An Eye on Perceptual Graphics: Eye-Tracking Methodology

A. T. Duchowski[1], K. Krejtz[2], I. Krejtz[3], R. Mantiuk[4], B. Bazyluk[4]

[1]Clemson University, Clemson, SC, USA
[2]Information Processing Institute, Warsaw, Poland
[3]University of Social Sciences and Humanities, Warsaw, Poland
[4]West Pomeranian University of Technology, Szczecin, Poland

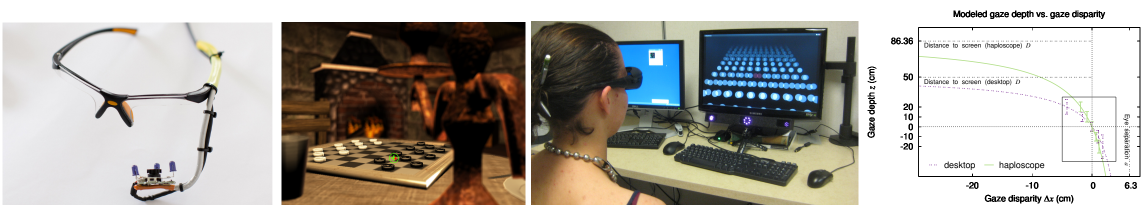

Figure 1: *Tutorial syllabus: eye tracking technology, real-time applications, experimental design, diagnostic applications.*

Abstract

Eye-tracking technology has evolved considerably over the last decade. The tutorial provides attendees with state-of-the-art advancements and their relevance to computer graphics research, one of the most important being the proliferation of Do-It-Yourself (DIY) techniques. Following a summary of how to build your own, we will cover real-time graphics applications, including advancements in gaze-contingent displays. The second half of the tutorial will focus on offline, diagnostic graphics applications, where gaze is used to evaluate visual aspects of rendered scenes. We will present a methodological "pipeline" that we have evolved and adapted to various experiments. The tutorial differs from previous ones by largely ignoring aspects of human vision and focusing on technical details that are most pertinent to the EuroGraphics audience.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction Techniques; Ergonomics

1. Tutorial Details

Title of tutorial:	An Eye On Perceptual Graphics: Eye-Tracking Methodology
Half or full day:	Half
Audience:	Intermediate to Advanced; knowledgeable about vision

2. Tutorial Outline

In 2000, Duchowski and Vertegaal [DV00] presented *Course 05: Eye-Based Interaction in Graphical Systems: Theory & Practice*,[†] introducing SIGGRAPH attendees to theoretical aspects of dynamic human vision, characteristics of eye movements, and visual attention. The course presented system integration techniques, including a description of available video-based eye-tracking hardware; requirements for development of software drivers; techniques for developing real-time, interactive, gaze-contingent applications, and off-line diagnostic eye movement analysis. The course notes served as the basis for Duchowski's subsequent *Eye Tracking Methodology* monograph [Duc03].[‡] Eye-tracking technology has evolved considerably since its introduction to the SIGGRAPH community over a decade ago.

† http://eyecu.ces.clemson.edu/sigcourse/

‡ http://andrewd.ces.clemson.edu/book/

This tutorial at EuroGraphics 2013 will provide attendees with an up-to-date summary of the most important eye tracking advancements and their relevance to computer graphics research. One of the most important developments has been the proliferation of Do-It-Yourself (DIY) eye tracking techniques pioneered by Pelz et al. [PCB00] who went on to provide open-source software that inspired development of cheap but functional equipment at various laboratories. The EG tutorial will open with a review of eye tracking technology and provide a summary of how to build your own, providing information on equipment, operational characteristics, and a description of the algorithms required to obtain real-time coordinates of a user's gaze point. The tutorial is divided into four sections:

1. Eye tracking technology review (including DIY)
2. Real-time graphics applications
3. Experimental design
4. Diagnostic graphics applications

Following the first section, we will summarize real-time graphics applications, including advancements in gaze-contingent displays, discussing usage of model-based approaches and GPU-based simulations. The second half of the tutorial will focus on offline, diagnostic graphics applications of eye tracking, where gaze is used to evaluate some visual aspect of the media presented to the viewer. The most important methodological advancement we will present is the notion of an experimental analytics "pipeline" that we have evolved and adapted to various experiments.

