

Eye Tracking Methodology

Andrew T. Duchowski

Eye Tracking Methodology

Theory and Practice

Third Edition

 Springer

Andrew T. Duchowski
School of Computing
Clemson University
Clemson, SC
USA

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Preface to the Third Edition

Ten years (almost to the day) have elapsed since the writing of the second edition. As the technology has proliferated, so has the research output associated with the use of the eye tracker. While the ACM Symposium on Eye Tracking Research & Applications (ETRA) is now fairly well established, drawing high-quality scientific content, a number of specialized venues have also appeared, including (in no particular order):

- Eye Tracking South Africa (ETSA)
- Pervasive Eye Tracking and Mobile Eye-Based Interaction (PETMEI)
- Solutions for Automatic Gaze-Data Analysis (SAGA)
- Eye Tracking for Spatial Research (ET4S)
- Eye Tracking and Visualization (ETVIS)

The amount of literature related to eye tracking methodology is now considerable. In addition to journal articles (including the Journal of Eye Movement Research [JEMR] and the Transactions on Applied Perception [TAP]) and conference proceedings, a number of notable monographs and textbooks have also appeared, including those of Holmqvist et al. (2011), Majaranta et al. (2011), Sundstedt (2011), and Bojko (2013).

While new technology precipitated the writing of the second edition, the third edition draws inspiration from advancements in analytical techniques and the increased availability of scholarly contributions. Concordantly, the third edition includes advancements concerning:

1. calibration accuracy, precision, and correction;
2. convolution-based eye movement analysis;
3. eye movement analysis including ambient/focal fixation classification with the \mathcal{K} coefficient and gaze transition comparison with transition matrix entropy;
4. binocular eye movement analysis;
5. broadened application examples including design and Geo-Information Systems (GIS); and
6. eye movement synthesis (e.g., for testing fixation filters and for rendering of avatar eye rotations).

The third edition also includes more programming examples, this time in Python, which has enabled rapid development of analytical techniques (e.g., a gaze analytics pipeline).

Zürich, Switzerland
(on sabbatical)
April 2016

Andrew T. Duchowski

Preface to the Second Edition

Since the writing of the first edition, several important advancements in the field of eye tracking have occurred in the span of just a few short years. Most important, eye tracking technology has improved dramatically. Due to the increased speed of computer processors and improved computer vision techniques, eye tracking manufacturers have developed devices falling within the fourth generation of the following technological taxonomy.

1. First generation: eye-in-head measurement of the eye consisting of techniques such as scleral contact lens/search coil, electro-oculography
2. Second generation: photo- and video-oculography
3. Third generation: analog video-based combined pupil/corneal reflection
4. Fourth generation: digital video-based combined pupil/corneal reflection, augmented by computer vision techniques and Digital Signal Processors (DSPs)

Often the most desired type of eye tracking output (e.g., for human-computer interaction usability studies) is estimation of the projected Point Of Regard (POR) of the viewer, i.e., the (x, y) coordinates of the user's gaze on the computer display. First- and second-generation eye trackers generally do not provide this type of data. (For second-generation systems, eye movement analysis relies on off-line, frame-by-frame visual inspection of photographs or video frames and does not allow easy POR calculation.) Combined video-based pupil/corneal reflection eye trackers easily provide POR coordinates following calibration, and are today *de rigueur*. Due to the availability of fast analog-to-digital video processors, these third-generation eye trackers are capable of delivering the calculated POR in real-time. Fourth-generation eye trackers, having recently appeared on the market, make use of digital optics. Coupled with on-chip Digital Signal Processors (DSPs), eye tracking technology has significantly increased in its usability, accuracy, and speed while decreasing in cost.

The state of today's technology can best be summarized by a brief functional comparison of older and newer equipment, given in the following table. If, to those new to this book and uninitiated with eye tracking devices, the comparison in the table is not immediately suggestive, consider two use scenarios of both old and new technology presented in the next table.

Functional eye tracker comparison.

