A Case Study with Implications of the Mobile Cognitive Pupillometry Research Toolkit

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Abstract

Pupillometry involves measuring changes in the diameter of the eye's pupil. Such pupillary responses have been well studied by scientists to link with a great variety of cognitive processes. However, the responses are typically investigated in the lab settings since they are easily influenced by light sources. To pave the way to expand pupillometry research methods, our paper will showcase design implications of a mobile cognitive pupillometry toolkit that can be integrated beyond the state-of-the-art experimental conditions. We discuss benefits, as well as challenges, of conducting cognitive pupillometry experiments in the less-controlled settings.

Keywords : Cognitive Pupillometry, Mobility, Research Toolkit

1. Introduction

Measuring the size of the eye's pupil using a video-based eye tracker has been widely done in cognitive science research. Changes in the pupil size have been regarded as cues to internal mechanisms, and there is a notable body of research investigating cognitive processes through pupillary responses [4]. For example, Naber's group conducted various pupillometry studies that examined pupil constriction influenced by awareness or imaginary stimuli [17, 18]. Research has also explored the relationship of dilating pupils with arousal [2] as well as a with perceived attractiveness [22].

To correctly investigate if there is correlation between cognitive aspects and the pupil's response, pupillometry experiments are restricted to well-controlled settings. It is crucial for experimenters to regulate the confounding factor of pupillary light reflex, as pupils noticeably constrict in response to bright light and dilate under dim light. Therefore, the controlled set up involves correcting experimental room light sources [10, 13] and luminance levels of stimuli [17, 18], or stabilizing head position or movememnt of participants using a chin- or head-rest [1, 18].

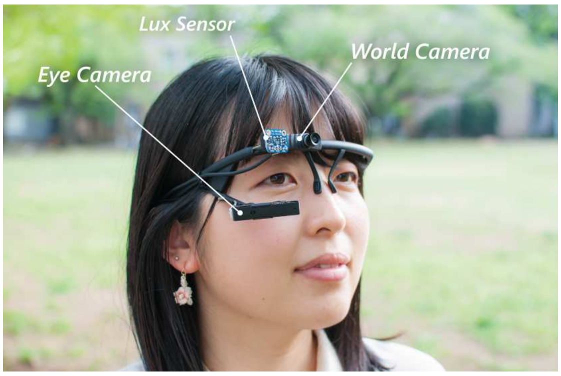

Fig. 1 Pupillometry Toolkit with Light Sensor.

While some pupillometry experiments have considered light-adapted pupil size [15, 19, 24] or cameras that can compensate for small head movements [8, 6], less-controlled settings are not yet applicable to trials beyond the lab. To maintain validity of the research, mobile aspects are mostly out of the scope in the design of experiments. Even with the availability of wearable eye trackers [21, 23], potential applications in cognitive pupillometry research have not been investigated.

In this research, we aim to address the potential applications of a mobile pupillometry toolkit that can expand the experimental conditions and fields of analysis in cognitive understanding. We conducted a case study to use a mobile equipment in replicated cognitive pupillometry experiments originally performed in well-controlled settings. As our initial mobile platform, we exploited an open-source eye tracking offered by [21] and integrated light sensor values when capturing pupil diameter from the eye camera and attended stimuli from the scene camera (Shown in Figure 1).

The main contribution of this work is to discuss the challenges and benefits of a mobile pupillometry platform. Based on our case study results, we analyzed the effects between the less-controlled and traditional scenarios. We found that our mobile toolkit was able to resemble the proxy of one's cognitive state in goal-oriented task performance. We bring about advantages of a mobile pupillometry toolkit and discuss how we can improve the technical limitations to motivate research in understanding cognitive mechanisms towards real world applications.

2. Background and Related Work

The most popular method for measuring the pupil size is to use video-based eye trackers that can compute the pupil diameter from imaging of the eye as part of estimating the direction of gaze. High precision measurements of pupil diameter depend on a setup, and head-mounted or table-top trackers with chin rests are usually preferred to maintain a fixed camera-pupil distance [9]. However, they are notorious for obtrusive measurements and mostly interfere with cognitive experimental protocols [13]. Remote eye trackers today are approaching a less invasive setup, with cameras placed further from and not fixed to the participant's head [9], though stabilized luminance environments or stimuli become more crucial.

