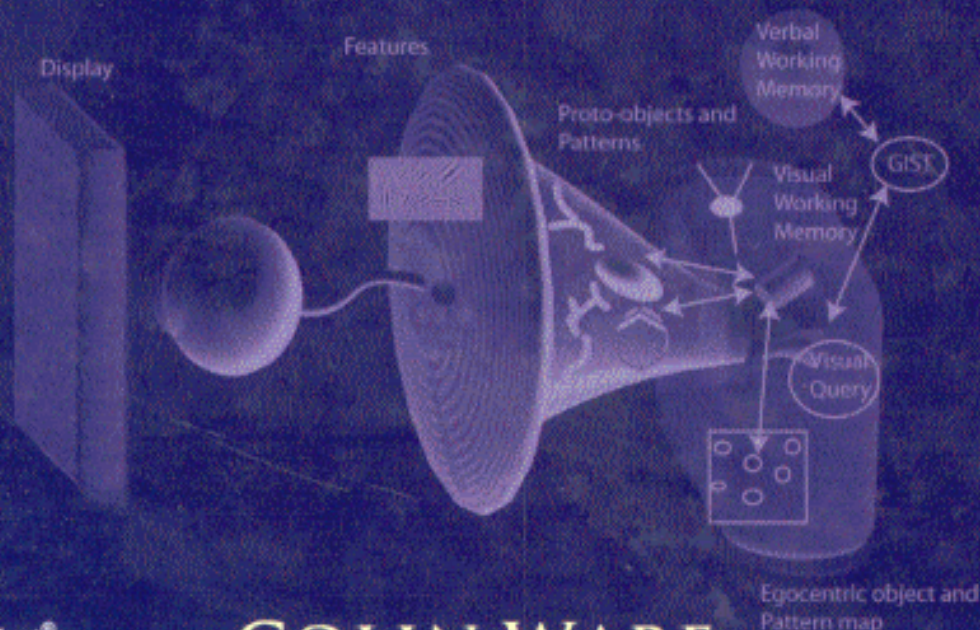


SECOND EDITION

INFORMATION VISUALIZATION

PERCEPTION FOR DESIGN



COLIN WARE

CONTENTS

Figure Credits xv

Foreword xvii

Preface xix

Preface to the First Edition xxi

CHAPTER 1

Foundation for a Science of Data Visualization 1

Visualization Stages 4

Experimental Semiotics Based on Perception 5

Semiotics of Graphics 6

Pictures as Sensory Languages 8

Sensory versus Arbitrary Symbols 10

Properties of Sensory and Arbitrary Representation 13

Testing Claims about Sensory Representations 15

Arbitrary Conventional Representations 15

The Study of Arbitrary Conventional Symbols 17

A Model of Perceptual Processing 20

Stage 1: Parallel Processing to Extract Low-Level Properties of the Visual Scene 20

Stage 2: Pattern Perception 21

Stage 3: Sequential Goal-Directed Processing 22

Types of Data 23

Entities 23

Relationships 23

Attributes of Entities or Relationships 24

Operations Considered as Data 25

Metadata 26

Conclusion 27

CHAPTER 2

The Environment, Optics, Resolution, and the Display 29

The Environment	30
<i>Visible Light</i>	30
<i>Ecological Optics</i>	30
<i>Optical Flow</i>	32
<i>Textured Surfaces and Texture Gradients</i>	33
<i>The Paint Model of Surfaces</i>	35
The Eye	38
<i>The Visual Angle Defined</i>	40
<i>The Lens</i>	41
<i>Optics and Augmented-Reality Systems</i>	42
<i>Optics in Virtual-Reality Displays</i>	45
<i>Chromatic Aberration</i>	45
<i>Receptors</i>	46
<i>Simple Acuities</i>	47
<i>Acuity Distribution and the Visual Field</i>	50
<i>Brain Pixels and the Optimal Screen</i>	53
<i>Spatial Contrast Sensitivity Function</i>	57
<i>Visual Stress</i>	62
The Optimal Display	62
<i>Aliasing</i>	63
<i>Number of Dots</i>	65
<i>Superacuities and Displays</i>	65
<i>Temporal Requirements of the Perfect Display</i>	66
Conclusion	67

CHAPTER 3

Lightness, Brightness, Contrast, and Constancy 69

Neurons, Receptive Fields, and Brightness Illusions	70
<i>Simultaneous Brightness Contrast</i>	72
<i>Mach Bands</i>	74
<i>The Chevreul Illusion</i>	74