	Legacy Systems	State-of-the-Art
Technology	Analog video	Digital video
Calibration	5- or 9-point, tracker-controlled	Any number, application-controlled
Optics	Manual focusing/thresholding	Auto-focus
Communication	Serial (polling/streaming)	TCP/IP (client/server)
Synchronization	Status byte word	API callback

Eye tracker use comparison.

Typical session with old system	Typical session with new system
1. Login to console	1. Login to console
2. Turn on eye tracking equipment	2. Turn on eye tracking PC
3. Turn on eye/scene monitors	3. Run eye tracking program
4. Turn on eye tracking PC	4. Calibrate
5. Run eye tracking program	5. Run
6. Turn on camera	
7. Turn on illumination control	
8. Adjust head/chin rest	
9. Adjust pan/tilt unit	
10. Adjust camera zoom	
11. Adjust camera focus	
12. Adjust pupil/corneal thresholds	
13. Calibrate	
14. Run	

The disparity in the use of old and new technologies is mainly due to the use of different optics (camera). New systems tend to use an auto-focusing digital camera, e.g., embedded in a flat panel display. Although embedding within a flat panel display may restrict a user's physical position somewhat, it is generally preset to operate at a comfortable range (e.g., 50–60 cm focal distance). Unlike older systems, as long as the user sits within this distance, no chin rests and no further parameter adjustments are needed. In contrast, older devices required the use of a pan/tilt unit to position the camera, the camera to be manually focused and zoomed, and software to be set to appropriate pupil and corneal reflection detection thresholds. None of these cumbersome operations are required with newer systems.

Furthermore, one of the most important features of the new technology, especially for application development, is an individual's ability to self-calibrate. With older technology, whenever a developer wished to test a new feature, she or he had

to recruit a (very patient) subject for testing. This was quite problematic. The newer systems' calibration routines are a much-needed improvement over older (third-generation) technology that significantly accelerate program and application development.

A third-generation eye tracker was used for most of the eye tracking research on which the first edition of this book was based. The availability of new technology precipitated the writing of the second edition. The second edition therefore fills several important gaps not covered previously, namely:

1. Client/server model for developing an eye tracking client application
2. Client-controlled display, calibration, data collection
3. New programming examples

Beyond updated technical descriptions of client programming, the second edition also includes what the first edition lacked: an overview of the methodology behind the use of eye trackers, that is, experimental design issues that are often needed to conduct eye tracking studies. The second edition briefly reviews experimental design decisions, offers some guidelines for incorporating eye movement metrics into a study (e.g., usability), and provides examples of case studies.

Finally, the second edition expands the third part of the book: eye tracking applications. A great deal of new and exciting eye tracking work has appeared, undoubtedly driven by the availability of new technology. In fact, there now appears to be a rather refreshing shift in the reporting of eye tracking and eye movement studies. Authors now tend to understate the “gee-whiz” factor of eye trackers and their technical machinations needed to obtain eye movement data and are now emphasizing scientific results bolstered by objective evidence provided by users' gaze and hence attention. Eye tracking finally appears to be entering into mainstream science, where the eye tracker is becoming less of a novelty and more of a tool. It is hoped that this second edition may inspire readers with the simplicity of application development now made possible by fourth-generation eye trackers and continue on the road to new applications and scientific insights.

Clemson, USA
April 2006

Andrew T. Duchowski

Preface to the First Edition

The scope of the book falls within a fairly narrow human–computer interaction domain (i.e., describing a particular input modality), however, it spans a broad range of interdisciplinary research and application topics. There are at least three domains that stand to benefit from eye tracking research: visual perception, human–computer interaction, and computer graphics. The amalgamation of these topics forms a symbiotic relationship. Graphical techniques provide a means of generating rich sets of visual stimuli ranging from 2D imagery to 3D immersive virtual worlds and research exploring visual attention and perception in turn influences the generation of artificial scenes and worlds. Applications derived from these disciplines create a powerful human–computer interaction modality, namely interaction based on knowledge of the user’s gaze.

