Exploring the Effects of Visual Cognitive Load and Illumination on Pupil Diameter in Driving Simulators

Oskar Palinko, Andrew L. Kun
University of New Hampshire
oskar.palinko@unh.edu, andrew.kun@unh.edu

Abstract

Pupil diameter is an important measure of cognitive load. However, pupil diameter is also influenced by the amount of light reaching the retina. In this study we explore the interaction between these two effects in a simulated driving environment. Our results indicate that it is possible to separate the effects of illumination and visual cognitive load on pupil diameter, at least in certain situations.

CR Categories: H.5.2 User Interfaces

Keywords: eye tracking, pupillometry, cognitive load

1 Introduction

Today, more and more in-vehicle devices contend for the driver's attention: cell phones, personal navigation devices, entertainment systems, etc. Interactions with these devices can increase the driver's cognitive load, which could result in distraction and overload [Coughlin et al. 2010], with possibly disastrous consequences. For this reason researchers and developers have a keen interest in estimating the driver's cognitive load during interactions with in-vehicle devices.

Cognitive load is estimated using performance, physiological and subjective measures. Physiological measures include heart rate variability, skin conductance, and pupillometry [Bailey and Iqbal 2008]. In pupillometry the pupil diameter is measured over time. When the cognitive load of a participant increases due to a task, the pupil tends to dilate. This effect is called the Task Evoked Pupillary Response (TEPR), [Beatty 1982].

However, cognitive load is not the only factor influencing pupil diameter. The pupil regulates the amount of light reaching the retina. When there is too much light, the *sphincter pupillae* muscle group will contract the pupil, to reduce influx. When there is not enough light, the *dilator pupillae* muscle group will dilate the pupil. Our long term goal is to design an algorithm to use pupil diameter as a measure of cognitive load in driving simulator experiments, even when the light reaching the pupil from the simulator screen changes over time.

In prior work we found that it is possible to separate the TEPR and the pupil's light reflex for participants scanning static images in a driving simulator [Palinko and Kun 2011]. Specifically, participants in our study were engaged in a visual target-following task and an aural vigilance task. The target-following task was a rough simulation of driving, in which the driver has to scan the forward scene and different parts of the scene are of different brightness. The aural vigilance task simulated spoken interaction with an in-vehicle device. We were able to identify the TEPR due to participants' engagement in the aural vigilance task, even though pupil diameter also changed as participants engaged in the target-following task and changed their visual focus between brighter and darker parts of the static image.

Of course, in-vehicle devices often also demand the driver's visual attention. The goal of the current study is to extend the findings of the work presented in [Palinko and Kun 2011] by establishing if it is possible to separate the effects of TEPR and the pupil's light reflex when participants are engaged in two visual tasks: one that simulates driving and another that simulates engagement with an in-vehicle device. Wickens' multiple resource theory [Wickens 2002] predicts that two visual tasks will interfere with each other more than tasks that use different input channels (e.g. a visual and an auditory task). This might increase the overall cognitive load, and possibly reduce the relative effect of the TEPR on pupil diameter. We hypothesize that, even with this interference, it is possible to separate the effects of TEPR and the pupil's light reflex.

2 Related Research

Pupil diameter can be measured using eye tracking devices. Eye trackers can be head mounted or remotely located. Head mounted systems are more precise, but recently even remote trackers have been proven to deliver very usable pupil size measures [Klingner et al. 2008]. These trackers provide a nonintrusive method for physiological estimation of cognitive load, since they do not require any contact with the participant.

Recarte and Nunes [2000] used monoscopic remote eye tracking in a naturalistic driving experiment. The eye tracker measured gaze information as well as pupil diameter. While driving on the road, participants were given two kinds of secondary mental tasks: a verbal and a spatial-imagery task. Pupil diameter measures showed differences between secondary task and no secondary task conditions, but did not show significance for the different kinds of secondary tasks.

Pomplun and Sunkara [2003] demonstrated the effects of cognitive load and lighting on average pupil diameter. The authors suggest subtracting the predicted pupil diameter for a given lighting level from the overall pupil diameter, resulting in diameter changes that are presumably due to changes in cognitive load only. We also suggest taking this approach, but in contrast to Pomplun and Sunkara, we use the pupil's entire time-domain response, not only the time-averaged response for different levels of cognitive load and lighting. We expect that this approach will allow us to track rapid cognitive load-induced changes.