Since SIGGRAPH 2002, several eye-tracking related tutorials have appeared, including short courses taught by Duchowski at the Universitat Autònoma de Barcelona, Spain (June, 2009 and 2012), Tampere University, Finland (August 2008), and at CHI (April 2008). Pelz et al. also taught an eye-tracking course earlier at CHI, and Sundstedt recently presented a gaze-based gaming course at SIGGRAPH [Sun11]. With the exception of the SIGGRAPH courses, most of these dealt with usability testing applications.

The EG tutorial differs from previous tutorials at SIGGRAPH and CHI by largely ignoring aspects of human vision and visual attention and focusing on technical details that we think are the most pertinent to the EuroGraphics audience. Details of the four main sections are given below.

2.1. Eye tracking technology review (including DIY)

The cost of eye tracking is falling (a do-it-yourself device can be constructed for less than 30 EURs [AMB10, MKNB12]). Estimating the user's gaze position is therefore affordable. There are freely available open source software packages that support all eye tracking computational steps including pupil and corneal glint detection, calibration, and gaze tracking [IG09]. Commercial vendors offer various types of eye trackers ranging from portable devices, through remote eye trackers, to highly accurate stationary devices that require chin rests or bite bars. In the proposed tutorial we will show how to build a low-cost eye tracker using cheap off-the-shelf components and how to implement or use existing software to control it. The reference device is shown in Fig. 1 (leftmost image), which we will introduce and demonstrate during the tutorial.

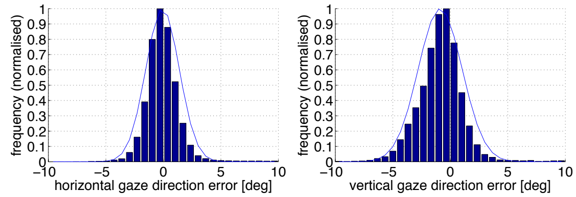

Figure 2: *Distribution of gaze direction error for an example dataset of gaze points captured during eye tracking experiments (results averaged for 40 observers and 59 measurement sessions).*

We observe that accuracy of eye tracking systems is the main factor limiting its widespread use. This is hard to overcome as most eye trackers rely on faint corneal reflections and are affected by head movements, lids occluding the pupil, variation in lighting, shadows, and sunlight interfering with the infra-red (IR) light sources. But even if perfect registration of the eye position and orientation was possible, eye movements do not strictly follow the attention patterns of the visual system [HNA*11]. Even if an observer is focused on a single point, the eye will wander around that point because of the microsaccadic eye movements and tremors. Fig. 2 shows the distribution of error between intended and captured gaze direction. We will discuss accuracy, precision, and robustness of contemporary eye trackers in real-world applications, primarily in computer graphics systems.

2.2. Real-time applications

Gaze-contingent displays have been used in various graphical applications, ranging from model-based peripheral geometry "compression" [MD01a] to GPU-based simulations of Age-related Macular Degeneration scotoma [DE09] (for a review, see Duchowski and Çöltekin [Dc07]).

A model of gaze direction and visual acuity degradation (eccentricity-dependent CSF) can be used to reduce the complexity of computation in the parafoveal and peripheral regions of the field of view. This property is exploited in view-dependent polygon simplification techniques that vary the level-of-detail (LOD) [LH01, MD01b], reduce sampling in ray casting [MDT09] and volume rendering [LW90], or manipulate ambient occlusion rendering [MJ12] in a gaze-dependent manner.