<i>Simultaneous Contrast and Errors in Reading Maps</i>	75
<i>Contrast Effects and Artifacts in Computer Graphics</i>	75
<i>Edge Enhancement</i>	77
Luminance, Brightness, Lightness, and Gamma	80
<i>Luminance</i>	81
<i>Brightness</i>	83
<i>Adaptation, Contrast, and Lightness Constancy</i>	84
<i>Contrast and Constancy</i>	86
<i>Perception of Surface Lightness</i>	87
<i>Lightness Differences and the Gray Scale</i>	88
<i>Monitor Illumination and Monitor Surrounds</i>	90
Conclusion	93

CHAPTER 4

Color 97

Trichromacy Theory	98
Color Blindness	99
Color Measurement	100
<i>Change of Primaries</i>	102
CIE System of Color Standards	103
<i>Chromaticity Coordinates</i>	104
<i>Color Differences and Uniform Color Spaces</i>	108
Opponent Process Theory	110
<i>Naming</i>	110
<i>Cross-Cultural Naming</i>	112
<i>Unique Hues</i>	112
<i>Neurophysiology</i>	113
<i>Categorical Colors</i>	113
<i>Properties of Color Channels</i>	113
Color Appearance	116
<i>Color Contrast</i>	117
<i>Saturation</i>	117
<i>Brown</i>	118

Applications of Color in Visualization	119
<i>Application 1: Color Specification Interfaces and Color Spaces</i>	119
<i>Application 2: Color for Labeling</i>	123
<i>Application 3: Color Sequences for Data Maps</i>	127
<i>Application 4: Color Reproduction</i>	138
<i>Application 5: Color for Exploring Multidimensional Discrete Data</i>	140
Conclusion	143

CHAPTER 5

Visual Attention and Information that Pops Out 145

Searching the Visual Field	146
<i>Useful Field of View</i>	146
<i>Tunnel Vision and Stress</i>	147
<i>The Role of Motion in Attracting Attention</i>	147
Reading from the Iconic Buffer	147
<i>Preattentive Processing</i>	149
<i>Rapid Area Judgments</i>	154
<i>Coding with Combinations of Features</i>	154
<i>Conjunctions with Spatial Dimensions</i>	155
<i>Highlighting</i>	156
<i>Designing a Symbol Set</i>	157
Neural Processing, Graphemes, and Tuned Receptors	159
<i>The Grapheme</i>	160
The Gabor Model and Texture in Visualization	161
<i>Texture Segmentation</i>	163
<i>Tradeoffs in Information Density: An Uncertainty Principle</i>	163
Texture Coding Information	164
<i>Primary Perceptual Dimensions of Texture</i>	164
<i>Generation of Distinct Textures</i>	166
<i>Spatial-Frequency Channels, Orthogonality, and Maps</i>	167
<i>Texture Resolution</i>	169
<i>Texture Contrast Effects</i>	170
<i>Other Dimensions of Visual Texture</i>	170
<i>Texture Field Displays</i>	172

Glyphs and Multivariate Discrete Data	176
<i>Restricted Classification Tasks</i>	177
<i>Speeded Classification Tasks</i>	178
<i>Integral-Separable Dimension Pairs</i>	180
<i>Monotonicity of Visual Attributes</i>	181
<i>Multidimensional Discrete Data</i>	182
<i>Stars, Whiskers, and Other Glyphs</i>	184
Conclusion	185

CHAPTER 6

Static and Moving Patterns 187

Gestalt Laws	189
<i>Proximity</i>	189
<i>Similarity</i>	190
<i>Connectedness</i>	191
<i>Continuity</i>	191
<i>Symmetry</i>	192
<i>Closure</i>	194
<i>Relative Size</i>	196
<i>Figure and Ground</i>	196
More on Contours	198
<i>Perceiving Direction: Representing Vector Fields</i>	200
<i>Comparing 2D Flow Visualization Techniques</i>	201
Perception of Transparency: Overlapping Data	205
<i>Pattern Learning</i>	206
The Perceptual Syntax of Diagrams	210
<i>The Grammar of Node-Link Diagrams</i>	210
<i>The Grammar of Maps</i>	215
Patterns in Motion	217
<i>Form and Contour in Motion</i>	219
<i>Moving Frames</i>	220
<i>Expressive Motion</i>	221
<i>Perception of Causality</i>	222

Perception of Animate Motion 223
Enriching Diagrams with Simple Animation 224

Conclusion 225

CHAPTER 7

Visual Objects and Data Objects 227

Image-Based Object Recognition 228
Applications of Images in User Interfaces 230

Structure-Based Object Recognition 233
Geon Theory 233
Silhouettes 233

Faces 237

The Object Display and Object-Based Diagrams 239
The Geon Diagram 241

Perceiving the Surface Shapes of Objects 243
Spatial Cues for Representing Scalar Fields 244
Integration of Cues for Surface Shape 247
Interaction of Shading and Contour 248
Guidelines for Displaying Surfaces 252
Bivariate Maps: Lighting and Surface Color 254

