

## Contents

## Part I Introduction to the Human Visual System (HVS)

|          |   |    |
|----------|---|----|
| <b>1</b> | <b>Visual Attention</b>                       | 3  |
| 1.1      | Visual Attention: A Historical Review         | 4  |
| 1.1.1    | Von Helmholtz's "Where"                       | 4  |
| 1.1.2    | James' "What"                                 | 5  |
| 1.1.3    | Gibson's "How"                                | 5  |
| 1.1.4    | Broadbent's "Selective Filter"                | 6  |
| 1.1.5    | Deutsch and Deutsch's "Importance Weightings" | 6  |
| 1.1.6    | Yarbus and Noton and Stark's "Scanpaths"      | 7  |
| 1.1.7    | Posner's "Spotlight"                          | 10 |
| 1.1.8    | Treisman's "Glue"                             | 10 |
| 1.1.9    | Kosslyn's "Window"                            | 11 |
| 1.2      | Visual Attention and Eye Movements            | 11 |
| 1.3      | Summary and Further Reading                   | 13 |
| <b>2</b> | <b>Neurological Substrate of the HVS</b>      | 15 |
| 2.1      | The Eye                                       | 18 |
| 2.2      | The Retina                                    | 18 |
| 2.2.1    | The Outer Layer                               | 21 |
| 2.2.2    | The Inner Nuclear Layer                       | 21 |
| 2.2.3    | The Ganglion Layer                            | 22 |
| 2.3      | The Optic Tract and M/P Visual Channels       | 23 |
| 2.4      | The Occipital Cortex and Beyond               | 24 |
| 2.4.1    | Motion-Sensitive Single-Cell Physiology       | 25 |
| 2.5      | Summary and Further Reading                   | 26 |

|          |  |    |
|----------|--|----|
| <b>3</b> | <b>Visual Psychophysics . . . . .</b>                                | 29 |
| 3.1      | Spatial Vision . . . . .   | 29 |
| 3.2      | Temporal Vision . . . . .  | 33 |
| 3.2.1    | Perception of Motion in the Visual Periphery . . . . .               | 35 |
| 3.2.2    | Sensitivity to Direction of Motion in the Visual Periphery . . . . . | 35 |
| 3.3      | Color Vision . . . . .   | 36 |
| 3.4      | Implications for Attentional Design of Visual Displays . . . . .     | 37 |
| 3.5      | Summary and Further Reading . . . . .                                | 38 |
| <b>4</b> | <b>Taxonomy and Models of Eye Movements . . . . .</b>                | 39 |
| 4.1      | The Extraocular Muscles and the Oculomotor Plant . . . . .           | 39 |
| 4.2      | Saccades . . . . .   | 40 |
| 4.3      | Smooth Pursuits . . . . .  | 43 |
| 4.4      | Fixations (Microsaccades, Drift, and Tremor) . . . . .               | 44 |
| 4.5      | Nystagmus . . . . .  | 45 |
| 4.6      | Implications for Eye Movement Analysis . . . . .                     | 45 |
| 4.7      | Summary and Further Reading . . . . .                                | 45 |

## Part II Eye Tracking Systems

|          |  |    |
|----------|--|----|
| <b>5</b> | <b>Eye Tracking Techniques . . . . .</b>                       | 49 |
| 5.1      | Electro-OculoGraphy (EOG) . . . . .                            | 50 |
| 5.2      | Scleral Contact Lens/Search Coil . . . . .                     | 51 |
| 5.3      | Photo-OculoGraphy (POG) or Video-OculoGraphy (VOG) . . . . .   | 52 |
| 5.4      | Video-Based Combined Pupil/Corneal Reflection . . . . .        | 52 |
| 5.5      | Classifying Eye Trackers in “Mocap” Terminology . . . . .      | 56 |
| 5.6      | Summary and Further Reading . . . . .                          | 57 |
| <b>6</b> | <b>Head-Mounted System Hardware Installation . . . . .</b>     | 59 |
| 6.1      | Integration Issues and Requirements . . . . .                  | 59 |
| 6.2      | System Installation . . . . .                                  | 62 |
| 6.3      | Lessons Learned from the Installation at Clemson . . . . .     | 64 |
| 6.4      | Summary and Further Reading . . . . .                          | 65 |
| <b>7</b> | <b>Head-Mounted System Software Development . . . . .</b>      | 67 |
| 7.1      | Mapping Eye Tracker Screen Coordinates . . . . .               | 68 |
| 7.1.1    | Mapping Screen Coordinates to the 3D Viewing Frustum . . . . . | 68 |
| 7.1.2    | Mapping Screen Coordinates to the 2D Image . . . . .           | 69 |
| 7.1.3    | Measuring Eye Tracker Screen Coordinate Extents . . . . .      | 70 |
| 7.2      | Mapping Flock of Birds Tracker Coordinates . . . . .           | 71 |
| 7.2.1    | Obtaining the Transformed View Vector . . . . .                | 71 |
| 7.2.2    | Obtaining the Transformed up Vector . . . . .                  | 71 |
| 7.2.3    | Transforming an Arbitrary Vector . . . . .                     | 71 |