Researchers have attempted to take into account environmental or stimuli effects and several other factors, such as the individual's light sensitivity, that might co-vary with pupil size measurements. In [19, 24], adjusting pupil diameter data to compensate for the overall luminance of stimuli have been introduced. An algorithmic strategy to keep stable illumination conditions throughout the captured images is approached for a wearable eye tracking device [12]. Pupil sensitivity or baseline correction have also been considered to remove random fluctuations in pupil size [15, 16].

Cognitive pupillometry is still subject to restrictions that make it least integrated into a mobile platform, compared to how EEG headsets [20] or EOG glasses [5] are expanding to sensing of cognitive or emotional states in daily activity logs. Many commercially-available wearable eye trackers are meant for estimating gaze direction. One of a few mobile devices integrating pupillometry is [14] that measures the pupil size to assess brain injury in a VR scenario. Since cognitive pupillometry research has been significantly viable in the lab settings, there is no explicit understanding of "how much" less-controlled aspects will have exploitation possibilities to expand the current research.

3. Toolkit Description

To investigate the potential applications of the mobile cognitive pupillometry, we utilized the off-the-shelf wearable eye tracker called Pupil Labs [21] and attached a light sensor (TSL2561 luminosity sensor[1]) to measure lux values of presented stimuli correlated with the changes in the pupil diameter. Figure 1 shows our actual prototype of the toolkit. The light sensor can detect ranges from up to 40,000 Lux, and the values were transmitted through a USB serial from a microcontroller (Feather M0 Basic Proto[2]). With the eye camera and the open-source eye-tracking algorithm, 3d model fitting of the eye is captured and constantly updated based on observations of the eye being tracked. World camera captures a scene from the wearer's 100 degree field of view.

Figure 2 shows our recorder application. It receives 3D pupil diameter data through ZMQ connection at 120 frames per second and the lux values at every second. The application also takes in the events data synched with pupil and lux information to capture corresponding conditions of visual stimuli. The tracker is connected to a laptop to receive all of these data. Before we start the recorder application, we run the calibration software offered from [21] to reflect accurate tracking of the individual's eye movements.

4. Case Study

We present a case study to gain a deeper understanding of potential impacts and design challenges of the deployable mobile cognitive pupillometry. Our study method involves collecting necessary data to replicate the classic studies on pupillary responses using our

[1] https://cdn-shop.adafruit.com/datasheets/TSL2561.pdf Accessed: Jun 29, 2019

[2] https://cdn-learn.adafruit.com/downloads/pdf/adafruit-feather-m0-basic-proto.pdf Accessed: Jun 29, 2019

Fig. 2 Recorder application capturing pupil diameter (mm), lux values (Lux), and stimuli events.

mobile toolkit discussed above. We expect to see quantitative and qualitative differences of the pupillary results with the original experimental settings. The findings will enable us to elaborate design requirements as a mobile platform.

4.1 Replication of Prior Studies

We performed two cognitive pupillary tests which were explored in different setup properties. Head position, visual stimulus luminance, and lighting source were controlled in Test 1 as a baseline to validate our use of the lux sensor in the mobile toolkit. On the other hand, we conducted Test 2 in less-controlled settings, accepting free head movements under semi-controlled stimulus luminance and lighting to investigate the scope of mobile cognitive pupillometry. The followings are the details of the replication of previous studies:

Test 1

Our first test was based on the work from [18] that observed the pupil to constrict when exposed to brightness illusions. Specifically, participants were given with pictures of natural scenes with the sun and without the sun. While observing the images on a display screen, the participants' pupil constriction was seen more under the sun condition than no-sun condition, even though the sun images were lower in luminance than those without the sun.

Controlled Setup

The perception test of light sources was chosen for the initial validation of our lux data collection under the similar well-controlled settings as the original research. We used a chin rest to control head movements and allow for a fixed display-pupil distance. The experimental room had no illumination other than the screen. As shown in Figure 3(1a), we employed the original light-intensity-corrected image dataset for both conditions of scenes with sun or no sun. However, we collected data from 7 subjects, whereas the original experiments had 26 subjects. Moreover, we showed 10 images per condition, compared to 20 images in the original design. We always had a gray baseline screen between the images.