Cushion Maps 255

Integration 255

Conclusion 257

CHAPTER 8

Space Perception and the Display of Data in Space 259

Depth Cue Theory 259
Perspective Cues 260
Pictures Seen from the Wrong Viewpoint 263
Occlusion 265
Depth of Focus 266

<i>Cast Shadows</i>	266
<i>Shape-from-Shading</i>	268
<i>Eye Accommodation</i>	269
<i>Structure-from-Motion</i>	269
<i>Eye Convergence</i>	270
<i>Stereoscopic Depth</i>	271
<i>Problems with Stereoscopic Displays</i>	273
<i>Making Effective Stereoscopic Displays</i>	274
<i>Artificial Spatial Cues</i>	279
<i>Depth Cues in Combination</i>	280
Task-Based Space Perception	283
<i>Tracing Data Paths in 3D Graphs</i>	284
<i>Judging the Morphology of Surfaces and Surface Target Detection</i>	287
<i>Patterns of Points in 3D Space</i>	288
<i>Judging Relative Positions of Objects in Space</i>	289
<i>Judging the Relative Movement of Self within the Environment</i>	290
<i>Reaching for Objects</i>	291
<i>Judging the “Up” Direction</i>	292
<i>The Aesthetic Impression of 3D Space (Presence)</i>	293
Conclusion	294

CHAPTER 9

Images, Words, and Gestures 297

Coding Words and Images	297
The Nature of Language	299
Visual and Spoken Language	301
<i>Images vs. Words</i>	303
<i>Links between Images and Words</i>	306
<i>Static Links</i>	307
<i>Gestures as Linking Devices</i>	309
<i>Deixis</i>	309
<i>Symbolic Gestures</i>	310
<i>Expressive Gestures</i>	311
<i>Visual Momentum in Animated Sequences</i>	311
Animated Visual Languages	312
Conclusion	315

CHAPTER 10

Interacting with Visualizations 317

- Data Selection and Manipulation Loop 318
 - Choice Reaction Time* 318
 - 2D Positioning and Selection* 319
 - Hover Queries* 320
 - Path Tracing* 321
 - Two-Handed Interaction* 321
 - Learning* 322
 - Control Compatibility* 322
 - Vigilance* 324
- Exploration and Navigation Loop 325
 - Locomotion and Viewpoint Control* 325
 - Frames of Reference* 333
 - Map Orientation* 337
 - Focus, Context, and Scale* 338
 - Rapid Interaction with Data* 345
- Conclusion 349

CHAPTER 11

Thinking with Visualizations 351

- Memory Systems 352
 - Visual Working Memory* 352
 - Visual Working Memory Capacity* 355
 - Rensink's Model* 362
- Eye Movements 363
 - Accommodation* 364
 - Eye Movements, Search, and Monitoring* 364
 - Long-Term Memory* 366
- Problem Solving with Visualizations 370
 - Visual Problem Solving Processes* 371
 - The Problem Solving Strategy* 372
 - Visual Query Construction* 372

<i>The Pattern-Finding Loop</i>	373
<i>The Eye Movement Control Loop</i>	374
<i>The Intrasaccadic Scanning Loop</i>	374
<i>Implications for Interactive Visualization Design</i>	374
<i>Interfaces to Knowledge Structures</i>	379

Creative Problem Solving 383

Conclusion 385

APPENDIX A

Changing Primaries 387

APPENDIX B

CIE Color Measurement System 389

APPENDIX C

The Perceptual Evaluation of Visualization Techniques and Systems 393

Research Goals 393

Psychophysics 394

Detection Methods 395

Method of Adjustment 397

Cognitive Psychology 397

Structural Analysis 398

Testbench Application for Discovery 398

Structured Interviews 399

Rating Scales 399

Statistical Exploration 400

Principal Components Analysis 400

Multidimensional Scaling 400

<i>Clustering</i>	401
<i>Multiple Regression</i>	401
Cross-Cultural Studies	401
Child Studies	401
Practical Problems in Conducting User Studies	402
<i>Experimenter Bias</i>	402
<i>How Many Subjects to Use?</i>	403
<i>Combinatorial Explosion</i>	403
<i>Task Identification</i>	404
<i>Controls</i>	404
<i>Getting Help</i>	404
Bibliography	405
Subject Index	451
Author Index	479
About the Author	485