|           |  |            |
|-----------|--|------------|
| 7.3       | 3D Gaze Point Calculation . . . . .  | 76         |
| 7.3.1     | Parametric Ray Representation of Gaze Direction . . . . .  | 78         |
| 7.4       | Virtual Gaze Intersection Point Coordinates . . . . .  | 79         |
| 7.4.1     | Ray/Plane Intersection . . . . .   | 79         |
| 7.4.2     | Point-in-Polygon Problem . . . . .   | 81         |
| 7.5       | Data Representation and Storage . . . . .  | 82         |
| 7.6       | Summary and Further Reading . . . . .  | 83         |
| <b>8</b>  | <b>Head-Mounted System Calibration . . . . .</b>   | <b>85</b>  |
| 8.1       | Software Implementation . . . . .  | 87         |
| 8.2       | Ancillary Calibration Procedures . . . . .   | 90         |
| 8.2.1     | Internal 2D Calibration . . . . .  | 90         |
| 8.2.2     | Internal 3D Calibration . . . . .  | 94         |
| 8.3       | Summary and Further Reading . . . . .  | 96         |
| <b>9</b>  | <b>Table-Mounted System Hardware Installation . . . . .</b>  | <b>97</b>  |
| 9.1       | Integration Issues and Requirements . . . . .  | 98         |
| 9.2       | System Installation . . . . .  | 100        |
| 9.3       | Lessons Learned from the Installation at Clemson . . . . .   | 101        |
| 9.4       | Summary and Further Reading . . . . .  | 102        |
| <b>10</b> | <b>Table-Mounted System Software Development . . . . .</b>   | <b>105</b> |
| 10.1      | Linux Tobii Client Application Program Interface . . . . .   | 106        |
| 10.1.1    | Tet_Init . . . . .   | 107        |
| 10.1.2    | Tet_Connect, Tet_Disconnect . . . . .  | 107        |
| 10.1.3    | Tet_Start, Tet_Stop . . . . .  | 108        |
| 10.1.4    | Tet_CalibClear, Tet_CalibLoad<br>FromFile, Tet_CalibSaveToFile,<br>Tet_CalibAddPoint, Tet_CalibRemove<br>Points, Tet_CalibGetResult,<br>Tet_CalibCalculateAndSet . . . . . | 108        |
| 10.1.5    | Tet_SynchronizeTime,<br>Tet_PerformSystemCheck . . . . .   | 110        |
| 10.1.6    | Tet_GetSerialNumber,<br>Tet_GetLastError, Tet_GetLastError<br>AsText . . . . .   | 111        |
| 10.1.7    | Tet_CallbackFunction . . . . .   | 112        |
| 10.2      | A Simple OpenGL/GLUT GUI Example . . . . .   | 112        |
| 10.3      | Caveats . . . . .  | 116        |
| 10.4      | Summary and Further Reading . . . . .  | 118        |
| <b>11</b> | <b>Table-Mounted System Calibration . . . . .</b>  | <b>121</b> |
| 11.1      | Software Implementation . . . . .  | 122        |
| 11.2      | Summary and Further Reading . . . . .  | 130        |

