CONTENTS

Pı	Preface	
C	Contributors and Referees	
	Part I Historic retrospection	
1	Translation of CIE 1931 Resolutions on Colorimetry <i>Translated by P. Bodrogi</i>	1
	Decision 1 Decision 2 Appendix to Decision 2 Decision 3 Decision 3a Decision 4 Decision 5	1 4 5 5 8 8 8 8
2	Professor Wright's Paper from the Golden Jubilee Book: The Historical and Experimental Background to the 1931 CIE System of Colorimetry W. D. Wright	9
	Color mixture and measurement in the Nineteenth Century American contributions to photometry and colorimetry, 1900–24 The run-up to the 1931 observer: 1924–30 The drama of 1931 Postscript to 1931 Note added in proof References	9 11 12 17 21 22 22

Part II Colorimetric fundamentals

3	CIE Colorimetry	25
	János Schanda	
	Introduction	25
	CIE standard colorimetric observers	27
	The CIE 1931 standard colorimetric observer	29
	Determination of the $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ color-matching functions	29
	Derivation of the CIE XYZ trichromatic system from the	
	CIE RGB trichromatic system	29
	Tristimulus values and chromaticity coordinates	31
	CIE 1964 standard colorimetric observer	35
	k_{10} in the tristimulus values of self-luminous objects for	
	the 10° observer	36
	k_{10} in the tristimulus values of non-self-luminous objects for	
	the 10° observer	36
	Chromaticity coordinates for the 10° observer	37
	Notes on the use of the CIE 1964 standard colorimetric observer	37
	CIE illuminants and sources	37
	CIE standard illuminant A and Planckian radiators	38
	Daylight illuminants	40
	CIE standard illuminant D65	42
	CIE illuminants	43
	CIE sources and simulators for colorimetry	44
	Source A	44
	Sources B and C	45
	Source D65	45
	Standards and recommendations for measuring	
	reflecting/transmitting materials	47
	Terms used in conjunction with transmission	
	and reflection measurement	47
	Phenomena	47
	Quantities to describe reflection and transmission	48
	Measuring geometries	49
	The sample plane and influx geometry	50
	Directional geometries	54
	Quantities using different measuring geometries	55
	Nonstandard geometries	55
	Recommended geometry for transmission measurements	55
	Standards of reflectance	57
	Uniform chromaticity diagram and uniform color spaces	58
	Uniform chromaticity diagram, CIE 1976 UCS diagram	59
	CIE 1976 uniform color spaces	60

CONTENTS

	CIE 1976 ($L^*a^*b^*$) color space, CIELAB color space	61
	CIE 1976 $(L^*u^*v^*)$ color space, CIELUV color space	64
	Descriptors of chromaticity	65
	Dominant/complementary wavelength and purity	65
	Correlated color temperature	67
	Whiteness	68
	Metamerism	70
	Special metamerism index: change in illuminant	71
	Special metamerism index: change in observer	72
	Summary	74
	Appendix A	74
	Appendix B	75
	References	76
4	CIE Color Difference Metrics	79
	Klaus Witt	
	Introduction	79
	MacAdam's experiments on variable stimuli	80
	Adams' and Nickerson's contribution to color	
	difference evaluation	82
	Constant stimuli experiments	83
	CIE 1976 color difference formulas	84
	Testing and improving CIELAB	88
	Collection of new datasets	91
	Development of CIEDE2000	91
	Further developments	97
	References	98
5	Spectral Color Measurement	101
	Yoshi Ohno	
	Introduction	101
	General practice in spectral color measurements	102
	Type of instruments	102
	Use of spectroradiometers for light	102
	source color measurement	103
	Irradiance mode	104
	Radiance mode	105
	Total flux mode	106
	Colorimetric calculation	107
	Use of spectrophotometers for object color measurements	107
	Geometries for reflectance color measurement	108
	Color calculation	109

