Computer Vision Based Systems for Human Pupillary Behavior Evaluation: A Systematic Review of the Literature

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***Abstract*—Analyzing human pupillary behavior is a noninvasive and alternative method for assessing neurological activity. Changes in this behavior are correlated with various health conditions, such as Parkinson's, Alzheimer's, autism and diabetes. Examining pupil behavior is a simple, low-cost method that can be used as a complementary diagnosis in comparison with other neurological evaluation methods. This approach is made by recording the pupillary behavior against light stimuli and measuring the pupil diameter through the video. The relation of pupillometry with digital image processing creates a dependency for computer vision based systems. Therefore, this paper presents a systematic review of the literature (SRL) conducted in order to analyze the progress of pupillometry systems based on computer vision. The main goal was to establish the state of art and identify possible gaps.**

Keywords: ***Pupil, Pupillary behavior, Pupillometry systems, Computer vision, Pupillometer.***

I. Introduction

Human pupillary behavior has been a major topic in scientific research, especially in the medical field. Because of its neurological relationship, examining pupil behavior is a non-invasive method to evaluate neural activity [1], which when abnormal may indicate: Alzheimer [2], Autism [3] and Diabetes [4].

The pupillary behavior presents two reflexes that aimed to control the pupil diameter based on the intensity of illumination in the eyes. The first reflex, shown in Figure 1 (A), called dilation or mydriasis, is activated by lower illumination intensities and is responsible for increasing the amount of light that enters in the eye [5]. The second reflex, Figure 1 (B), is called contraction or miosis and allows less light inputs in moments when there are greater intensities of light [6].

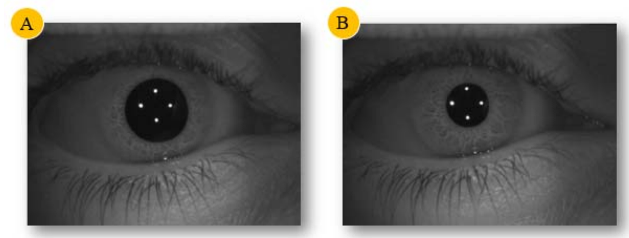

Figure 1. Pupillary reflexes: (A) Dilation and (B) Contraction.

As an important indicator for medical studies, the pupillary behavior can be evaluated by measuring the pupil diameter, in which visual and/or luminous stimuli are used to induce the reflexes, such process is known as Pupillometry [7] and it has a dependency on devices with infrared cameras since dilation can only be observed in low light conditions. Such devices, combined with computer vision software are responsible for the image acquisition, processing, and feature extraction, essential steps for pupillary behavior evaluation.

In this scenario, pupillometry systems can provide an efficient solution by extracting reliable data for medical evaluations. Due to the relevance of these solutions based computer vision for the success of pupillometry, an analysis of the current literature is crucial. Such kind of analysis can provide an understanding of state of the art and the possible gaps in this area. Therefore, this paper presents a systematic review of the literature that reveals and evaluate the main published papers in this area of computer vision.

The remaining of this paper is organized as follows. Section II describes the adopted systematic review process [8] and exposes its development, showing the selected research questions, the databases which have been analyzed, the research terms used to find the studies, the selection criteria and finally the answers for each research question.

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In Section III we present the conclusions.

II. Systematic Review Procedure

The comprehension of current research topics is one of the most important factors to researchers that want to develop studies that will bring relevant contributions to their research area. However, knowing the most recent and relevant investigations of a study area, which is called state of the art, is not a trivial task since nowadays the majority of scientific fields are regularly receiving new research.

In this context, Systematic Reviews of Literature (SRL) emerge as a viable solution to understand the previous investigations, established methods and strategies, and open topics in a particular area by identifying, evaluating, and synthesizing relevant research [8]. In this sense, this paper consists on an SRL that analyzes the state of the art in the context of computer vision based systems for pupillometry following the methodology proposed by Kitchenham [8], which is composed of: planning, conducting and reporting.

A. Planning review

The first step of an SRL consists of designing a revision protocol to identify articles that meet the specifications that classifies them within the area of interest [8]. This pre-defined protocol aims to discard papers that are not related to the research area. The revision protocol includes the definition of which databases will be used to find the studies, what will be the search terms, the selection criteria, and research questions that will be answered through the analysis of the selected papers. The revision protocol phase was made in collaboration with the <blindreview> members of the <blindreview>, aimed to reduce bias.

