Contents

About the Authors xv

Series Preface xvii

Preface xix

Acknowledgements xxi

1 **Colour Vision** 1
- 1.1 Introduction . . . 1
- 1.2 The spectrum . . . 1
- 1.3 Construction of the eye . . . 3
- 1.4 The retinal receptors . . . 4
- 1.5 Spectral sensitivities of the retinal receptors . . . 5
- 1.6 Visual signal transmission . . . 8
- 1.7 Basic perceptual attributes of colour . . . 9
- 1.8 Colour constancy . . . 10
- 1.9 Relative perceptual attributes of colours . . . 11
- 1.10 Defective colour vision . . . 13
- 1.11 Colour pseudo-stereopsis . . . 15

References . . . 16

General References . . . 17

2 **Spectral Weighting Functions** 19
- 2.1 Introduction . . . 19
- 2.2 Scotopic spectral luminous efficiency . . . 19
- 2.3 Photopic spectral luminous efficiency . . . 21
- 2.4 Colour-matching functions . . . 26
- 2.5 Transformation from R, G, B to X, Y, Z . . . 32
- 2.6 CIE colour-matching functions . . . 33
- 2.7 Metamerism . . . 38
- 2.8 Spectral luminous efficiency functions for photopic vision . . . 39

References . . . 40

General References . . . 40

3 Relations between Colour Stimuli **41**
3.1 Introduction . . . 41
3.2 The Y tristimulus value . . . 41
3.3 Chromaticity . . . 42
3.4 Dominant wavelength and excitation purity . . . 44
3.5 Colour mixtures on chromaticity diagrams . . . 46
3.6 Uniform chromaticity diagrams . . . 48
3.7 CIE 1976 hue-angle and saturation . . . 51
3.8 CIE 1976 lightness, L^* . . . 52
3.9 Uniform colour spaces . . . 53
3.10 CIE 1976 colour difference formulae . . . 57
3.11 CMC, CIE94, and CIEDE2000 color difference formulae . . . 61
3.12 An alternative form of the CIEDE2000 colour-difference equation . . . 64
3.13 Summary of measures and their perceptual correlates . . . 64
3.14 Allowing for chromatic adaptation . . . 65
3.15 The evaluation of whiteness . . . 66
3.16 Colorimetric purity . . . 67
3.17 Identifying stimuli of equal brightness . . . 67
3.18 CIEDE2000 worked example . . . 69
References . . . 71
General References . . . 72

4 Light Sources **73**
4.1 Introduction . . . 73
4.2 Methods of producing light . . . 74
4.3 Gas discharges . . . 74
4.4 Sodium lamps . . . 75
4.5 Mercury lamps . . . 76
4.6 Fluorescent lamps . . . 78
4.7 Xenon lamps . . . 81
4.8 Incandescent light sources . . . 82
4.9 Tungsten lamps . . . 86
4.10 Tungsten halogen lamps . . . 87
4.11 Light emitting diodes . . . 88
4.12 Daylight . . . 89
4.13 Standard illuminants and sources . . . 91
4.14 CIE standard illuminant A . . . 91
4.15 CIE illuminants B and C . . . 92
4.16 CIE sources . . . 93
4.17 CIE illuminants D . . . 94
4.18 CIE indoor daylight . . . 94
4.19 Comparison of commonly used sources . . . 96
References . . . 97
General References . . . 97

5 Obtaining Spectral Data and Tristimulus Values **99**
5.1 Introduction . . . 99
5.2 Radiometry and photometry . . . 99
5.3 Spectroradiometry . . . 100
5.4 Tele-spectroradiometry . . . 100
5.5 Spectroradiometry of self-luminous colours . . . 101
5.6 Spectrophotometry of non-self-luminous colours . . . 101
5.7 Reference whites and working standards . . . 102
5.8 Geometries of illumination and viewing . . . 103
5.9 CIE Geometries of illumination and measurement . . . 104
5.10 Spectroradiometers and spectrophotometers . . . 108
5.11 Choice of illuminant . . . 110
5.12 Calculation of tristimulus values from spectral data . . . 111
5.13 Colorimeters using filtered photo-detectors . . . 114
References . . . 115
General References . . . 115

