Pupil Diameter as a Measure of Emotion and Sickness in VR

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ABSTRACT

Eye tracking is rapidly becoming popular in consumer technology, including virtual and augmented reality. Eye trackers commonly provide an estimate of gaze location, and pupil diameter. Pupil diameter is useful for interactive systems, as it provides means to estimate cognitive load, stress, and emotional state. However, there are several roadblocks that limit the use of pupil diameter. In VR HMDs there are a lack of models that account for stereoscopic viewing and the increased brightness of near eye displays. Existing work has shown correlations between pupil diameter and emotion, but have not been extended to VR environments. The scope of this work is to bridge the gap between existing research on emotion and pupil diameter to VR, while also attempting to use pupillary data to tackle the problem of simulator sickness in VR.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; *User studies*; Interactive systems and tools; • **Applied computing** → **Psychology**;

KEYWORDS

Pupil Diameter, Virtual Reality, Pupillary Light Reflex, Arousal Classification, Simulator Sickness

ACM Reference Format:

Brendan John. 2019. Pupil Diameter as a Measure of Emotion and Sickness in VR. In *2019 Symposium on Eye Tracking Research and Applications (ETRA '19)*, June 25–28, 2019, Denver, CO, USA. ACM, New York, NY, USA, 3 pages. <https://doi.org/10.1145/3314111.3322868>

1 INTRODUCTION

The human eye provides a wealth of information regarding the individual, and many say it serves as a window into the soul. It is well documented that pupil diameter can be used to reveal information regarding cognitive load [Beatty 1982; Krejtz et al. 2018; Marshall 2002], task performance [White and French 2017], emotional arousal [Bradley et al. 2008], and stress [Pedrotti et al. 2014]. Despite a large body of work establishing pupil diameter as an index of cognitive load and emotional state, this modality is not commonly integrated into sensor suites. The scope of this work is to establish pupil diameter as a method of measuring emotional arousal and simulator sickness induced by VR displays.

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ETRA '19, June 25–28, 2019, Denver, CO, USA

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ACM ISBN 978-1-4503-6709-7/19/06.

<https://doi.org/10.1145/3314111.3322868>

2 RESEARCH OBJECTIVES

To generate research objectives I will first identify roadblocks that confound the use of pupil diameter in current VR displays. First, note that the vast majority of prior research in pupil diameter applications have been performed on traditional 2D displays. These displays present content at a single depth. VR HMDs display immersive 3D content to the user with binocular viewing. As a result these displays create a vergence/accommodation conflict, where the eyes converge to a depth other than that of the display.

Second, it is well established that the brightness of light entering the eye triggers a response in pupil diameter with a short latency [De Groot and Gebhard 1952; Reeves 1918; Young and Biersdorf 1954]. Pupils constrict to a smaller size with bright light, and dilate to a larger size in dark environments. This response should be removed from the signal for accurate classification.

Third, there is a need for a simple model that would allow for pupil diameter to replace established measures. Ground truth emotional response and simulator sickness is most commonly found through self reports [Bradley and Lang 1994; Kennedy et al. 1993] or real time annotation [Cowie et al. 2000; Mavridou et al. 2018]. Currently the types of sensors most strongly correlated with ground truth include EEG, HRV, and GSR. Pupil diameter is difficult to correlate with these established sensors, in part because of the one dimensional of data being produced. Based on these open issues within the field, my research objectives are as follows:

- R_1 : Validate the use of existing pupillary light response models within a stereoscopic VR display. This is necessary to apply pupil diameter as a measure in VR environments.
- R_2 : Establish a correlation between pupil diameter and existing measures as an index of emotion and simulator sickness in VR environments. This is necessary to show pupil diameter is an alternative to more complex and invasive sensors.

3 HYPOTHESIS AND PROBLEM STATEMENT

My research goals can be split into two components. The first component would require successfully modeling pupillary light reflex (PLR) in VR. Second, there is a need to evaluate models that classify emotion or simulator sickness based on changes in pupil diameter of the user. Formally my hypotheses are as follows:

- H_1 : The calibration procedure and application of a PLR model at a fixed depth in VR produces errors at the same scale as traditional 2D displays.
- H_2 : The calibration procedure and application of a PLR model at multiple depths in VR produces errors at the same scale as traditional 2D displays.
- H_3 : A light compensated PLR model shows significant correlation with emotional arousal and valence in VR.
- H_4 : A light compensated PLR model shows significant correlation with simulator sickness in VR.