1) Databases and Search terms:

In order to find relevant papers, four consolidated databases were selected. All searches were performed using the advanced option, that allows the use of strings with logical operators. The search engines used for each database can be accessed in the web addresses, as below:

- ACM Library (http://www.acm.org).
- IEEE Explorer (http://ieeexplore.ieee.org/).
- Science Direct (http://www.sciencedirect.com).
- Scopus (https://www.scopus.com/).

Due to the wide variety of terms, a more general search string was employed and five words were selected: pupil, pupillary, pupillometer, pupillometry and pupillometric. For all of them, the 'OR' operator was applied, resulting in: "pupil or pupillary or pupillometer or pupillometry or pupillometric".

2) Selection criteria:

To select articles to be included into the review, an approval/reject process is performed. This process involves three steps. The first is reading each paper, title and abstract, and including/excluding them according to the established criteria. If both title and abstract had no relevant information for the review, then the article is excluded. In the second step, the remaining studies pass to a full read to guarantee the approval and the same criteria is applied. All the criteria defined are presented below:

Inclusion:

- Full papers written in English and published since 2012.
- Papers peer-reviewed and available in full-text.
- Papers related to systems based on computer vision for pupillometry.

Exclusion:

- Duplicated papers.
- Papers that were unavailable on-line.
- Papers not focused on human pupillary behavior.
- Papers not presenting methodology and/or results.

The goal of the inclusion criteria was to find articles published in the last five years which were selected by a rigorous process. The exclusion criteria remove less relevant work such as short papers and tutorials or duplicated articles.

3) Research Questions:

The research questions are one of the most valuable assets of a Systematic Reviews of Literature since they synthesize the content of selected papers and can provide researchers relevant information about the study area which is analyzed by the SRL. For example, research questions can show which are the most popular methods and processes employed or which are the open topics. In this sense, six research questions were formulated, as follows:

- **Q01.** What are the specifications of devices used for image acquisition? And what are the types of environment where images are taken?
- **Q02.** What are the methods applied for pupil segmentation? And what are the languages and/or platform of programming used?
- **Q03.** What are the procedures used to induce pupillary behavior?
- **Q04.** What are the methods used to interpolate the blinking gaps?
- **Q05.** What are the features extracted for pupillary behavior evaluation?
- **Q06.** What are the levels of accuracy from the proposed systems?

The first research question seeks to expose what kind of equipment is used in this type of investigation, and in what conditions the images are acquired. Question 2 focuses on analyzing which programming languages, platforms, and computer vision methods are used. Question 3 focuses on what kind of stimuli is used to evaluate pupillary behavior. Question 4 identifies the interpolation methods that are applied, considering that the blinking is one of the most common segmentation issues. Question 5 analyzes what information can be inferred, and Question 6 verifies the level of efficiency of the proposed systems.

B. Conducting review

According to the previously established review strategy, see subsection 2.1, the search string presented in subsection 2.1 was applied in the databases as shown in Figure 2 (A). As a result, a total of 3.500 studies was selected, the distribution for each database can be seen in Figure 2 (B).

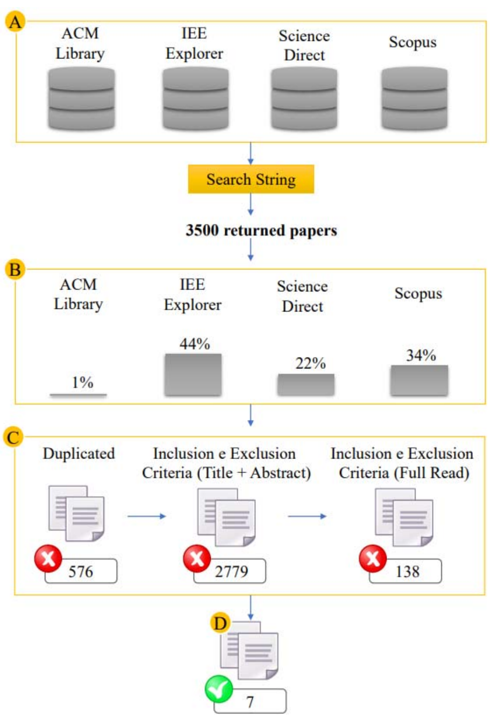

Figure 2. Systematic review scheme and results: (A) Selected databases, (B) Returned papers distribution, (C) Excluded papers and (D) Selected papers.