Test 2

Our second test was based on the work from [15] that observed the pupil to dilate when exposed to goal-oriented visual search for targets. The original research showed images of natural scenes to the participants who were asked to find a hidden letter. When looking for less-obvious targets, which required mental effort to achieve the goal, the observers had fixations over the images with large pupils.

Semi-Controlled Setup

Based on the pupil response findings from [15], we employed the experimental procedures of visual search of "Finding Waldo" from [7]. As shown in Figure 3(2a), the conditions were split into 1) no-goal-driven viewing of example images with obvious targets and 2) goal-driven viewing for non-obvious targets. We expected the rise of the pupil diameter when evoked in goal-oriented performance. We did not utilize a chin rest and had regulated light sources other than the display screen. Images were not precisely corrected but we made sure the images had no originial light intensity differences (measured at a fixed distance from our light sensor) more than 1 Lux. We gave 5 images per condition, and 24 subjects' data were collected, in comparison to 16 subjects with 100 search-for-target images per condition in the original study of [15].

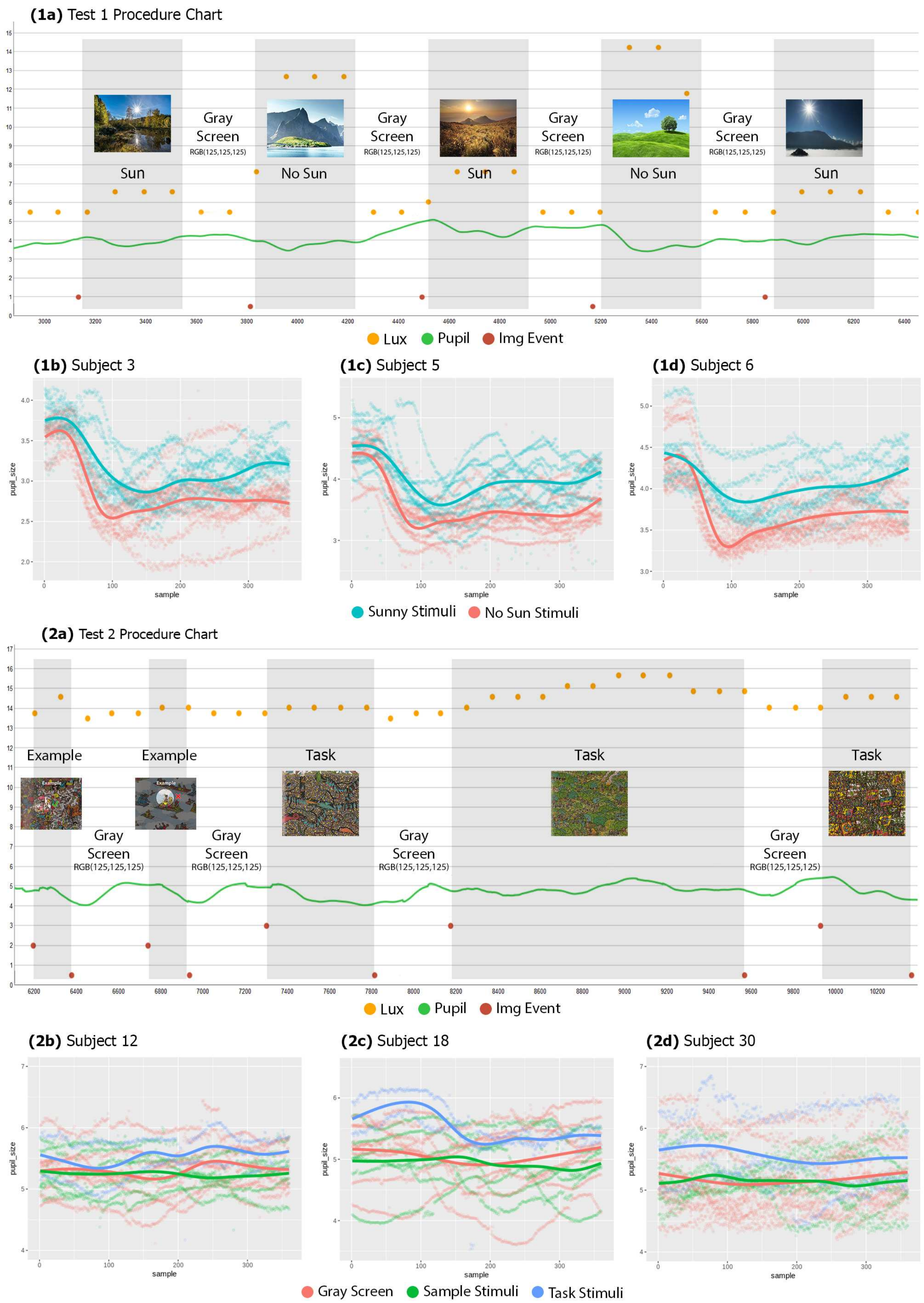

Fig. 3 Test 1: Subjective Perception of Brightness Illusions, Test 2: Mental Effort in Goal-Driven Performance; **(a)** Data collection procedures with actual values of lux and pupil size captured, and events of stimuli; **(b, c, d)** Average change in pupil diameter in mm (solid lines) under each condition as a function of sampling frames.

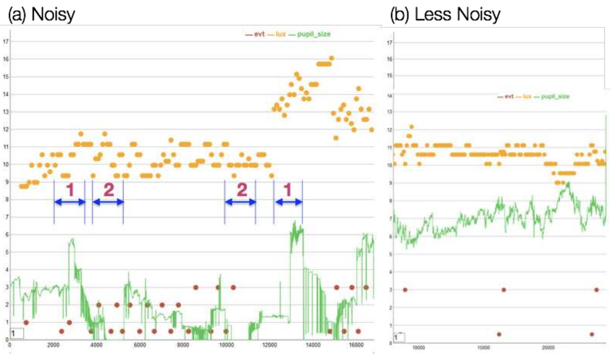

Fig. 4 Examples of Pupil Size Data Shown in Green; **(a)** Noisy data with loss of tracking, with 1. sudden jumps and 2. zero values; **(b)** Less noisy data.

5. Findings

We provide quantitative and qualitative findings to explore the possibilities and limitations of less-controlled settings under our mobile platform when running cognitive pupillary research.

5.1 Statistical Analysis