Gaze tracking can simulate a number of visual phenomena that depend on gaze direction that are difficult to reproduce on a display. For example, blurring due to accommo-

Figure 3: *Screenshot from the computer game* Invasion. *Spaceship information is displayed only when an observer is looking at it. Gaze also aids mouse-based aiming.*

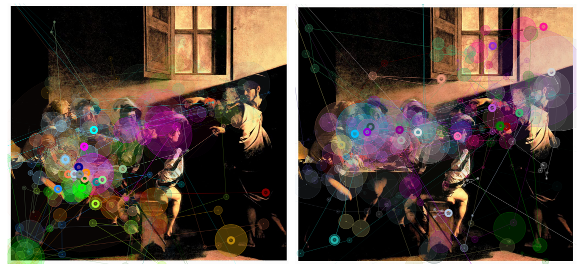

Figure 4: *Exemplary scanpaths from a between-subjects experiment. Two groups of viewers were shown Caravaggio's* The Calling of St. Matthew*: the left panel depicts scanpaths guided by experimental manipulation while the right shows scanpaths from "free viewing" in the control condition.*

dation of the eye can be simulated by rendering scenes of reduced depth-of-field (DoF), focused at the current gaze position [MBT11] (see Fig. 1). Local light adaptation can be simulated in tone-mapping that adapts to the gaze position [RFM*09]. In virtual environments and computer-based entertainment (e.g., gaming), gaze direction can lead to improved user's immersion and can make gameplay more exciting (see Fig. 3). When viewing stereo images, depth disparity can be adjusted to the user's gaze [DRE*11]. We will show how real-time gaze depth is measured from binocular eye tracker gaze position coordinates and its response to stereo stimulus [WPDH12] (see Fig. 1).

Beyond state-of-the-art real-time applications of eye tracking, we will present working demos of gaze-dependent depth of field simulation and a gaze-controlled video game, covering the technical details of both user-side and behind-the-scenes logic needed for integration with an eye tracker.

2.3. Experimental design

Beyond real-time usage, commonly reported diagnostic (offline) eye movement metrics include mean number of fixations, mean gaze duration, proportion of gaze on Areas Of Interest (AOIs), and gaze transitions between them [JK03, WR08]. Statistics on these types of metrics are often corroborated with measures of attention and/or performance (e.g., time to completion of some tasks, usability of some interface, etc.). Qualitative eye tracking studies often rely on visualizations of gaze (e.g., scanpaths (see Fig. 4 and heatmaps), whereas quantitative studies usually rely on careful experimental design and inferential statistics.

Transition matrices are particularly effective for analysis of generalized patterns of fixations [PSF95, AH12], e.g., when reading web pages or graphics and viewing art (see Fig. 5). We will show how to construct and interpret transition matrices. Perceptual computer graphics can benefit from this type of analysis whenever visibility of some graphical element (e.g., specular highlight, amount of contrast, etc.) is meant to be tested. Beyond gaze transitions, other important metrics include first fixations (what is attention directed to first), repeated fixation points (refixations), and/or scanpaths and heatmaps depicting gaze during picture exploration.

We will review the basics of human-subjects research methodology, including experimental designs, notion of null hypothesis testing, and independent and dependent variables. Following methodological issues, we will discuss statistical tests commonly used in eye-tracking research, such as between- and within-subjects ANalysis Of VAriance (ANOVA), correlations, and simple regression.

We will give practical examples of how to set up a basic eye tracking experiment, going over an analytics "pipeline" that we have employed to help automate the process. Briefly, the pipeline relies on scripts developed in `Python` to arrange raw data files for processing by `R`, the language and environment for statistical computing and graphics [R D11]. `R` is freely available on multiple platforms, and because of its scriptability, source code used to analyze experiments can be shared among research collaborators. `R` scripts are executed

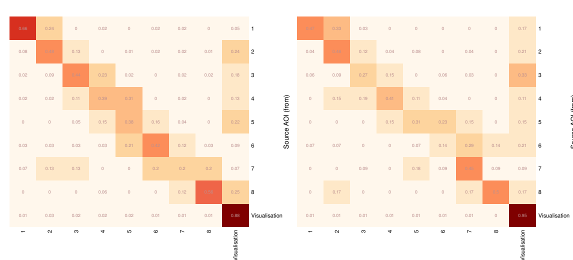

Figure 5: *Exemplary transition matrices from reading text accompanied by either an interactive applet or an animation. These matrices summarize scanpaths of 48 participants and the importance of the visual aids.*