As first step all title and abstract were submitted to the approval/reject process mentioned in subsection 2.1. A total of 2.779 papers were excluded, not including 576 that were duplicated, Figure 2 (C). The remaining 145 passed to a full-read and the same approval/reject process was applicated, resulting in seven papers that are aligned to the purpose of this SRL, Figure 2 (D). The next subsection presents the synthesis and discussion of the seven selected papers.

C. Reporting review

After selecting the relevant studies related to the subject addressed by the SRL, the reporting review stage presents a synthesis of each study and answers the proposed research questions. In this sense, a brief discussion is showed below to highlight the most important information for each question, for more details the tables can be consulted at the end.

*1) **Q01.** What are the specifications of devices used for image acquisition? And what are the types of environment where images are taken?:*

The details regarding the hardware settings of the pupillometry systems can be consulted in Table I. When analyzing the data it is perceived that the cameras were chosen mainly to prioritize the low cost of the final systems, considering that the pupillometers available on the market can cost up to $ 10.000 [9].

All systems were equipped with infrared cameras, a factor that allows the pupil dilation to be captured, and which also simplifies the process of pupil identification, since the images lose their colored features. Another observation is related to the choice for controlled environments, what can be explained taking that it is difficult to establish segmentation methods invariant to light [10].

The most common image frame capture rate was 30 fps, enough speed to capture changes in the pupil diameter. Finally, the wave length used for the emission of the infrared LEDs, also remained homogeneous, 850 nm, following the recommended standards for eye safety by infrared exposure time [11].

*2) **Q02.** What are the methods applied for pupil segmentation? and what are the languages and/or platform of programming used?:*

The Gaussian filter along with the morphological transformations were the most used techniques for the noise removal in the images. For segmentation of the pupils there was a division between manual binarization and use of classifiers. It should be noted that the segmentation approaches were not very well detailed, and in some systems it was not even mentioned. Finally, it is important to note that there was a certain difficulty in establishing approaches that were 100% automated and invariant to luminosity, a field that still needs more efforts.

In terms of programming language, only two were used, C ++ and M, with C ++ being the main one, Table II. The choice of Matlab occurred when a more user-friendly graphical interface was prioritized and agility in development was needed. In contrast, the C ++ language was applied when interest was the performance, real-time processing systems. The OpenCV API was used in all the works that chose C ++, a well-established library for computer vision, mainly for its performance and use for mobile application development.

*3) **Q03.** What are the procedures used to induce pupillary behavior?:*

As the target systems have a focus on pupillometry, and have made the choice for controlled environments, there is a need to induce the pupillary reflexes so that they can then be analyzed. The choice to use LEDs as a source of stimulus is the primary form identified, Table II, followed by images and figures with solid colors that simulate light and dark. Only one paper [12] made use of LEDs with different colors. Using different lighting colors makes the segmentation process difficult, since in each situation the image characteristics drastically changes. However, it is important to emphasize that as the eyes have photosensitive cells in different amounts per color [13], each color of stimulus can generate different reactions and consequently different features.

From the moment that the reflexes are induced, it is essential to record the filming of these reflexes. There are two types of reflexes, those of the eye that is receiving the stimulus, called the direct pupillary reflex, and from the eye that is not being stimulated, known as consensual pupillary reflex [14]. Regardless of which side is illuminated, both pupillary reflexes are expected to be symmetrical [14]. It can be seen from Table II that the right side is the primary target for the capture of the direct reflex, a reflection that is also the main interest of the studies, since the consensual reflex was the focus of only two [7][15] of them.

*4) **Q04.** What are the methods used to interpolate the blinking gaps? :*

Since humans blink very often, one of the major problems in establishing pupil localization methods is to identify times when there is no pupil in the image or times when a reconstruction is needed from a partially visible pupil. This problem also occurs when the image loses focus. So seeing that overcoming this problem is inevitable, interpolation methods are important to fill the gaps in the signal. Only two papers reported their method of interpolation, Table II, being the methods of bi-cubic interpolation [16] and neighborhood average [7]. Here it is important to point out that the most commonly used interpolation method in these cases is actually the linear interpolation method [1][3][17].