Figure 1. *Eye tracker on dashboard.*

Our group has recently started using remote eye tracking in a high fidelity driving simulator for estimating cognitive load while driving. We found that more complex conversation tasks produced significantly higher levels of pupil diameter than less complex spoken tasks [Palinko et al. 2010]. However, this study did not explore the interaction between cognitive load and the pupil's light reflex. Instead we confirmed that the average illumination of the simulator screen for each simulation frame was within +/-5% of the overall mean calculated over the entire length of the experiment. Based on this calculation we made the assumption that the light reflex did not significantly influence pupil diameter.

In a subsequent study we explored illumination and cognitive load effects in more detail [Palinko and Kun 2011]. We employed an illumination task and an aural vigilance task to affect the pupil diameter and then continued on to separate these effects. As mentioned above, this study used an aural task to lessen the interference with the primary, illumination task. In the current study we use a visual secondary task to explore this interference. Also, in the previous work we did not establish the statistical significance of the effect of cognitive load on pupil diameter, which we do in this study.

3 Experiment

3.1 Equipment

The study was conducted in a DriveSafety DS-600C high fidelity driving simulator. Although no driving was done for this study the simulator was used to project images and to create a realistic driving environment. Gaze direction and pupil size were recorded using a SeeingMachines faceLAB 5.02 remote eye tracker. The eye tracker was mounted on the dashboard in front of the driver (Figure 1).

3.2 Method

3.2.1 Participants

The experiment was completed by 12 male college students, all native speakers of English. We offered a gift card compensation of $10 for completing the experiment and an additional $5 for good performance, which was always awarded. The participants' average age was 18.9 years. A condition of participation was not to wear glasses, because of the possible interference of the infrared illuminator's reflection off the glasses with pupil tracking.

3.2.2 Tasks

The participants completed three different tasks: Illumination, Visual Vigilance and Combined Task.

Figure 2. *The image of three trucks presented during the Illumination and Combined Tasks.*

In the **Illumination Task (IT)** participants were instructed to follow a visual target with their gaze. The target was displayed on a static image of three trucks of different shades of gray (Figure 2). This image was projected on the front simulator screen, with all other screens turned off. The left truck was nearly black with 10% of the projector's maximum brightness (1.3 lux, measured with Velleman DVM1300 light meter). The middle truck was gray with 50% brightness (31.6 lux), while the right truck was nearly white with 90% of brightness (193.1 lux). While the trucks were without color, their environment was naturally colored. The image represented a city intersection with traffic lights, thus simulating waiting at a red light. Double zeros were displayed on all trucks in order for this task to be similar to the Combined Task. The target was represented by a bracket surrounding a pair of zeros (on gray truck in Figure 2). The target moved periodically, and participants were instructed to shift their gaze accordingly. The target and the numbers were white on the black and gray trucks, and gray on the white truck.

The task started with the target on the middle (gray) truck, where it stayed for 15 seconds, providing time for the pupil to adapt. After this period the target moved from one truck to another 12 times, remaining on each of the trucks for 9 seconds. The order in which the target moved between trucks was kept constant for all participants. Participants fixated on each truck 4 times and they experienced each transition between brightness levels (black to gray, white to black, etc.) twice.

The **Visual Vigilance Task (VVT)** was adapted from Klingner et al. [2008]. Our participants watched a sequence of numbers displayed in the middle of the simulator screen. The numbers changed from 1 through 18 (we displayed each as a two digit number to keep illumination similar, inserting a leading 0 when needed). Participants were told that every 6th number (6, 12, and 18) might be out of order. They were instructed to press a button on the steering wheel if they detected an out-of-order number. The task increased cognitive load at every 6th number, as this was the point where participants had to identify if a number was out of order. This increase in cognitive load triggered the TEPR, manifesting in a short dilation of the pupil. The 1-18 counting sequence was repeated 4 times, thus participants had to pay attention to 4 x 18/6 = 12 possible errors (they encountered 6 errors). The location of errors was randomly selected but kept constant for all participants. The time between the start of each number was 1.5 seconds. Numbers were displayed in white on a gray background.

In the **Combined Task (CT)** participants performed the IT and the VVT simultaneously. The numbers used in the VVT were visible on all three trucks and they changed synchronously. In order to make it easier to separate the light reflex and the TEPR,

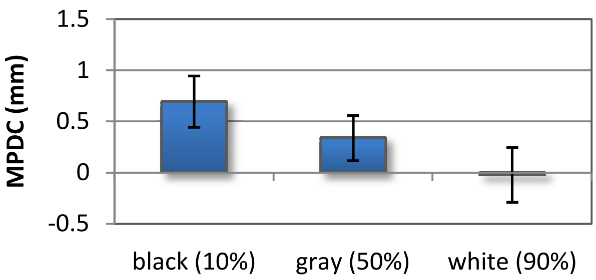

Figure 3. *Pupil size dependence on truck brightness.*

we synchronized the IT and the VVT such that pupil size changes due to the light reflex would be complete before the changes due to the TEPR would appear. We accomplished this by moving the target from one truck to another 0.5 seconds before the numbers 3, 9 and 15 were displayed. As a new number was displayed every 1.5 seconds, this synchronization allowed an ample (see Section 4.1) $0.5 + 3 \times 1.5 = 5\ seconds$ for the pupil to settle after a target change and before the numbers 6, 12 and 18 appeared.