Recent advancements in eye tracking technology, specifically the availability of cheaper, faster, more accurate, and easier to use trackers, have inspired increased eye movement and eye tracking research efforts. However, although eye trackers offer a uniquely objective view of overt human visual and attentional processes, eye trackers have not yet gained widespread use beyond work conducted at various research laboratories. This lack of acceptance is due in part to two reasons: first, the use of an eye tracker in an applied experimental setting is not a widely taught subject. Hence, there is a need for a book that may help in providing training. It is not uncommon for enthusiastic purchasers of eye tracking equipment to become discouraged with their newly bought equipment when they find it difficult to set up and operate. Only a few academic departments (e.g., psychology, computer science) offer any kind of instruction in the use of eye tracking devices. Second, to exacerbate the lack of training in eye tracking methodology, even fewer sources of instruction exist for system development. Setting up an eye tracking lab and integrating the eye tracker into an available computer system for development of gaze-contingent applications is a fairly complicated endeavor, similar to the development and integration of virtual reality programs. Thus far, it appears no textbook other than this one exists providing this type of low-level information.

The goal of this book is to provide technical details for implementation of a gaze-contingent system, couched in the theoretical context of eye movements,

visual perception, and visual attention. The text started out as the author's personal notes on the integration of a commercial eye tracker into a virtual reality graphics system. These technical considerations comprise the middle chapters of the book and include details of integrating a commercial eye tracker into both a 3D virtual environment, and a 2D image display application. The surrounding theoretical review chapters grew from notes developed for an interdisciplinary eye tracking methodology course offered to both undergraduates and graduates from four disciplines: psychology, marketing, industrial engineering, and computer science. An early form of these notes was presented as a short course at the Association for Computing Machinery (ACM) Special Interest Group on Graphics' SIGGRAPH conference, 23–28 July 2000, New Orleans, LA.

Overview

As of the second edition, the book is divided into four parts, presented thematically in a top-down fashion, providing first an introduction to the human visual system (Part I), then briefly surveying eye tracking systems (Part II), then discussing eye tracking methodology (Part III), and finally ending by reviewing a number of eye tracking applications (Part IV).

In the first part, "Introduction to the Human Visual System (HVS)," the book covers the concept of visual attention, mainly from a historical perspective. The first chapter focuses on the dichotomy of foveal and peripheral vision (the "what" versus the "where"). This chapter covers easily observable attentional phenomena. The next chapter covers the neurological substrate of the HVS presenting the low-level neurological elements implicated in dynamic human vision. This chapter discusses the primary dual pathways, the parvo- and magno-cellular channels, which loosely correspond to the flow of visual information permitted by the retinal fovea and periphery. Following this description of the visual "hardware", observable characteristics of human vision are summarized in the following chapter on visual perception. Here, results obtained mainly from psychophysics are summarized, distinguishing foveal and peripheral visual perception. The first part ends by discussing the mechanism responsible for shifting the fovea, namely eye movements. Having established the neurological and psychophysical context for eye movements, the following chapter on the taxonomy and models of eye movements gives the common terms for the most basic of eye movements along with a signal-analytic description of recordable eye movement waveforms.

The second part of the book, "Eye Tracking Systems", presents a brief survey of the main types of available eye tracking devices, followed by a detailed technical description of the requirements for system installation and application program development. These details are mainly applicable to video-based, corneal-reflection eye trackers, the most widely available and most affordable type of eye trackers. This part of the book offers information for the development of three general systems: one for binocular 3D eye tracking in virtual reality, one for monocular 2D

eye tracking over a 2D display (e.g., a television monitor on which graphical information can be displayed), and one for binocular 2D eye tracking on the desktop. The descriptions of the first two former systems are very similar because they are based on the same kind of (older) eye tracking hardware (ISCAN in this instance). The latter system description is based on modern eye tracking technology from Tobii. Both system descriptions include notes on system calibration. This part of the book ends with a description of data collection and analysis independent of any particular eye tracking hardware.

The fourth part of the book surveys a number of interesting and challenging eye tracking applications. Applications identified in this part are drawn from psychology, human factors, marketing and advertising, human–computer interaction and collaborative systems, and computer graphics and virtual reality.

