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A review of eye tracking systems and its applications

Pramodini A. Punde[1] , Dr. Ramesh R. Manza[2]
[1]*Department of Computer Science, Vivekanand College, Aurangabad*
[2]*Department of Computer Science and Information Technology, Dr. Babasaheb Ambedkar Marathwada University, Aurangabad*

Abstract— Eye movements are a continuous part of sensory perception of a scene. Whenever we interact with the visual environment we generate saccadic eye movements. Saccades move the eyes in a ballistic manner from one point to another, interspersed by fixations where the eye is stable. Scan paths describe the sequence of fixations and saccades. This eye movement signature data can be collected as a part of a person's daily activities and can be analyzed to detect eye diseases, psychological disorders. Eleven papers which use different techniques and applications of eye tracking are reviewed here. Eye tracking systems including visible spectrum and infrared spectrum imaging, bright pupil and dark pupil techniques are reviewed and reported. Various applications of eye tracking systems including neurological, psychological, usability studies, biomedical applications, Human Computer Interaction applications are discussed.

Keywords– Eye tracking, eye movement signature

I. INTRODUCTION

Eye is a composite component consisting of retina, pupil, comea, scelra, iris, fovea, etc. Activities of these elements can be captured and used as control signals. To capture the eye movements, some components such as infrared camera, infrared light beam are used. An Eye Tracking System is based on a device to track the movement of the eyes to know exactly where a person is looking and for how long. These devices capture eye movement metrics as fixations, saccades, scanpath, blink rate, and pupil size.this information can be analyzed because the output is available in the form of gaze plots, heat maps, and area of interest.

STRUCTURE OF HUMAN EYE

Eye is an organ associated with vision. The eye allows us to see and interpret the shapes, colors and dimensions of objects in the world by processing the light they reflect or emit. It is housed in socket of bone called orbit and is protected from the external air by the eyelids. To the outside of the eye is a transparent sheet called conjunctiva, followed by white sclera.

Next to sclera is Choroids, which form the vascular layer of the eye. Choroid supplies nutrition to the eye structures. Light enters the eye through the cornea, pupil, and lens and is focused on the retina. Image formed on the retina is transmitted to brain by optic nerve. Iris regulates the amount of light entering the eye by changing the size of the pupil. In order of the eye to focus on objects at different distances, the ciliary's muscle reshape the elastic lens through the zonular fibres. Structure of human eye is shown in the figure1.

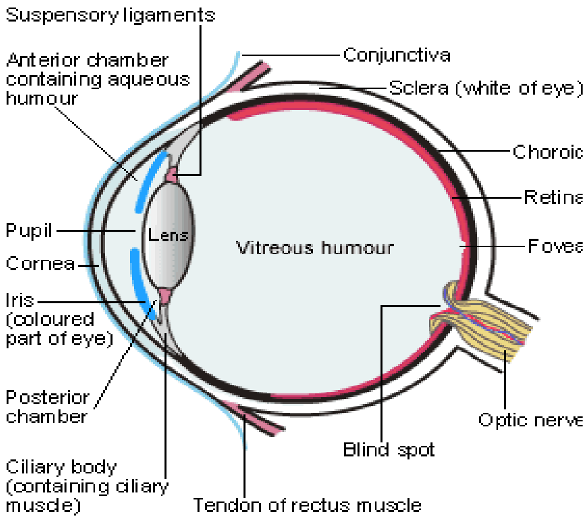

Figure 1 Structure of Human Eye[1]

Eye movements are a continuous part of sensory perception of a scene. Whenever we interact with the visual environment we generate saccadic eye movements. Saccades move the eyes in a ballistic manner from one point to another, interspersed by fixations where the eye is stable. Scan paths describe the sequence of fixations and saccades.