vii

	Critical parameters of spectrometers for color measurement	109
	Sampling interval and bandpass of instruments	109
	Sampling interval for object color measurement	110
	Effect of bandpass in object color measurement	112
	Effect of bandpass and scanning interval in measurement	
	of light sources	112
	Wavelength scale error	116
	Uncertainties in measured spectral values	118
	Stray light in the monochromator	119
	Other sources of error	122
	Methods for corrections of error	123
	Correction of bandpass error	123
	ASTM E308	123
	Stearns and Stearns' method	124
	Extended method for bandpass correction	125
	Summary for bandwidth and scanning interval requirements	127
	Correction of stray light	128
	Uncertainty analysis	129
	Basic steps	130
	Numerical method for sensitivity coefficient	131
	Acknowledgment	132
	References	132
6	Tristimulus Color Measurement of Self-Luminous Sources	135
č	János Schanda, George Eppeldauer, and Georg Sauter	100
	· · · ·	105
	Introduction	135
	Basic structure of a tristimulus colorimeter	136
	Input optics of a colorimeter for self-luminous objects	137
	Illuminance-meter-type input optics	137
	Luminance-meter-type input optics	138
	Image-taking colorimeters	139
	Spectral matching of the colorimeter	139
	Electronics	142
	Calibration	142
	Calibration with a standard source Calibration based on standard detectors	142
		144
	Introduction	144
	The spectral responsivity based calibration method Calibration and measurement considerations	144
	Campranon and measurement considerations	
		145
	Transfer of calibration	147
	Transfer of calibration Uncertainty estimation of a tristimulus colorimeter measurement	
	Transfer of calibration Uncertainty estimation of a tristimulus colorimeter measurement Principle of the tristimulus calibration for a self-luminous	147 148
	Transfer of calibration Uncertainty estimation of a tristimulus colorimeter measurement	147

CC	CONTENTS	
	Calibration for selected spectral distributions	152
	Glossary	154
	Basic terms	154
	Specific terms	155
	References	156
7	Color Management	159
	Ján Morovič and Johan Lammens	
	Introduction	159
	Color reproduction objectives	160
	Viewing a pair of colors	161
	Conceptual stages of color reproduction	163
	Device color spaces	164
	Device characterization and calibration	165
	Color appearance model	166
	Color and image enhancement	166
	Color gamut mapping	167
	Completing the process	168
	The ICC color management framework	168
	sRGB color management	170
	Challenges of color management	171
	Does color need to be managed?	172
	Analog color management	174
	Watercolor reproduction scenario	176
	Original to scan	177
	Challenges of scanner characterization	178
	Scanner characterization models	180
	Scanner ICC profiles	181
	Scanned watercolor	182
	Scan to display	182
	Challenges of display characterization	183
	Display characterization models and their implementation	
	in profiles	183
	Transforming scanned data to data for display	184
	Editing and page layout	185
	Proofing	188
	Proof printer calibration	189
	Proof printer characterization	190
	Rendering intents for proofing	191
	Evaluation of proof prints	192
	Challenges and opportunities	193
	Poster and leaflet production	193
	Future opportunities	194
	Self-calibrating and self-profiling devices	195
	our-catorading and sen-promiting devices	195

8

Workflow automation	196
Automatic adaptation to viewing environment	198
Spatial processing	200
Smart CMMs	200
Multispectral imaging (CIE TC8-07)	202
Conclusion	202
Acknowledgments	202
References	203
Color Rendering of Light Sources János Schanda	207
Introduction	207
The official CIE test sample method of color	
rendering evaluation	208
Recent investigations to update the color-rendering index calculation	211
Supplementary methods to describe color quality of light sources	213
Summary	214
References	215

Part III Advances in colorimetry

9	Color-Matching Functions: Physiological Basis	219
	Françoise Viénot and Pieter Walraven	
	The link between colorimetry and physiology	219
	The definition of cone fundamentals	220
	Historical background	220
	Decision by CIE	220
	Available experimental data	220
	State of the art in physiology	220
	In vitro measurements	220
	The principle of univariance	221
	Dartnall nomogram: dilute pigment: effective transmission	
	optical density	221
	Available psychophysical measurements	222
	Spectral sensitivity functions of dichromats and the	
	König hypothesis	222
	Spectral sensitivity functions of isolated cone mechanisms	222
	Short description of colorimetric databases	223
	Extending colorimetric data from 10° field to any field size	
	from 10° to 1°	226
	The cone fundamentals	226
	Linear transformation that yields the 10° cone fundamentals	227
	Validation of cone fundamentals	228