6 Metamerism and Colour Constancy **117**
6.1 Introduction . . . 117
6.2 The cause of metamerism . . . 117
6.3 The definition of metamerism . . . 118
6.4 Examples of metamerism in practice . . . 119
6.5 Degree of metamerism . . . 121
6.6 Index of metamerism for change of illuminant . . . 122
6.7 Index of metamerism for change of observer . . . 122
6.8 Index of metamerism for change of field size . . . 124
6.9 Colour matches and geometry of illumination and measurement . . . 124
6.10 Correcting for inequalities of tristimulus values . . . 125
6.11 Terms used in connection with metamerism . . . 126
6.12 Colour inconstancy . . . 127
6.13 Chromatic adaptation transforms . . . 129
6.14 The Von Kries transform . . . 130
6.15 The CAT02 transform . . . 131
6.16 A colour inconstancy index . . . 134
6.17 Worked examples . . . 135
References . . . 141

7 Colour Rendering by Light Sources **143**
7.1 Introduction . . . 143
7.2 The meaning of colour rendering . . . 144
7.3 CIE colour rendering indices . . . 145
7.4 Spectral band methods . . . 147
7.5 Other methods for assessing the colour rendering of light sources . . . 150

7.6 Comparison of commonly used sources 151
References 152
General References 154

8 Colour Order Systems **155**
8.1 Introduction 155
8.2 Variables 155
8.3 Optimal colours 157
8.4 The Munsell System 159
8.5 The Munsell Book of Color 164
8.6 Unique hues and colour opponency 168
8.7 The Natural Colour System (NCS) 170
8.8 Natural Colour System Atlas 172
8.9 The DIN System 179
8.10 The Coloroid System 182
8.11 The Optical Society of America (OSA) System 183
8.12 The Hunter Lab System 187
8.13 The Tintometer 190
8.14 The Pantone System 191
8.15 The RAL System 191
8.16 Advantages of colour order systems 192
8.17 Disadvantages of colour order systems 192
References 194
General References 195

9 Precision and Accuracy in Colorimetry **197**
9.1 Introduction 197
9.2 Sample preparation 198
9.3 Thermochromism 199
9.4 Geometry of illumination and measurement 199
9.5 Reference white calibration 200
9.6 Polarisation 200
9.7 Wavelength calibration 202
9.8 Stray light 202
9.9 Zero level and linearity 202
9.10 Use of secondary standards 203
9.11 Bandwidth 203
9.12 Correcting for errors in the spectral data 204
9.13 Calculations 207
9.14 Precautions to be taken in practice 214
References 215

10 Fluorescent Colours **219**
10.1 Introduction 219
10.2 Terminology 219
10.3 Use of double monochromators 220

10.4 Illumination with white light . . . 221
10.5 Correcting for differences between an actual and the desired source . . . 222
10.6 Two-monochromator method . . . 224
10.7 Two-mode method . . . 225
10.8 Filter-reduction method . . . 226
10.9 Luminescence-weakening method . . . 226
10.10 Practical considerations . . . 227
References . . . 230

11 RGB Colorimetry **231**
11.1 Introduction . . . 231
11.2 Choice and specification of matching stimuli . . . 231
11.3 Choice of units . . . 233
11.4 Chromaticity diagrams using r and g . . . 233
11.5 Colour-matching functions in RGB systems . . . 234
11.6 Derivation of XYZ from RGB tristimulus values . . . 235
11.7 Using television and computer displays . . . 239
References . . . 240
General Reference . . . 240

12 Colorimetry with Digital Cameras **241**
12.1 Introduction . . . 241
12.2 Camera characterisation . . . 242
12.3 Metamerism . . . 244
12.4 Characterisation methods . . . 244
12.5 Practical considerations in digital camera characterisation . . . 249
12.6 Practical example . . . 251
12.7 Discussion . . . 254
References . . . 255
General References . . . 256

13 Colorant Mixtures **257**
13.1 Introduction . . . 257
13.2 Non-diffusing colorants in a transmitting layer . . . 257
13.3 Non-diffusing colorants in a layer in optical contact with a diffusing surface . . . 259
13.4 Layers containing colorants which diffuse and absorb light . . . 262
13.5 The use of multi-spectral analysis to reduce metamerism in art restoration . . . 264
References . . . 265
General References . . . 265