II. EYE TRACKING METHODS

[Dongheng Li, David Winfield, Derrick J. Parkhurst] Eye-tracking systems can be divided into remote and head-mounted systems. Each type of system has its respective advantages. For example, remote systems are not as intrusive but are not as accurate or flexible as head-mounted systems. In other work, they have developed a low-cost head-mounted eye tracker. This eye tracker consists of two consumer-grade CCD cameras that are mounted on a pair of safety glasses . One camera captures an image of the eye while the other captures an image of the scene. The two cameras are synchronized and operate at 30hz each capturing 640x480 pixels.
In this paper the authors developed an eye-tracking algorithm applicable for use with images captured from this type of head mounted system. However, the proposed algorithm could also be applied to video captured with a remote system. Two types of imaging processes are commonly used in eye tracking, visible and infrared spectrum imaging [2].
Visible spectrum imaging is a passive approach that captures ambient light reflected from the eye. In these images, it is often the case that the best feature to track in visible spectrum images is the contour between the iris and the sclera known as the limbus. The three most relevant features of the eye are the pupil - the aperture that lets light into the eye, the iris - the colored muscle group that controls the diameter of the pupil, and the sclera, the white protective tissue that covers the remainder of the eye. Visible spectrum eye tracking is complicated by the fact that uncontrolled ambient light is used as the source, which can contain multiple specular and diffuse components.
Infrared imaging eliminates uncontrolled specular reflection by actively illuminating the eye with a uniform and controlled infrared light not perceivable by the user. A further benefit of infrared imaging is that the pupil, rather than the limbus, is the strongest feature contour in the image both the sclera and the iris strongly reflect infrared light while only the sclera strongly reflects visible light. Tracking the pupil contour is preferable given that the pupil contour is smaller and more sharply defined than the limbus.

Furthermore, due to its size, the pupil is less likely to be occluded by the eye lids. The primary disadvantage of infrared imaging techniques is that they cannot be used outdoors during daytime due to the ambient infrared illumination. In this paper, authors focus the algorithm development on infrared spectrum imaging techniques but aim to extend these techniques to visible spectrum imaging as well. Infrared eye tracking typically utilizes either bright-pupil or dark-pupil techniques .
Bright-pupil techniques illuminate the eye with a source that is on or very near the axis of the camera. The result of such illumination is that the pupil is clearly demarcated as a bright region due to the photoreflective nature of the back of the eye. Dark-pupil techniques illuminate the eye with an off-axis source such that the pupil is the darkest region in the image, while the sclera, iris and eye lids all reflect relatively more illumination. In either method, the first-surface specular reflection of the illumination source off of the cornea (the outer-most optical element of the eye) is also visible. This vector between the pupil center and the corneal reflection is typically used as the dependent measure rather than the pupil center alone. This is because the vector difference is insensitive to slippage of the head gear - both the camera and the source move simultaneously.
In this paper the authors focused on algorithm development for dark-pupil techniques however this algorithm could be readily applied to bright pupil techniques [2].

Kyung Nam Kim and S.R. Ramakrishnan in 1999 proposed a vision based eye gaze tracking for human computer interaction. They proposed that eye gaze is an input mode which has the potential of an efficient computer interface. Eye movement has been the focus of research in this area. Non intrusive eye gaze tracking that allows slight head movement is used in this paper. A small 2D mask is employed as a reference to compensate for this movement. The iris center has been chosen for purposes of measuring eye movement. The gaze point is estimated after acquiring the eye movement data. Preliminary experimental results are given through a screen pointing application [3].

III. EYE TRACKING APPLICATIONS

Eye tracking has a variety of applications in Human Computer interaction systems.

Andrew T. Duchowski in his paper reports on eye tracking methodologies spanning three disciplines: neuroscience, psychology, and computer science, with brief remarks about industrial engineering and marketing. A breadth first survey is given, proceeding from the diagnostic use of eye trackers to interactive applications. As the present review demonstrates, eye trackers have traditionally shown themselves to be valuable in diagnostic studies of reading and other information processing tasks. The diagnostic use of an eye tracker, as exemplified by the research reviewed here, can be considered the eye tracker's mainstay application at the present time and probably in its near future. As also documented in this review, because eye trackers are able to provide a quantitative measure of realtime overt attention, they are valuable components of interactive systems. For disabled users, an eye tracking interface may be an indispensable form of communication (e.g., eye typing) [4].

Eye Tracking Metrics Most Commonly Reported in Usability Studies

Robert J. K. Jacob and Keith S. Karn in their review stated that eye movement research and eye tracking flourished in the 1970s, with great advances in both eye tracking technology and psychological theory to link eye tracking data to cognitive processes. To interpret eye tracking data, the usability researcher must choose some aspects (dependent variables or metrics) to analyze in the data stream. A review of the literature on this topic reveals that usability researchers use a wide variety of eye tracking metrics.