We run non-pairwise T-tests to compare the conditions (Test 1: Sun and No-Sun, Test 2: Goal-Driven and No-Goal-Driven). Due to loss of pupil diameter tracking for multiple factors, we were able to use 10 participants' data in Test 2 even though the total number of participants was 24. Since the main purpose of Test 1 was to validate our light sensor, we used all of the data from 7 participants. Figure 4 shows examples of pupil size data that were captured with random value fluctuations and jumps, in comparison to less noisy data we used in our analysis.

In Test 1, the average lux value captured under the sun condition was 7.75 Lux, which was statistically different from the no-sun condition with the average of 14.00 Lux ($p = 0.02$). The average pupil size under the sun condition across subjects was 3.93mm. In the no-sun condition, the average size was 3.58mm. During the baseline gray screen, the pupil size average was 4.28mm. While we did not observe smaller pupil size under the sun condition, there was a strong trend toward significance between the sun and no-sun conditions ($p = 0.076$). Also, gray default screen and image conditions were found statistically different ($p < 0.02$ with Sun, $p < 0.01$ with No-Sun).

In Test 2, since the original research examined large pupils at fixations during tasks which required heavy mental effort, we also measured the average pupil size around fixations over images per condition. Fixation clusters and timestamps were extracted using gaze analysis software offered from Pupil Labs [21]. The pupil size average in the condition to search for Waldo was 5.03mm, whereas 4.43mm during no search for Waldo. This showed the median of pupil diameter size was larger during goal-oriented visual search. The statistical significance was, however, not observed between the goal-driven and no-goal-driven conditions ($p = 0.244$).

5.2 Subjective Analysis

As for the initial validation of our lux data collection, our mobile toolkit was able to measure lux values within the view angle of the sensor, which were consistent throughout each corresponding visual stimuli condition with respect to pupil diameters over time. Figure 3(1a) especially showed how our lux meter captured appropriate values according to the stimuli.