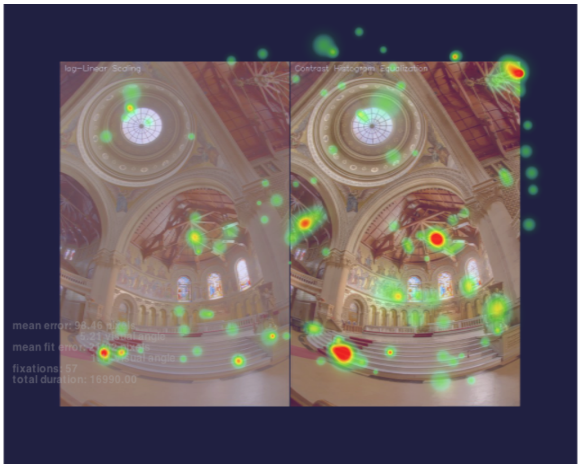

Figure 6: *HDR image with differing methods of manipulating spatial contrast [MMS06] overlayed with heatmaps representing proportion of fixation atop regions. We will use examples like this to compare fixations across the images.*

to generate statistics results as well as publication-quality plots. The entire pipeline is often set up, controlled, and executed with the help of a single `Makefile`. Examples of this type of processing will be given in the context of a computer graphics-related eye tracking experiment.

2.4. Diagnostic applications

The analytics pipeline will be demonstrated through a mock experiment designed to evaluate the perceptual quality of High Dynamic Range (HDR) images with differing levels of spatial contrast, following Mantiuk et al. [MMS06]. The operational hypothesis states that a larger number of fixations is cast atop fine detail preserved by HDR.

2.5. Tutorial schedule / syllabus

The tutorial will include live demos of both DIY eye tracking analysis of a mock experiment. Attendees will be shown typical eye-tracking steps involving calibration, and then either effects of real-time display generation or offline data collation and analysis. The tutorial schedule is given in Table 1.

Table 1: *Preliminary tutorial schedule.*

25 min	Section 1.: technology review (incl. DIY)
30 min	Section 2.: real-time graphics applications
30 min	DIY eye tracker demo
–	*coffee break*
30 min	Section 3.: experimental design
30 min	Section 4.: diagnostic graphics applications
30 min	Data analysis demo

3. Presenter Details

Andrew Duchowski	`duchowski@clemson.edu`
Krzystof Krejtz	`kkrejtz@opi.org.pl`
Iza Krejtz	`iza.krejtz@gmail.com`
Radoslaw Mantiuk	`rmantiuk@wi.zut.edu.pl`
Bartosz Bazyluk	`bbazyluk@wi.zut.edu.pl`

4. Presenter Bios

Andrew Duchowski is a professor of Computer Science at Clemson University. He received his BSc (1990) from Simon Fraser University, Canada, and PhD (1997) from Texas A&M University, USA, both in Computer Science. His research and teaching interests include visual attention and perception, eye tracking, computer vision, and computer graphics. He is a noted research leader in the field of eye tracking, having produced a corpus of work related to eye tracking research, and has delivered courses and seminars on the subject at international conferences.

Krzysztof Krejtz received his PhD in Psychology from the University of Warsaw (2003). He is an assistant professor in the Department of Psychology, University of Social Science and Humanities and the head of Interactive Technologies Laboratory at the Information Processing Institute, Warsaw, Poland. His research interests include visual attention, Human-Computer Interaction, as well as psychological and social aspects of the Internet and new media. Krejtz has a body of methodological and statistical publications and has extended experience teaching statistics and methodology of social and cognitive research including eye-tracking methods at universities as well as international conferences.

Izabela Krejtz received her PhD in social psychology from the Institute of Psychology, Polish Academy of Sciences (2002). She is an assistant professor at University of Social Sciences and Humanities in Warsaw, Poland. She teaches research methods and statistics for social scientists, as well as applications of eye tracking in social neuroscience. Her research interests include neurocognitive and educational psychology. Her applied work focuses on controlled attention training, eye-movement studies in perception of audio-visual material and emotion regulation.