Figure 1: Top: Pupillary data for participant s015 performing a 2D PLR calibration. Solid red lines indicate when a grayscale intensity was presented, and red circles indicate the extracted pupil diameter associated with each intensity. Bottom: Grayscale intensity images for $I = 64$ and $I = 196$.

4 METHODOLOGY

4.1 PLR Modelling

For the PLR calibration I am using an approach proposed by [Raiturkar et al. 2016b], that displays a range of grayscale intensities on screen while recording pupil diameter. The grayscale image appears for a duration of one second, and then the screen returns to black for eight seconds. Figure 1 shows pupil diameter during the calibration procedure, and example stimuli.

Once this calibration has been performed there is a one to one mapping between pupil diameter in millimeters, and grayscale intensity in the range $[0, 255]$. [Watson and Yellott 2012] provide a review of the models commonly used to predict pupil diameter from PLR, including linear, cubic, and exponential models. The model is used to compute the pupil diameter from PLR, PD_{PLR} ; which is then subtracted from the recorded values during an experiment to generate a light compensated pupil diameter, $PD_E = PD - PD_{PLR}$, where PD is the pupil diameter after pre-processing.

4.2 User Studies & Classification

Computing PD_E is straightforward after a calibration. Classifying these values to a specific state, i.e. aroused or sick, is not as straightforward. One simple approach is compare the average PD_E over a time window to an average baseline value computed during a neutral part of the experiment [Krejtz et al. 2018].

To branch into a more complex understanding of pupillary data, I propose correlating PD_E with ground truth measures of arousal and simulator sickness in VR. An initial user study, S_1 , would be conducted to correlate this feature with self reports provided during, and after the VR experience. Self reports will take the form of Likert style questionnaire responses and real-time feedback from a joystick used to report arousal and valence [Cowie et al. 2000; Mavridou et al. 2018]. There are three independent variables: the VR format, emotional arousal/valence, and level of motion inducing sickness.

A second study, S_2 , would then be designed based on findings from the initial data collection. The goal of this study is to make the classification system more robust. This study would integrate

Figure 2: PLR models from one participant (s003) in VR.

additional physiological sensors into the data collection, removing the task of reporting real-time emotional feedback from the user. It is hypothesized that the reporting adds a significant amount of cognitive load and mental processing to the user [Malandrakis et al. 2011; Yannakakis and Martinez 2015].

A variety of models and machine learning techniques have been applied with similar data, including linear discriminants [Klotzsche et al. 2018], SVMs [Ramirez and Vamvakousis 2012], LSTM networks [Hofmann et al. 2018], and decision trees [Padmanaban et al. 2018]. The performance of machine learning models and feature selection techniques, such as PCA and random forests, will highlight how pupil diameter is linked to emotion and simulator sickness.

5 PRELIMINARY RESULTS

Preliminary work conducted thus far is concerned with R_1 , and answering H_1 . I worked to extend the calibration procedure described in Section 4.1 to a VR HMD, while increasing the number of intensity values from eight to sixteen and tested the effect of varying the order in which intensities were presented [John et al. 2018]. Linear, cubic, and exponential models were fit for each for each participant. Figure 2 shows one such model. We found that the exponential model performed best, which is in contrast to the 2D viewing scenario where the linear model performed best. We also found that the predictive error from the VR calibration was on the same scale as that of the 2D calibration, with an average error of 0.27mm. This has confirmed H_1 , but there is still a need to evaluate these models at different depths.

6 FUTURE WORK

There are two components planned for future work. First, I must continue exploring R_1 , and confirm if H_2 is true. If H_2 holds, we can proceed with exploring R_2 . Otherwise, the model will have to be modified to account for depths at multiple stimuli. I would then use a calibration performed at different depths, and integrate the current gaze depth into the PLR model to predict pupil diameter from depth and light intensity.

Once H_1 and H_2 have been answered I will proceed with conducting studies S_1 and S_2 . I already have access to a VR HMD with integrated eye tracker and a device to compute HRV and GSR (as described in [Raiturkar et al. 2016a]). The ultimate goal of my work is to produce a system that can use pupil diameter to predict emotional state or motion sickness in VR.

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