3.2.3 *Procedure*

The order of the tasks was counterbalanced between participants. Each of the tasks was preceded by a minute of training and followed by filling out the NASA-TLX form. At the end of the experiment participants completed a subjective opinion questionnaire.

4 Results

4.1 Illumination Task

First, we analyzed pupil size averages while looking at trucks of different shades of gray. For this we defined the pupil diameter change (PDC) as the left pupil diameter less the mean of the left pupil diameter for a given task and participant. This was done to eliminate the differences due to participants having different average pupil sizes. For each participant we found the mean PDC (MPDC) for every 9 second time period when the target was on a given truck. We then calculated the average MPDC over all instances when the participant was looking at black, gray and white truck, resulting in three values per participant. These results (Figure 3) were statistically analyzed using one-way repeated measures ANOVA. The results showed statistical significance with brightness being the independent variable, F(2,22)=53.6, p<0.001.

Next, we examined pupil diameter response to an increase in illumination (gaze change from black to gray, black to white or gray to white truck). We averaged the pupil diameter for all participants and all 9 second segments during which the target was on a gray or white truck, having previously been on a darker truck. We display the resulting average pupil diameter in Figure 4. In this figure, 0 seconds denotes the time when the target moves to a lighter truck. Note that, on average, participants react to this move in about 0.5 seconds, at which time the pupil size starts to drop rapidly. By 3 seconds the pupil reaches its steady state. This response justifies our design of the CT, in which we allow 5 seconds for the effects of the light reflex to settle.

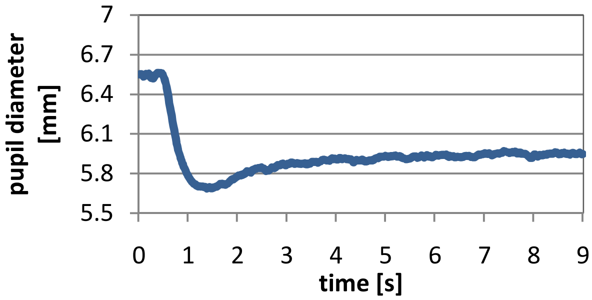

Figure 4. *Response to increase in illumination.*

4.2 Visual Vigilance Task

In order to inspect the effect of the TEPR on pupil diameter, we averaged pupil size over all participants and over each 9 second time period in which six consecutive numbers were displayed (1 to 6, 7 to 12 and 13 to 18). As each of the 12 participants saw the 1-18 sequence 4 times, we averaged $12 \times 3 \times 4 = 144$ time periods, each 9 seconds long. The result is shown in Figure 5. We divided the resulting curve into 1.5 second long segments, as shown in this figure. We denote each segment with a segment number based on the following formula:

$$segment = n - \lfloor n\!:\!6 \rfloor \times 6$$

where $n \in \{1,2,\dots,18\}$ is the number on the screen and $\lfloor x \rfloor$ is the largest integer less than or equal to x. Visual inspection indicates that pupil diameter increases in segment 6, as participants observenumbers 6, 12 or 18. Note that in Figure 5 we present the segments starting with segment 3 and ending with segment 1, in order to match the x-axis with that of Figure 4 – in both figures the beginning of the time axis (time = 0 seconds) denotes the time when the target shifts from one truck to another.

Next, we calculated the mean pupil size for segments 1, 3, 4, 5 and 6 for each participant (overall means shown as blue bars in Figure 5). We analyzed participant means using a one-way repeated measures ANOVA. (The reason for leaving segment 2 out of the analysis will become apparent in the next section.) Since sphericity could not be assumed, the Greenhouse-Geisser correction was applied. The main effect was found to be significant with F(1.77,19.4)=29.1, p<0.001. Pair-wise comparisons showed that pupil diameter in segment 6 is significantly larger than the diameter in all other segments, with at least p<0.001.