10

Calculation ashama from dilute photonigment exectral	
Calculation scheme from dilute photopigment spectral	228
absorbance to color-matching functions, and reverse Lens and other preretinal media	228
Macular pigment	229
Calculation scheme from dilute photopigment spectral	
absorbance to cone spectral absorbance, and reverse	229
S-cone fundamental from 510 to 615 nm	
$(2^{\circ} \text{ field and } 10^{\circ} \text{ field})$	231
Extension to any field size	231
The aging observer	231
The calculation of tristimulus values	232
CIE recommendations from CIE and final tables	233
Discussion and perspectives	235
An isoluminant fundamental chromaticity diagram	235
Units and luminous efficiency function	235
The <i>l</i> , <i>s</i> chromaticity diagram	235
A CIE-like chromaticity diagram	230
Individual variations	237
At the receptoral level	238
Postreceptoral processing: weighting L-signals and M-signal	
for luminance	238
Examples of applications: The future	238
Color vision deficiencies	238
Observer metamerism	239
Color differences	239
Color appearance models	239
Conclusion	240
Acknowledgments	240
References	240
References	210
Open Problems on the Validity of Grassmann's Laws	245
Michael H. Brill and Alan R. Robertson	
Definition of the problem	245
Historical review	246
Theoretical approaches	248
Generalizations of grassmann additivity	248
Theory of transformation of primaries	250
Numerical experiment	251
Summary of the method	251
Results and discussion	252
Conclusion	254
Activities of CIE TC 1–56	254
The future	257
References	258

xi

11	CIE Color Appearance Models and Associated Color Spaces <i>M. Ronnier Luo and Changjun Li</i>	261	
	Introduction	261	
	Viewing conditions	262	
	Stimulus	262	
	Proximal field	263	
	Background		
	Surround	263	
	Adapting field Color appearance datasets		
	Chromatic adaptation transforms	264	
	Light and chromatic adaptation	264	
	Physiological mechanisms	264	
	Chromatic adaptation	264	
	Development of the CAT02 used in CIECAM02	266	
	CIE Color appearance models	268	
	CIECAM97s	269	
	CIECAM02	270	
	Color appearance phenomena	271	
	Chromatic adaptation	271	
	Hunt effect Stevens effect		
	Surround effect Lightness contrast effect Helmholtz-Kohlrausch effect Helson-Judd effect Uniform Color Spaces based on CIECAM02	275 276 276 277	
			CIECAM02-based color spaces
		Comparing the performance of the new UCSs with some	
	selected color models	278	
	Conclusions	280	
	References	281	
	Appendix A: chromatic adaptation transform: CAT02	284	
	Part 1: Forward Mode	284	
	Part 2: Reverse Mode	285	
	Appendix B: CIE color appearance model: CIECAM02	286	
	Part 1: The Forward Mode	286	
	Part 2: The Reverse Mode	291	
12	Image Appearance Modeling	295	
	Garrett M. Johnson and Mark D. Fairchild		

Introduction	295
From simple to complex color appearance	296

xii

CONTENTS

	Image appearance modeling	300
	The general iCAM framework for image appearance	301
	Specific implementations of image appearance models:	
	high-dynamic range tone-mapping	308
	Testing high-dynamic range rendering algorithms	312
	An implementation of image appearance for calculating	
	image differences	314
	Spatial frequency adaptation	318
	Calculating image differences	319
	Conclusions and future considerations	320
	References	321
13	Spatial and Temporal Problems of Colorimetry	325
	Eugenio Martinez–Uriegas	
	Introduction	325
	Radiometry, photometry, colorimetry, and human vision	325
	Standards of color: the role of biology and psychophysics	326
	Spatial and temporal constraints of colorimetry: a selective overview	329
	Spectral, spatial, and temporal dimensions of visible light	329
	Classical separation of spatial, temporal, and color vision	330
	Two examples of spatial limitations of colorimetry	331
	Representation of spatial and temporal properties of visible light	335
	Spatial and temporal distributions of visible light	335 338
	Detection and discrimination thresholds	330
	Visual multiplexing of spatiotemporal chromatic	340
	and achromatic information	340
	Developing CSF standards	342
	General approach: data-based or theory-based standard Initial results	343
	Multiscale colorimetry: a spatiotemporal path forward	345
	Example of multiscale image decomposition	345
	Scale-shifting conjecture	348
	Multiscale colorimetry: a spatiotemporal path forward	348
	Summary thoughts	352
	References	352
14	The Future of Colorimetry in the CIE	355
	Robert W.G. Hunt	
	Introduction	355
	Color matching	355
	Color difference	357
	Color appearance	359
	Sources of funds	362
	References	362