Radosław Mantiuk is a research worker and lecturer at West Pomeranian University of Technology in Szczecin, Poland. He received his MSc degree in Computer Science (1994), MSc degree in Ocean Technology (1995), and his PhD in Computer Graphics (1999) from Szczecin University of Technology. His research combines interdisciplinary aspects of imaging, image and color appearance, image synthesis and modern computer hardware technologies. His recent interests focus on the application of eye tracking in Computer Graphics and High Dynamic Range imaging.

Bartosz Bazyluk is a PhD student at West Pomeranian University of Technology in Szczecin, Poland, where he had received his MSc degree (2010). His research interests cover the areas of gaze-based interaction, gaze-contingent rendering and the general use of eye tracking in real-time applications. During student courses he teaches interactive 3D graphics programming and the basics of computer games development. Being passionate about these fields, he successfully combines eye tracking and virtual environments pursuing new ways for visually appealing interactivity.

5. Acknowledgments

Some of the work to be presented was supported in part by the US National Science Foundation under Award #0722313, and in part by the Polish Ministry of Science and Higher Education through grant no. N N516 508539.

References

[AH12] ACARTÜRK C., HABEL C.: Eye tracking in multimodal comprehension of graphs. In *TEDR-2012: Proceedings of the Workshop on Technology-Enhanced Diagrams Research* (2012), Cox R., (Ed.), pp. 11–25. 3

[AMB10] AGUSTIN J., MOLLENBACH E., BARRET M.: Evaluation of a low-cost open-source gaze tracker. In *Proc. of ETRA 2010, Austin, TX, March 22-24* (2010), pp. 77–80. 2

[Dc07] DUCHOWSKI A. T., ÇÖLTEKIN A.: Foveated Gaze-Contingent Displays for Peripheral LOD Management, 3D Visualization, and Stereo Imaging. *Transactions on Multimedia Computing, Communications and Applications 3*, 4 (December 2007). 2

[DE09] DUCHOWSKI A. T., EADDY T. D.: A Gaze-Contingent Display Compensating for Scotomata. In *EuroGraphics (Short Presentations)* (Munich, Germany, March 30-3 April 2009), EuroGraphics. 2

[DRE*11] DIDYK P., RITSCHEL T., EISEMANN E., MYSZKOWSKI K., SEIDEL H.-P.: A perceptual model for disparity. *ACM Transactions on Graphics (Proceedings SIGGRAPH 2011, Vancouver) 30*, 4 (2011). 3

[Duc03] DUCHOWSKI A. T.: *Eye Tracking Methodology: Theory & Practice*. Springer-Verlag, Inc., London, UK, 2003. 1

[DV00] DUCHOWSKI A. T., VERTEGAAL R.: *Course 05: Eye-Based Interaction in Graphical Systems: Theory & Practice*. ACM SIGGRAPH, New York, NY, July 2000. SIGGRAPH 2000 Course Notes, URL: http://eyecu.ces.clemson.edu/sigcourse/, last accessed 10/22/12. 1

[HNA*11] HOLMQVIST K., NYSTROM M., ANDERSSON R., DEWHURST R., JARODZKA H., VAN DE WEIJER J.: *Eye Tracking: A comprehensive guide to methods and measures*. Oxford University Press, USA; 1 edition (November 1, 2011), 2011. 2

[IG09] ITU-GAZEGROUP: *ITU, Itu gaze tracker software*. Tech. rep., IT University of Copenhagen, 2009. 2

[JK03] JACOB R. J. K., KARN K. S.: Eye Tracking in Human-Computer Interaction and Usability Research: Ready to Deliver the Promises. In *The Mind's Eye: Cognitive and Applied Aspects of Eye Movement Research*, Hyönä J., Radach R., Deubel H., (Eds.). Elsevier Science, Amsterdam, The Netherlands, 2003, pp. 573–605. 3