The usability researcher must choose eye tracking metrics that are relevant to the tasks and their inherent cognitive activities for each usability study individually. To provide some idea of these choices, Table 1 summarizes different usability studies that have incorporated eye tracking. The table includes a brief description of the users, the task and the eye tracking related metrics used by the authors [5].

Table 1: Summary of usability studies incorporating eye tracking:

Authors	**Users and Tasks**	**Eye Tracking Related Metrics**
Fitts, *et al*. (1950)	40 military pilots. Aircraft landing approach.	• Gaze rate (# of gazes/minute) on each area of interest • Gaze duration mean, on each area of interest • Gaze % (proportion of time) on each area of interest • Transition probability between areas of interest
Harris and Christhilf (1980)	4 instrument-rated pilots. Flying maneuvers in a simulator	• Gaze % (proportion of time) on each area of interest • Gaze duration mean, on each area of interest
Kolers, Duchnicky and Ferguson (1981)	20 university students. Reading text on a CRT in various formats with various scroll rates.	• Number of fixations, • Number of fixations on each area of interest • Number of words per fixation • Fixation rate overall (fixations/s) • Fixation duration mean, overall
Card (1984)	3 PC users. Searching for and selecting specified item from computer pull-down menu.	• Scan path direction (up/down) • Number of fixations, overall
Hendrickson (1989)	36 PC users. Selecting 1 to 3 items in various styles of computer menus.	• Number of fixations • Fixation rate overall (fixations/s) • Fixation duration mean, overall • Number of fixations on each area of interest • Fixation rate on each area of interest • Fixation duration mean, on each area of interest • Gaze duration mean, on each area of interest • Gaze % (proportion of time) on each area of interest • Transition probability between areas of interest •
Graf and Kruger (1989)	6 participants. Search for information to answer overall questions on screens of varying organization.	• Number of *voluntary* (>320 ms) fixations, • Number of *involuntary* (<240 ms) fixations • Number of fixations on target
Backs and Walrath (1992)	8 engineers Symbol search and counting tasks on color or monochrome displays.	• Number of fixations, overall • Fixation duration mean, overall • Fixation rate overall (fixations/s)
		• Scan path duration

Kotval and Goldberg (1998)	12 university students. Select command button specified directly from buttons grouped with various strategies.	• Scan path length • Scan path area (convex hull) • Fixation spatial density • Transition density • Number of fixations, overall • Fixation duration mean, overall • Fixation/saccade time ratio • Saccade length
Table 1 Continue…….. Redline and Lankford (2001)	25 adults. Fill out a 4-page questionnaire (of various forms) about lifestyle.	• Scan path
Josephson and Holmes (2002)	8 university students with web experience. Passively view web pages.	• Scan path
Albert and Liu	12 licensed drivers. Simultaneous driving and navigation using electronic map in simulator.	• Number of dwells, overall • Gaze duration mean on area of interest (map) • Number of dwells on each area of interest

The list provided in Table 1 is not a complete list of all applications of eye tracking in usability studies, but it provides a good sense of how these types of studies have evolved over these past years.

Ujjwal, K Sai Deepak, Arunava and Jayanthi propsed a novel approach for saliency detection based on visual saliency. In this paper, they explored if visual saliency can have a role in CAD algorithm design. They proposed visual saliency based framework for abnormality detection and illustrated it for bright lesion detection and discrimination in retinal images. The proposed framework is evaluated on several public datasets. The obtained results indicate that saliency maps are a good source of information for detecting/discriminating bright lesions. There is much scope to explore as there are numerous available saliency models of which one was applied in this work. They used steps: preprocessing, saliency computation, feature extraction and classification which can be performed in two levels using saliency map [6].

Authors Shuo Samuel Liu, Andrew Rawicz used EyeLive's GUI . Nine individuals (eight healthy and one with ALS) were recruited for experiments with the EyeLive system. The individual with ALS did not finish the test. The procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2004. The primary safety concern is the intensity of the infrared light emitted from the LEDs. The light intensity from the LEDs in EyeLive is below 1 mW/cm2, which is only 10% of the exposure limit in the ICNIRP (1997) guidelines for infrared radiation, and similar to the average corneal exposure from infrared radiation in sunlight. The safety concerns were explained to the test subjects and written consent was obtained.