ppendix 1 Measurement Uncertainty Georg Sauter	3
Introduction	3
Definitions and types for the evaluation of uncertainty	3
Definitions of terms	3
Types for the evaluation of uncertainty	3
Model of evaluation of uncertainty	3
Monte Carlo method	3
Model with two or more output quantities	3
Expanded uncertainty	
Steps for evaluating uncertainty	2
Practical examples	3
Determination of the spectral irradiance of a source	3
Principle of a spectral irradiance measurement	3
Operation of a spectral irradiance standard	
Mechanical alignments	
Uncertainty Budget	
Determination of f'_1 values	
Uncertainty of f'_1 values with Monte Carlo method	
References	<u>-</u>
References ppendix 2 Uncertainties in Spectral Color Measurement James L. Gardner	3
ppendix 2 Uncertainties in Spectral Color Measurement	3
ppendix 2 Uncertainties in Spectral Color Measurement James L. Gardner	:
ppendix 2 Uncertainties in Spectral Color Measurement James L. Gardner Introduction Tristimulus values	2
ppendix 2 Uncertainties in Spectral Color Measurement James L. Gardner Introduction	
ppendix 2 Uncertainties in Spectral Color Measurement James L. Gardner Introduction Tristimulus values Uncertainty propagation	
ppendix 2 Uncertainties in Spectral Color Measurement James L. Gardner Introduction Tristimulus values Uncertainty propagation Tristimulus uncertainties by component	
ppendix 2 Uncertainties in Spectral Color Measurement James L. GardnerIntroductionTristimulus valuesUncertainty propagationTristimulus uncertainties by componentRandom component effects	
Appendix 2 Uncertainties in Spectral Color Measurement James L. Gardner Introduction Tristimulus values Uncertainty propagation Tristimulus uncertainties by component Random component effects Systematic component effects	
Appendix 2 Uncertainties in Spectral Color Measurement James L. Gardner Introduction Tristimulus values Uncertainty propagation Tristimulus uncertainties by component Random component effects Systematic component effects Propagation from tristimulus uncertainties to colour-value	
ppendix 2 Uncertainties in Spectral Color Measurement James L. GardnerIntroductionTristimulus valuesUncertainty propagationTristimulus uncertainties by componentRandom component effectsSystematic component effectsPropagation from tristimulus uncertainties to colour-valueuncertaintiesMethods of calculation for color triplets (x,y,Y) color coordinates	
ppendix 2 Uncertainties in Spectral Color MeasurementJames L. GardnerIntroductionTristimulus valuesUncertainty propagationTristimulus uncertainties by componentRandom component effectsSystematic component effectsPropagation from tristimulus uncertainties to colour-valueuncertaintiesMethods of calculation for color triplets	
ppendix 2 Uncertainties in Spectral Color Measurement James L. GardnerIntroductionTristimulus valuesUncertainty propagationTristimulus uncertainties by componentRandom component effectsSystematic component effectsPropagation from tristimulus uncertainties to colour-valueuncertaintiesMethods of calculation for color triplets (x,y,Y) color coordinates	
ppendix 2 Uncertainties in Spectral Color Measurement James L. GardnerIntroductionTristimulus valuesUncertainty propagationTristimulus uncertainties by componentRandom component effectsSystematic component effectsPropagation from tristimulus uncertainties to colour-valueuncertaintiesMethods of calculation for color triplets (x,y,Y) color coordinates (u,v,Y) color coordinates	
ppendix 2 Uncertainties in Spectral Color Measurement James L. GardnerIntroductionTristimulus valuesUncertainty propagationTristimulus uncertainties by componentRandom component effectsSystematic component effectsPropagation from tristimulus uncertainties to colour-value uncertaintiesMethods of calculation for color triplets (x,y,Y) color coordinates (u',y',Y) color coordinates (L^*,a^*,b^*) color coordinates (L^*,C^*,h^*) color coordinates (based on a^*, b^*)	
ppendix 2 Uncertainties in Spectral Color Measurement James L. GardnerIntroductionTristimulus valuesUncertainty propagationTristimulus uncertainties by componentRandom component effectsSystematic component effectsPropagation from tristimulus uncertainties to colour-value uncertaintiesMethods of calculation for color triplets (x,y,Y) color coordinates (u',y',Y) color coordinates (L^*, a^*, b^*) color coordinates	
ppendix 2 Uncertainties in Spectral Color Measurement James L. GardnerIntroductionTristimulus valuesUncertainty propagationTristimulus uncertainties by componentRandom component effectsSystematic component effectsPropagation from tristimulus uncertainties to colour-valueuncertaintiesMethods of calculation for color triplets (x,y,Y) color coordinates (u',y',Y) color coordinates (L^*, a^*, b^*) color coordinates (L^*, c^*, h^*) color coordinates (L^*, u^*, v^*) color coordinates (L^*, u^*, v^*) color coordinates (L^*, c^*, h) color coordinates	
ppendix 2 Uncertainties in Spectral Color Measurement James L. GardnerIntroductionTristimulus valuesUncertainty propagationTristimulus uncertainties by componentRandom component effectsSystematic component effectsPropagation from tristimulus uncertainties to colour-value uncertaintiesMethods of calculation for color triplets (x,y,Y) color coordinates (u',y',Y) color coordinates (L^*, a^*, b^*) color coordinates (L^*, c^*, h^*) color coordinates (L^*, u^*, v^*) color coordinates	
ppendix 2 Uncertainties in Spectral Color Measurement James L. GardnerIntroductionTristimulus valuesUncertainty propagationTristimulus uncertainties by componentRandom component effectsSystematic component effectsPropagation from tristimulus uncertainties to colour-valueuncertaintiesMethods of calculation for color triplets (x,y,Y) color coordinates (u',y',Y) color coordinates (L^*,a^*,b^*) color coordinates (L^*,c^*,h^*) color coordinates (L^*,c^*,h) color coordinates $(based on u^*,v^*)$ (L^*,s,h) color coordinates (based on u^*,v^*) (L^*,s,h) color coordinates (based on u^*,v^*)	
ppendix 2 Uncertainties in Spectral Color Measurement James L. GardnerIntroductionTristimulus valuesUncertainty propagationTristimulus uncertainties by componentRandom component effectsSystematic component effectsPropagation from tristimulus uncertainties to colour-valueuncertaintiesMethods of calculation for color triplets (x,y,Y) color coordinates (u',y',Y) color coordinates (L^*, a^*, b^*) color coordinates (L^*, a^*, b^*) color coordinates (L^*, a^*, v^*) color coordinates (L^*, c^*, h) color coordinates (based on u^*, v^*) (L^*, s, h) color coordinates (based on u^*, v^*)	