How to Read This Book

The intended audience for this book is an interdisciplinary one, aimed particularly at those interested in psychology, marketing, industrial engineering, and computer science. Indeed, this text is meant for undergraduates and graduates from these disciplines enrolled in a course dealing with eye tracking, such as the eye tracking methodology course developed by the author at Clemson University. In this course, typically all chapters are covered, but not necessarily in the order presented in the text. In such a course, the order of chapters may be as follows.

First, Part IV is presented outlining various eye tracking applications. Normally, this part should give the reader motivation for design and implementation of a semester-long eye tracking project. Coverage of this part of the book is usually supplemented by readings of research papers from various sources. For example, papers may be selected from the following conferences.

- The proceedings of the Eye Tracking Research & Applications (ETRA) conference
- The proceedings of the ACM Special Interest Group on Human–Computer Interaction (SIGCHI) conference (Human Factors in Computing)
- Transactions on Graphics, the proceedings of the annual Association for Computing Machinery (ACM) Special Interest Group on Graphics and Interactive Techniques (SIGGRAPH) conference series
- The proceedings of the Human Factors and Ergonomics Society (HFES)

To speed up development of an eye tracking application, Part II follows the presentation of Part IV, dealing in the technical details of eye tracker application development. The types of applications that can be expected of students will depend mainly on the programming expertise represented by members of interdisciplinary student teams. For example, in the eye tracking methodology course at Clemson, teams are formed by joining computer science students with one or more of the

other representatives enrolled in the class (i.e., from marketing, psychology, or industrial engineering). Although all group members decide on a project, students studying the latter subjects are mainly responsible for the design and analysis of the eventual eye tracking experiment.

Given commencement of an eye tracking application, Part III is then covered, going over experimental design. In the context of the usability measurement framework, the eye tracking methodology course advocates performance measurement, and therefore focuses on laboratory experiments and quantitative data analysis.

Part I of the text is covered last, giving students the necessary theoretical context for the eye tracking pilot study. Thus, although the book is arranged “top-down”, the course proceeds “bottom-up”.

The book is also suitable for researchers interested in setting up an eye tracking laboratory and/or using eye trackers for conducting experiments. Because readers with these goals may also come from diverse disciplines such as marketing, psychology, industrial engineering, and computer science, not all parts of the book may be suitable for everyone. More technically oriented readers will want to pay particular attention to the middle sections of the book which detail system installation and implementation of eye tracking application software. Readers not directly involved with such low-level details may wish to omit these sections and concentrate more on the theoretical and historical aspects given in the front sections of the book. The latter part of the book, dealing with eye tracking applications, should be suitable for all readers inasmuch as it presents examples of current eye tracking research.

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Special thanks go to Bruce McCormick, who always emphasized the importance of writing during my doctoral studies at Texas A&M University, College Station,

TX. Finally, special thanks go to Corey, my wife, for patiently listening to my various ramblings on eye movements, and for being an extremely patient eye tracking subject :).

I have gained considerable pleasure and enjoyment in putting the information I've gathered and learned on paper. I hope that readers of this text derive similar pleasure in exploring vision and eye movements as I have, and they go on to implementing ever interesting and fascinating projects—have fun!

Clemson, USA
June 2002 and July 2006

Andrew T. Duchowski

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Eye Tracker/Eye Tracking in Different Languages

During ETRA 2016 attendees were polled to provide the corresponding term for either *eye tracker* or *eye tracking* in some language other than English. Results, some tongue in cheek, nevertheless a testament to eye tracking's worldwide adoption, are below. Please forgive any inadvertent spelling blunders lost in translation.

English	Eye tracking
Canadian	Gaze monitoring
Danish	Eye tracking
Swedish	Ögonrörelsemätare
Finnish	Katseenseuranta
German	Augenbewegungsmessgerät/Blickerfassung
Slovak	Zariadenie na sledovanie pohľadu
Croatian	Uredaj za praćenje oka
Romanian	Monitarizarea privinii
Spanish (Colombia)	Sistema de seguimiento de mirada
Portuguese	Rastreador ocular
French	Oculomètre
Polish	Okulograf/okulometria

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