14 Factors Affecting the Appearance of Coloured Objects **267**
14.1 Introduction . . . 267
14.2 Measuring optical properties . . . 267
14.3 Colour . . . 268
14.4 Gloss . . . 271

14.5 Translucency 279
14.6 Surface texture 281
14.7 Conclusions 289
References 289

15 The CIE Colour Appearance Model CIECAM02 **293**
15.1 Introduction 293
15.2 Visual areas in the observing field 294
15.3 Chromatic adaptation in CIECAM02 294
15.4 Spectral sensitivities of the cones in CIECAM02 295
15.5 Cone dynamic response functions in CIECAM02 297
15.6 Luminance adaptation in CIECAM02 297
15.7 Criteria for achromacy and for constant hue in CIECAM02 299
15.8 Effects of luminance adaptation in CIECAM02 300
15.9 Criteria for unique hues in CIECAM02 303
15.10 Redness-greenness, a, and yellowness-blueness, b, in CIECAM02 303
15.11 Hue angle, h, in CIECAM02 305
15.12 Eccentricity factor, e, in CIECAM02 305
15.13 Hue quadrature, H, and hue composition, H_c, in CIECAM02 306
15.14 The achromatic response, A, in CIECAM02 308
15.15 Correlate of lightness, J, in CIECAM02 308
15.16 Correlate of brightness, Q, in CIECAM02 309
15.17 Correlate of chroma, C, in CIECAM02 310
15.18 Correlate of colourfulness, M, in CIECAM02 311
15.19 Correlate of saturation, s, in CIECAM02 311
15.20 Comparison of CIECAM02 with the natural colour system 311
15.21 Testing model CIECAM02 312
15.22 Filtration of projected slides and CIECAM02 314
15.23 Comparison of CIECAM02 with CIECAM97s 315
15.24 Uniform colour space based on CIECAM02 315
15.25 Some problems with CIECAM02 316
15.26 Steps for using the CIECAM02 model 316
15.27 Steps for using the CIECAM02 model in reverse mode 319
15.28 Worked example for the model CIECAM02 321
References 322

16 Models of Colour Appearance for Stimuli of Different Sizes **325**
16.1 Introduction 325
16.2 Stimuli of different sizes 325
16.3 Room colours 325
16.4 A model for predicting room colours 326
16.5 Steps in using the model for predicting room colours 327
References 328

17 Model of Colour Appearance for Unrelated Colours in Photopic and Mesopic Illuminances **329**
17.1 Introduction . . . 329
17.2 A model for predicting unrelated colours . . . 330
17.3 Input data required for the model . . . 331
17.4 Steps in using the model for unrelated colours . . . 332
17.5 Worked example in the model for predicting unrelated colours . . . 333
References . . . 334

Appendices **335**

Appendix 1 Radiometric and Photometric Terms and Units **337**
A1.1 Introduction . . . 337
A1.2 Physical detectors . . . 337
A1.3 Photometric units and terms . . . 338
A1.4 Radiant and quantum units and terms . . . 340
A1.5 Radiation sources . . . 340
A1.6 Terms for measures of reflection and transmission . . . 341
A1.7 Other spectral luminous efficiency functions . . . 343
A1.8 Mesopic photometry . . . 343
Reference . . . 344

Appendix 2 Spectral Luminous Efficiency Functions **345**

Appendix 3 CIE Colour-Matching Functions **347**

Appendix 4 CIE Spectral Chromaticity Co-Ordinates **351**

Appendix 5 Relative Spectral Power Distributions of Illuminants **355**
A5.1 Introduction . . . 355
A5.2 CIE illuminants . . . 355
A5.3 Representative fluorescent lamps . . . 359
A5.4 Planckian radiators . . . 368
A5.5 Gas discharge lamps . . . 371
A5.6 Method of calculating D illuminant distributions . . . 374

Appendix 6 Colorimetric Formulae **379**
A6.1 Chromaticity relationships . . . 379
A6.2 CIELUV, CIELAB, and U*V*W* relationships . . . 379

Appendix 7 Calculation of the CIE Colour Rendering Indices **383**
A7.1 Spectral radiance factors of test colours 383
A7.2 Worked example of the CIE colour rendering indices 388

Appendix 8 Illuminant-Observer Weights for Calculating Tristimulus Values **393**

Appendix 9 Glossary of Terms **431**
Reference 453

Index **455**