|           |  |     |
|-----------|--|-----|
| <b>12</b> | <b>Using an Open Source Application Program Interface . . . . .</b>    | 131 |
| 12.1      | API Implementation and XML Format . . . . .                            | 131 |
| 12.2      | Client/Server Communication . . . . .                                  | 132 |
| 12.3      | Server Configuration . . . . .   | 133 |
| 12.4      | API Extensions . . . . .   | 134 |
| 12.5      | Interactive Client Example Using Python . . . . .                      | 135 |
| 12.5.1    | Using Gazepoint's Built-in Calibration . . . . .                       | 136 |
| 12.5.2    | Using Gazepoint's Custom Calibration Capabilities . . . . .            | 137 |
| 12.6      | Summary and Further Reading . . . . .                                  | 140 |
| <b>13</b> | <b>Eye Movement Analysis . . . . .</b>                                 | 141 |
| 13.1      | Signal Denoising . . . . .   | 143 |
| 13.2      | Dwell-Time Fixation Detection . . . . .                                | 143 |
| 13.3      | Velocity-Based Saccade Detection . . . . .                             | 145 |
| 13.4      | Eye Movement Analysis in Three Dimensions . . . . .                    | 148 |
| 13.4.1    | Parameter Estimation . . . . .   | 152 |
| 13.4.2    | Fixation Grouping . . . . .  | 157 |
| 13.4.3    | Eye Movement Data Mirroring . . . . .                                  | 157 |
| 13.5      | Summary and Further Reading . . . . .                                  | 158 |
| <b>14</b> | <b>Advanced Eye Movement Analysis . . . . .</b>                        | 159 |
| 14.1      | Signal Denoising . . . . .   | 159 |
| 14.2      | Velocity-Based Saccade Detection . . . . .                             | 161 |
| 14.3      | Microsaccade Detection . . . . .                                       | 162 |
| 14.4      | Validation: Computing Accuracy, Precision, and Refitting . . . . .     | 163 |
| 14.5      | Binocular Eye Movement Analysis: Vergence . . . . .                    | 166 |
| 14.6      | Ambient/Focal Eye Movement Analysis . . . . .                          | 169 |
| 14.7      | Transition Entropy Analysis . . . . .                                  | 172 |
| 14.8      | Spatial Distribution Analysis . . . . .                                | 174 |
| 14.9      | Summary and Further Reading . . . . .                                  | 174 |
| <b>15</b> | <b>The Gaze Analytics Pipeline . . . . .</b>                           | 175 |
| 15.1      | Gaze Analytics in Five Easy Steps . . . . .                            | 176 |
| 15.1.1    | Step 0: Data Collection . . . . .                                      | 177 |
| 15.1.2    | Step 1 (dirs): Directory Creation . . . . .                            | 178 |
| 15.1.3    | Step 2 (raw): Extract Raw Gaze Data . . . . .                          | 178 |
| 15.1.4    | Step 3 (graph or process): Graph or Process Raw Data . . . . .         | 180 |
| 15.1.5    | Step 4 (collate): Collate Data Prior to Statistical Analysis . . . . . | 184 |
| 15.1.6    | Step 5 (stats): Perform Statistical Analyses . . . . .                 | 184 |
| 15.2      | Gaze Analytics: A Worked Example . . . . .                             | 185 |
| 15.2.1    | Scanpath Visualization . . . . .                                       | 186 |
| 15.2.2    | Traditional Eye Movement Metrics . . . . .                             | 187 |
| 15.2.3    | Advanced Eye Movement Analysis . . . . .                               | 187 |
| 15.3      | Summary and Further Reading . . . . .                                  | 191 |

|  |     |
|--|-----|
| <b>16 Eye Movement Synthesis . . . . .</b>   | 193 |
| 16.1 Procedural Simulation of Eye Movements . . . . .                              | 193 |
| 16.1.1 Modeling Saccades . . . . .   | 194 |
| 16.1.2 Modeling Fixations . . . . .  | 195 |
| 16.2 Adding Synthetic Eye Tracking Noise . . . . .                                 | 197 |
| 16.3 Summary and Further Reading . . . . .   | 197 |
| <b>Part III Eye Tracking Methodology</b>   |     |
| <b>17 Experimental Design . . . . .</b>  | 201 |
| 17.1 Formulating a Hypothesis . . . . .  | 201 |
| 17.2 Forms of Inquiry . . . . .  | 203 |
| 17.2.1 Experiments Versus Observational Studies . . . . .                          | 203 |
| 17.2.2 Laboratory Versus Field Research . . . . .                                  | 204 |
| 17.2.3 Idiographic Versus Nomothetic Research . . . . .                            | 204 |
| 17.2.4 Sample Population Versus Single-Case Experiment Versus Case Study . . . . . | 205 |
| 17.2.5 Within-Subjects Versus Between-Subjects . . . . .                           | 206 |
| 17.2.6 Example Designs . . . . .   | 207 |
| 17.3 Measurement and Analysis . . . . .  | 210 |
| 17.4 Summary and Further Reading . . . . .   | 213 |
| <b>18 Suggested Empirical Guidelines . . . . .</b>                                 | 215 |
| 18.1 Evaluation Plan . . . . .   | 216 |
| 18.1.1 Data Collection . . . . .   | 217 |
| 18.1.2 System Identification . . . . .   | 219 |
| 18.1.3 Constraints . . . . .   | 219 |
| 18.1.4 User Selection . . . . .  | 220 |
| 18.1.5 Evaluation Locale . . . . .   | 220 |
| 18.1.6 Task Selection . . . . .  | 221 |
| 18.2 Practical Advice . . . . .  | 222 |
| 18.3 Considering Dynamic Stimulus . . . . .  | 223 |
| 18.4 Summary and Further Reading . . . . .   | 223 |
| <b>19 Case Studies . . . . .</b>   | 225 |
| 19.1 Head-Mounted VR Diagnostics: Visual Inspection . . . . .                      | 226 |
| 19.1.1 Case Study Notes . . . . .  | 227 |
| 19.2 Head-Mounted VR Diagnostics: 3D Maze Navigation . . . . .                     | 227 |
| 19.2.1 Case Study Notes . . . . .  | 228 |
| 19.3 Desktop VR Diagnostics: Driving Simulator . . . . .                           | 229 |
| 19.3.1 Case Study Notes . . . . .  | 230 |
| 19.4 Desktop Diagnostics: Usability . . . . .                                      | 230 |
| 19.4.1 Case Study Notes . . . . .  | 239 |
| 19.5 Desktop Interaction: Gaze-Contingent Fisheye Lens . . . . .                   | 241 |
| 19.5.1 Case Study Notes . . . . .  | 244 |
| 19.6 Summary and Further Reading . . . . .   | 244 |