After the test subjects were introduced to the operation procedures of the system and allowed to practice for ten minutes, they were able to use the system accurately without any difficulty. To numerically verify the accuracy of the algorithm, the 8 healthy individuals with normal eye sight each performed 10 trials. Each subject first calibrated the system by looking at 5 dark gray spots on the screen. Then, the subject looked at the 5 dark gray spots and 20additional light gray spots on the screen (thus a total of 25 eye movements). The light gray spots define the boundary within which the user is most likely to look in each direction. The measurement for each light gray spot was then classified using the MAE, MSE, and PCA algorithms to determine whether the classification matched the intended direction [7].

Priyanka Thapak and Prof. Ajit Kumar analysed pupil dilation. Pupil dilation is rarely analyzed in usability studies. But it can be measured by most video-based eye tracking systems and produces highly relevant workload information. They presented a Pupil dilation system, which was tested using two databases. They used circular Hough Transform for localizing pupil regions and linear HT for localizing eye lids.They produced a bit wise biometric templates using 1D Log-Gabor filters, phase quantizing and from pupil dilation identified genders [8].

Other researchers, Tseng WL, Kawbata, Susan Shur-Fen Gau, Nicky R. Crick in 2013, have used eye movements to classify patients with Attention Deficit Hyperactivity Disorder (ADHD) and Parkinsons disease. The work of this type has attempted to demonstrate the classification of clinical populations from natural viewing [9].

Crawford and his co-workers have shown that errors in the ability to make anti saccades have been repeatedly implicated in AD. Anti saccade is an eye movement purposely directed in the opposite direction from a target. They also have shown that patients with AD have also been shown to display irregular eye movements when reading or in other tasks [10].

Phillip J. Benson, Sara A. Beedie, Elizabeth Shephard, investigated eye movement tests alone and combined can best separate schrezophenia cases from control subjects and their predictive validity. They used recorded eye movements and group differences on performance measures were examined by univariate and multivariate analyses. Model fitting was used to compare regression, boosted tree, and probabilistic neural network approaches. After examination and assessment of whole dataset, they concluded that a cross validated probabilistic neural network model was superior and could discriminate all cases from controls with near perfect accuracy at 98.3% [11].

David P. Crabb, Nicholas Smith and Haogang Zhu, test the hypothesis that age-related neurodegenerative eye disease can be detected by examining patterns of eye movement recorded whilst a person naturally watches a movie. They collected data from thirty-two elderly people with healthy vision (median age : 70, inter quartile range [IQR] 64–75years) and 44 patients with a clinical diagnosis of glaucoma (median age : 69, IQR63 – 77 years) had standard vision examinations including gautomat edperimetry. Disease severity was measured using a standard clinical measure (visual field mean deviation; MD). All study participants viewed three unmodified TV and film clips on a computer setup in corporating the Eyelink1000 eye tracker (SR Research, Ontario, Canada).Eye movement scan paths were plotted using novel methods that first filtered the data and then generated saccade density maps. Maps were then subjected to a feature extraction analysis using kernel principal component analysis (KPCA). Features from the KPCA were then classified using a standard machine based classifier trained and tested by a 10 – fold cross validation which was repeated 100 times to estimate the confidence interval (CI) of classification sensitivity and specificity[12].

IV. Conclusion

In the above discussed papers different eye tracking methods namely visible spectrum imaging and infrared imaging, dark pupil technique, dark pupil technique and various applications of eye tracking systems are studied. Most of the researchers used eye movement metrics for viewing eye patterns for abnormalities and psychological disorders and some researchers used it for machine learning, usability research and HCI. The research paper entitled 'What's on TV? Detecting age-related neurodegenerative eye disease using eye movement scan paths' by David P. Crabb, Nicholas Smith and Haogang Zhu have used eye movement scan paths to demonstrate that a group of patients with glaucoma can be reasonably well separated from a group of healthy people by considering these eye movement signatures alone.

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