[LH01] LUEBKE D. P., HALLEN B.: Perceptually-driven simplification for interactive rendering. In *Proceedings of the 12th Eurographics Workshop on Rendering Techniques* (London, UK, UK, 2001), Springer-Verlag, pp. 223–234. 2

[LW90] LEVOY M., WHITAKER R.: Gaze-directed volume rendering. In *Proceedings of the 1990 symposium on Interactive 3D graphics* (New York, NY, USA, 1990), I3D '90, ACM, pp. 217–223. 2

[MBT11] MANTIUK R., BAZYLUK B., TOMASZEWSKA A.: Gaze-dependent depth-of-field effect rendering in virtual environments. *Lecture Notes in Computer Science (Proc. of SGDA 2011) 6944* (2011), 1–12. 3

[MD01a] MURPHY H., DUCHOWSKI A. T.: Gaze-Contingent Level Of Detail. In *EuroGraphics* (Manchester, UK, September 4-7 2001), EuroGraphics. 2

[MD01b] MURPHY H., DUCHOWSKI A. T.: Gaze-contingent level of detail rendering. In *Proceedings of the EuroGraphics Conference* (2001), EuroGraphics Associates. 2

[MDT09] MURPHY H. A., DUCHOWSKI A. T., TYRRELL R. A.: Hybrid image/model-based gaze-contingent rendering. *ACM Trans. Appl. Percept. 5* (February 2009), 22:1–22:21. 2

[MJ12] MANTIUK R., JANUS S.: Gaze-dependent ambient occlusion. *Lecture Notes in Computer Science (Proc. of ISVC'12 Conference) 7431*, I (2012), 523–532. 2

[MKNB12] MANTIUK R., KOWALIK M., NOWOSIELSKI A., BAZYLUK B.: Do-it-yourself eye tracker: Low-cost pupil-based eye tracker for computer graphics applications. *Lecture Notes in Computer Science (Proc. of MMM 2012) 7131* (2012), 115–125. 2

[MMS06] MANTIUK R., MYSZKOWSKI K., SEIDEL H.-P.: A perceptual framework for contrast processing of high dynamic range images. *ACM Trans. Appl. Percept. 3*, 3 (July 2006), 286–308. 4

[PCB00] PELZ J. B., CANOSA R., BABCOCK J.: Extended Tasks Elicit Complex Eye Movement Patterns. In *Eye Tracking Research & Applications (ETRA) Symposium* (Palm Beach Gardens, FL, 2000), ACM, pp. 37–43. 2

[PSF95] PONSODA V., SCOTT D., FINDLAY J.: A probability vector and transition matrix analysis of eye movements during visual search. *Acta Psychologica 88* (1995), 167–185. 3

[R D11] R DEVELOPMENT CORE TEAM: *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2011. ISBN 3-900051-07-0. 3

[RFM*09] RAHARDJA S., FARBIZ F., MANDERS C., ZHIYONG H., LING J. N. S., KHAN I. R., PING O. E., PENG S.: Eye hdr: gaze-adaptive system for displaying high-dynamic-range images. In *ACM SIGGRAPH ASIA 2009 Art Gallery & Emerging Technologies: Adaptation* (New York, NY, USA, 2009), SIGGRAPH ASIA '09, ACM, pp. 68–68. 3

[Sun11] SUNDSTEDT V.: *Gazing at Games: An Introduction to Eye Tracking Control*. Synthesis Lectures on Computer Graphics and Animation. Morgan & Claypool Publishers, www.morganclaypool.com, 2011. 2

[WPDH12] WANG R., PELFREY B., DUCHOWSKI A. T., HOUSE D. H.: Online Gaze Disparity via Binocular Eye Tracking on Stereoscopic Displays. In *3D Interaction, Modeling, Processing, Visualization, and Transmission (3DimPVT)* (Zürich, Switzerland, October 13-15 2012). 3

[WR08] WEBB N., RENSHAW T.: Eyetracking in HCI. In *Research Methods for Human-Computer Interaction*, Cairns P., Cox A. L., (Eds.). Cambridge University Press, Cambridge, UK, 2008, pp. 35–69. 3