**Part IV Eye Tracking Applications**

|           |   |     |
|-----------|---|-----|
| <b>20</b> | <b>Diversity and Types of Eye Tracking Applications</b> | 247 |
| 20.1      | Summary and Further Reading                             | 248 |
| <b>21</b> | <b>Neuroscience and Psychology</b>                      | 249 |
| 21.1      | Neurophysiological Investigation of Illusory Contours   | 250 |
| 21.2      | Attentional Neuroscience                                | 250 |
| 21.3      | Eye Movements and Brain Imaging                         | 253 |
| 21.4      | Reading   | 254 |
| 21.5      | Scene Perception  | 258 |
| 21.5.1    | Perception of Art                                       | 261 |
| 21.5.2    | Perception of Film                                      | 264 |
| 21.6      | Visual Search   | 264 |
| 21.6.1    | Computational Models of Visual Search                   | 269 |
| 21.7      | Natural Tasks   | 274 |
| 21.8      | Eye Movements in Other Information Processing Tasks     | 277 |
| 21.9      | Summary and Further Reading                             | 279 |
| <b>22</b> | <b>Industrial Engineering and Human Factors</b>         | 281 |
| 22.1      | Aviation  | 281 |
| 22.2      | Driving   | 284 |
| 22.3      | Visual Inspection                                       | 290 |
| 22.4      | Summary and Further Reading                             | 299 |
| <b>23</b> | <b>Marketing/Advertising</b>                            | 301 |
| 23.1      | Copy Testing  | 303 |
| 23.2      | Print Advertising                                       | 304 |
| 23.3      | Ad Placement  | 307 |
| 23.4      | Television Enhancements                                 | 309 |
| 23.5      | Web Pages   | 310 |
| 23.6      | Product Label Design                                    | 313 |
| 23.7      | Summary and Further Reading                             | 314 |
| <b>24</b> | <b>Computer Science</b>                                 | 315 |
| 24.1      | Human–Computer Interaction and Collaborative Systems    | 315 |
| 24.1.1    | Classic Eye-Based Interaction                           | 316 |
| 24.1.2    | Cognitive Modeling                                      | 317 |
| 24.1.3    | Universal Accessibility                                 | 319 |
| 24.1.4    | Indirect Eye-Based Interaction                          | 320 |
| 24.1.5    | Attentive User Interfaces (AUIs)                        | 322 |
| 24.1.6    | Usability   | 322 |
| 24.1.7    | Collaborative Systems                                   | 324 |
| 24.2      | Gaze-Contingent Displays                                | 324 |
| 24.2.1    | Screen-Based Displays                                   | 326 |
| 24.2.2    | Model-Based Graphical Displays                          | 331 |
| 24.3      | Summary and Further Reading                             | 338 |

|                                |       |
|--------------------------------|-------|
| Contents                       | xxiii |
| <b>25 Conclusion . . . . .</b> | 341   |
| <b>References . . . . .</b>    | 343   |
| <b>Index . . . . .</b>         | 359   |