4.3 Combined Task

In our analysis of the CT we focus on separating the effects of cognitive load and an increase in illumination. Figure 6 presents the averaged time diagram for the CT and the IT. In the CT, the TEPR is visible as a bump in the pupil diameter around 9 seconds, during segment 6. Also, pupil diameter is larger throughout the more complex CT task than during the IT task.

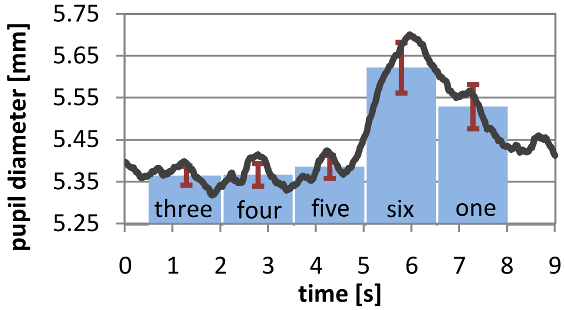

Figure 5. *Pupil diameter during the Visual Vigilance Task.*

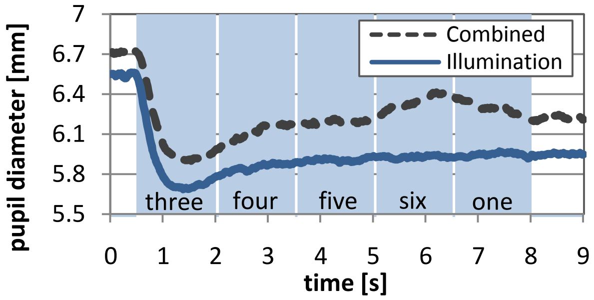

Figure 6. *Reaction to Combined Task and Illumination Task.*

In order to separate the effects of cognitive load and light reflex we subtracted the averaged pupil diameter during the IT from the pupil diameter during the CT. The result in Figure 7 resembles the TEPR-only signal from Figure 5. As with the VVT, we divided the pupil diameter difference into six 1.5 second segments, and for each participant we calculated the average pupil diameter difference for segments 1, 3, 4, 5 and 6. We analyzed these averages using a one-way repeated measures ANOVA and found a significant main effect with F(4,44)=5.29, p<0.001. We left segment 2 out of the analysis, as during this segment participants shifted their gaze between trucks, resulting in transients in the pupil diameter which we decided to ignore in this study.

Pair-wise comparisons indicate that pupil diameter is larger during segment 6 than during segments 3, 4 and 5. The prominence of segment 6 makes sense as we expect that participants' cognitive load peaked during this segment (when numbers 6, 12 and 18 were visible). Pupil diameter is also larger during segment 1 (which follows segment 6) than during segment 3. This result might be the consequence of the pupil relaxation time after cognitive load is reduced.

5 Conclusion & Future Direction

In this paper we report on the effects of cognitive load and illumination on pupil size, expanding on our work started in [Palinko and Kun 2011]. We confirm that looking at relatively small areas (trucks at an intersection) of different luminance causes significant differences in pupil size (Figure 3). Further, with the Visual Vigilance Task, we confirm that visual cognitive load is correlated with changes in pupil diameter (Figure 5).

Most importantly, we confirm that it is possible to separate the influence of visual cognitive load and illumination on pupil diameter.This is true even in our experimental case, where participants performed two visual tasks in parallel. Together with results of our prior work [Palinko and Kun 2011], which indicate that this separation is possible when participants perform one visual and one auditory task, these new results provide support for the hypothesis that it is possible to disambiguate the effects of cognitive load and illumination on pupil diameter, even in complex environments such as a driving simulator. While our results are encouraging, the tasks in our experiment were much simpler than those performed in a driving simulator, e.g. interacting with in-vehicle electronic devices while operating a simulated vehicle. Such tasks are fast-paced, and include a wide variety of human behaviors. In contrast, our tasks were relatively slow paced and highly constrained.

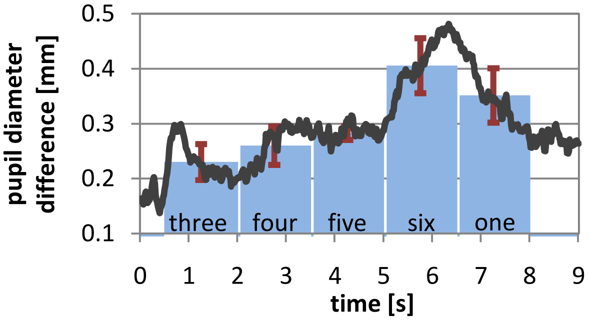

Figure 7. *Average pupil diameter difference between Combined and Illumination Tasks.*

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