Random scaling components	403
Systematic scaling components	403
Offsets in the spectral values	403
Random offset components	404
Systematic offset components	404
Wavelength errors	404
Random wavelength offsets	405
Systematic wavelength offsets	405
Determining measurement components	405
Background offsets	406
Noise versus drift	406
Source noise	407
Band-limited spectra	407
Wavelength uncertainties	407
Nonlinearity	408
Corrections	408
Conclusion	409
References	409
and Textile Industries Robert Hirschler and Joanne Zwinkels	411
Introduction	411
Pulp and paper applications	411
Introduction	411
Beneficiaries of CIE colorimetry	413
CIE illuminant C and CIE standard geometry d/0	413
Other CIE standard illuminants and standardized light sources	415
CIE color spaces	416
CIE reference standards	416
CIE whiteness and tint equations	418
Harmonized Terminology	419
Driving force in the development of CIE colorimetry	419
Establishment of new CIE technical committees	419
Practical simulator of illuminant D65	420
Future needs	422
Conclusion	422
Textile applications	423
Introduction	423
CIELAB color space and its derivations	423
Characterization of the buildup of colorants and of	
colorant combinations	423
Standard Depth (SD)	424
Color difference evaluation	425

xv

		-
¥	v	¥.

Shade sorting, tapering	425
Fastness evaluation	427
Determination of whiteness	427
Recipe formulation	429
Future needs	429
Conclusion	430
References	430
Appendix 4 List of CIE Publications	435
Recommendations	435
Standards	435
Technical committee reports	436
Proceedings of the sessions	441
Discs and other publications	442
Special publications	442
CIE publications on CD-ROM	443
Glossary	445
Index	453