*5) **Q05.** What are the features extracted for pupillary behavior evaluation?:*

Through the computer vision methods, it is possible to identify the pupil, after that; the most important task is to make these data useful, taking into account that a signal composed of the diameter as a function of time is generated. However, some works only analyzed the diameter at some moments of the recording [12][18][19], Table III. With this in mind, we highlight the works that dealt with more dynamic features, such as: maximum mydriasis [7], maximum miosis [7], amplitude [7][16], latency [7], time to maximum contraction and time to maximum dilation [7][15]. As accuracy was not published, it is not possible to analyze the impact of these variables in the application of the proposals.

*6) **Q06.** What are the levels of accuracy from the proposed systems?:*

None of the selected papers presented in their results the accuracy/performance of their computer vision methods. As for the measurement precision only the work [9] presented a result, with a precision error of 0.05 mm. This lack of accuracy/performance results may be explained by the fact that the papers were more focused on proving the viability of their systems. However, it is important to register the relevance of publishing such data, for the contribution of the computer vision methods already published and/or in development.

III. Conclusion

Through a systematic review, an investigation was conducted regarding the most recent pupillometry approaches based on computer vision. The main goal of this study was to analyze the progress of this kind of systems. In this SRL seven papers were selected from a total of 3.500. Our synthesis indicates that: there is a preference for the C ++ language in conjunction with the OpenCV API for system development due to its performance; the aim of most approaches is to offer a cheaper and portable alternative to this type of examination; there is a need for computer vision methods for pupil segmentation that are invariant to light; there is a necessity for exploring pupillary reflexes against RGB light rather that only white and better solutions to identify and correct the signals affected by blinking, one of the major segmentation problems.

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Author	Hardware Platafform		Resolution	FPS	Environment	Distance (cm)	Light Conditions	NIR Intensity (nm)
	Camera	Type						
[15]	-	IR	510x492	30	Controlled	5.2	Scotopic	850
[9]	Philips SPC530	IR	640x480	30	Controlled	20	Photopic	850
[16]	IR-based eye tracker	IR	1280x960	16	Controlled	60	Mesopic, Photopic	850
[18]	Sony XC-EI50CE	IR	752x582	30	Controlled	-	Photopic, Scotopic	850
[7]	Point Grey Fire-fly MTV022	IR	-	60	Controlled	30	Photopic, Scotopic	-
[12]	DFM 22BUC03	IR	-	30	Controlled	-	Photopic, Scotopic	945
[19]	Intel Realsense SR300	IR	640x480	60	Controlled	35	Scotopic	-

Table I
HARDWARE SETTINGS OF THE SELECTED PAPERS (NIR = NEAR INFRARED, FPS = FRAMES PER SECOND, SCOTOPIC = VISION FROM LOW LIGHT CONDITIONS, MESOPIC = VISION FROM MEDIUM LIGHT CONDITIONS, PHOTOPIC = VISION FROM HIGH LIGHT CONDITIONS)

Author	Segmentation	Identification	Blinking detection	Interpolation methods	Platform	Language	API
[15]	Sobel edge detector	Hough transform	-	-	-	-	-
[9]	Histogram equalization, Gaussian filter, Manual thresholding, Blobs labeling	Circularity filter	-	-	-	C++	OpenCV
[16]	Viola-Jones multi-scale object detector, Haar-like features	Integro-differential operator	Integro-differential operator	Bicubic interpolation	-	-	-
[18]	Manual thresholding, Gaussian filter	Modified starburst algorithm, Random sample consensus (RANSAC)	-	-	Matlab	M	-
[7]	-	-	-	Neighborhood average	-	C++	OpenCV
[12]	Binarization, Morphological transformation	-	-	-	Matlab	M	-
[19]	Histogram equalization, Morphological transformation	-	-	-	-	C++	OpenCV

Table II
COMPUTER VISION APPROACHES OF THE SELECTED PAPERS

Author	Stimulus	Stimulated eye	Recorded eye	Reflex Type	Features
[15]	White light	Right	Left	Consensual	Circularity, Diameter, Contraction and dilation time, Contraction and dilation rate
[9]	Images	Right	Right	Direct	Diameter, Gaze location
[16]	White light	-	-	Direct	Diameter, Amplitude
[18]	White light	-	-	Direct	Diameter
[7]	White light	Right	Left	Consensual	Maximum mydriasis, Maximum miosis, Amplitude, Latency, Time to maximum contraction, Time to maximum dilation
[12]	RGB light	-	Right, Left	Direct	Diameter
[19]	Black/White images	Right, Left	Right, Left	Direct	Diameter

Table III
PROCEDURE SETTINGS OF THE SELECTED PAPERS