gamut, Rendering, and Harmony: A Computational Example 311
- 6.5.3 Whiteness Perception and Light Source Chromaticity 316
- 6.6 Effect of Interobserver Variability of Color Vision on the Color Quality of Light Sources 318
- 6.6.1 Variations of Color Vision Mechanisms 319
- 6.6.2 Effect of Variability on Color Quality 320
- 6.6.2.1 Variability of the Visual Ratings of Color Quality 321
- 6.6.2.2 Variability of Perceived Color Differences and the Color Rendering Index 321
- 6.6.2.3 Variability of Similarity Ratings 322
- 6.6.3 Relevance of Variability for Light Source Design 324 Acknowledgments 324 References 324

7 Emerging Visual Technologies 329

- 7.1 Emerging Display Technologies 329
- 7.1.1 Flexible Displays 329
- 7.1.2 Laser and LED Displays 330
- 7.1.3 Color Gamut Extension for Multi-Primary Displays 334
- 7.2 Emerging Technologies for Indoor Light Sources 339
- 7.2.1 Tunable LED Lamps for Accent Lighting 339
- 7.2.2 Optimization for Brightness and Circadian Rhythm 341
- 7.2.3 Accentuation of Different Aspects of Color Quality 347
- 7.2.4 Using New Phosphor Blends 348
- 7.2.5 Implications of Color Constancy for Light Source Design 354
- 7.3 Summary and Outlook 357 Acknowledgments 360 References 360

Index 363