With respect to the luminance results, we plotted pupil diameters per stimulti condition in Figure 3 for both Test 1 and 2. In Test 1, we did not observe the same responses as the original experiment. While this test utilized a controlled setup, as shown in Figure 3(1b, 1c, 1d), there was no larger pupil constriction examined in average in the lower-brightness sun stimuli condition than the higher-brightness no-sun images. Though the amount of images and the number of participants that were almost half of what the original study prepared could be a strong factor, the eye tracker used in the original study [18] captured data at a rate of 1000 Hz. Moreover, increased high-level image processing and attention were mentioned in the previous results to explain larger pupil constrictions. We could interpret that the individual's responses in such scenarios for sun and no-sun images may vary strongly.

As shown in Figure 3(2b, 2c, 2d), we were able to observe the effects of large average pupils during the

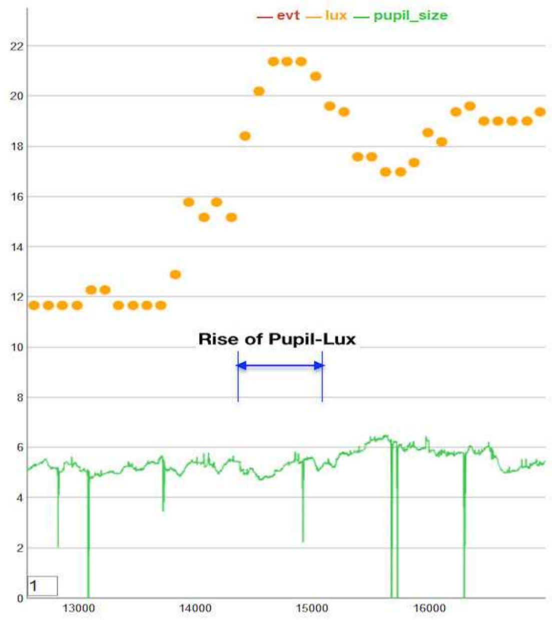

Fig. 5 Simultaneous pupil (green line) and lux (orange dots) rise with respect to sampling frames, observed from 10 participants in Test 2.

visual search for less-prominent targets, as originally found in [15]. In addition, we found a response of pupil size increase while the lux value increased due to the participants leaning closer to the screen during the task. Figure 5 shows a finding which contrasted with pupillary light reflex of pupil constriction under bright stimulus exposure, and how internal states such as their mental effort may have affected the response. As the participants spent more time in the task, we also observed the increase in pupil diameters during the collection of consistent lux values.

6. Design Implications

Mobile cognitive pupillometry research will expand the design of experiments to further understand about human cognition and intention. When taking into account free head movements as given in Test 2, we could consider the observer's state of mental focus and perception of task complexity. According to the original research of [15], the more mental effort it requires to complete the goal, the more dilation on the pupillary response. While lux values were constantly increasing in the semi-controlled lighting environment, the pupil size also increased in accordance with the time spent on the task.

Technical difficulties lie in the constant tracking of pupil size. While lux values in both Test 1 and Test 2 were mostly captured without any glitches, noise of pupil data affected our analysis in both setups of controlled and semi-controlled. Free head movements and less-restricted light conditions did not change the quality of the data capture process. With our use of the current tracker, we can frequently expect the loss of data under other various factors, resulting in sudden jumps and continuous fluctuations in data.

The question remains what kind of internal mechanisms can be best observed in mobile cognitive research. Out of the two tests, the subjective perception effects can be implied less than task-oriented mental focus and load. While more dataset/trials may be required to capture the similar results as originally found, top-down behaviors on task exploitation, rather than subjective perception, resembled more with existing cognitive pupillary responses.

7. Conclusion and Future Work

This research focuses on understanding the implications of the deployable pupillometry integrated mobile platform. With the mobile toolkit and testing of experiments outside of the lab, people's goal-driven behaviors and intentions can be analyzed based on the reflection of pupil size changes. Our future work involves extracting the pupil-lux patterns that we found and paving the way to detect the patterns for mental focus, attention, and load estimation. With our design implications, we aim to expand current research on cognitive processes beyond the traditional measuring settings.

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