Exploring the Effects of Size and Luminance of Visual Targets on the Pupillary Light Reflex

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ABSTRACT

In driving simulator studies pupil diameter is often employed as a physiological measure of cognitive load. However, pupil size is primarily influenced by the pupillary light reflex (PLR). In this paper, we explore the influence of the size and luminance of visual targets on the PLR. Our results indicate that even for small targets (angular radius of 2.5°) changes in luminance can result in PLR that can obscure cognitive load-related pupil diameter changes. We propose a weighting function to be used to predict the PLR and present initial results that support its utility.

Categories and Subject Descriptors

H.5.2 [Information Interf. and Presentation]: User Interfaces.

General Terms

Algorithms, Measurement, Experimentation, Human Factors.

Keywords

Cognitive Load, Eye Tracking, Pupillometry, Driving Simulator.

1. INTRODUCTION

An increasing number of in-vehicle electronic devices place more and more demand on the driver's attention. Interaction with these devices can increase the driver's cognitive load, which can result in distraction and overload [2], with possibly disastrous results. Thus, researchers and developers have interest in estimating the driver's cognitive load during interactions with in-vehicle devices.

In an effect called the task evoked pupillary response (TEPR), the pupil will dilate when a person is faced with a challenging cognitive task [1]. However, pupil size is primarily influenced by the pupillary light reflex (PLR), which controls the amount of light reaching the retina. Thus, the PLR might have to be accounted for when estimating cognitive load using changes in pupil diameter [5]. 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 demonstrated that it is possible to separate the TEPR and the PLR for participants scanning static images in a driving simulator [5] [6]. Specifically, participants were engaged in a visual target following task and an aural [5] or visual [6] vigilance task. The target-following task was a rough approximation of driving, in which the participant moved his gaze between targets of roughly equal size (with an angular radius of about r=7.5°), but of different luminance. The vigilance task simulated spoken or visual interaction with an in-vehicle device. In both cases we found that the difference in target luminance resulted in a relatively large PLR. However, we showed that it is possible to account for the PLR and identify the TEPR due to engagement in the vigilance task.

In full-fledged driving simulator studies, participants scan the driving scene containing visual targets of different size and luminance. Participants focus on different vehicles, each of a different size and luminance, such as when approaching a traffic light with other vehicles already waiting. In this study we use this latter example to explore the influence of the size and luminance of the visual target on the PLR. Specifically, the problem we address is that it is not clear if even small targets (those with an angular radius of less than r=7.5°) will result in a large enough PLR to potentially obscure the TEPR. If the answer is affirmative, our goal is to demonstrate this effect with a simple experiment.

Our first hypothesis is that even for small targets (those with an angular radius of about r=2.5°) a difference in luminance can have a large-enough effect on PLR to obscure the TEPR. Our second hypothesis is that PLR magnitude will be different between targets of the same luminance but of different size (size difference of about 2.5° to 5° in angular radius), and the size of the difference will be large enough to potentially obscure the TEPR.

2. RELATED RESEARCH

Klingner et al. demonstrated that pupil diameter can be effectively measured using remote eye tracking devices [4]. These trackers provide a nonintrusive method for physiological estimation of cognitive load. For example, we have used remote eye tracking in a high fidelity driving simulator to estimate the cognitive load of drivers engaged in verbal tasks [7]. However, in that study we did not explore the interaction between cognitive load and the PLR. Instead we confirmed that the average luminance 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 PLR did not significantly influence pupil diameter.

However, PLR can interfere with the estimation of the TEPR. Pomplun and Sunkara [8] suggested subtracting a predicted pupil diameter for a given luminance from the overall pupil diameter, resulting in diameter changes that are presumably due to changes

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in cognitive load only. In prior work we also explored this approach [5] [6], but in contrast to Pomplun and Sunkara, we used the pupil's entire time-domain response, not only the time-averaged response for different levels of cognitive load and luminance. This allows us to track rapid changes in TEPR.

In ophthalmology, a number of researchers explored how target eccentricity (relative to the point of fixation) and luminance affect the PLR. Schmid et al. [9], as well as Hong et al. [3], found that stimuli further away from the point of fixation cause a smaller PLR compared to stimuli closer to this point. As we will see, their results support the results of our study. Hong et al. also suggested using a visual target with an angular radius of r=2°, as a smaller target located in the nasal visual field might not elicit a large enough PLR. Our selection of target sizes is consistent with this suggestion. Finally, note that both of the above studies used controlled environments, while we measure pupil reactions in the somewhat realistic environment of a driving simulator.

3. EXPERIMENT

We conducted a mixed-design experiment in which three groups of participants followed visual targets across static images. The images presented 3 trucks at an intersection (Figure 1). The 3 trucks were of different color (white, gray and black), allowing us to explore the effect of target luminance on PLR. Each participant group viewed trucks of one size only: small (area on simulator screen of about A=210cm^2, with an angular radius of about r=2.5°), medium (A≈850cm^2, r≈5°) or large (A≈1835cm^2, r≈7.5°), allowing us to explore the effect of target size on PLR.

3.1 Equipment

The study was conducted in a DriveSafety DS-600C high fidelity driving simulator. While no driving was involved, the simulator was used to project images and to create a realistic driving environment. Pupil size was recorded using a SeeingMachines faceLAB 5.02 remote eye tracker. The eye tracker was mounted on the dashboard in front of the driver (Figure 2).

3.2 Method

3.2.1 Participants

The experiment was completed by 24 college students. Twelve viewed large trucks, 6 viewed medium and 6 viewed small trucks. In this paper we report on results from 18 participants: the first 6 who viewed large trucks, and the 12 who viewed medium and small trucks. The data with 12 participants viewing large truck was originally collected to explore the effects of target luminance and cognitive load on pupil diameter [5]. Data for the additional 12 participants was collected to extend that work by also exploring the effects of target size on PLR.

Participants received $10 for completing the experiment and an additional $5 for good performance, which was always awarded. The participants' average age was 20.3 years. We did not accept participants who wore glasses, as the reflection of the eye tracker’s infrared illuminator from the glasses can interfere with pupil tracking. Participants with contact lenses were accepted.

3.2.2 Task

Each group of 6 participants was given three tasks as in [5]. Two of these tasks explored the use of pupil diameter to estimate cognitive load. In this paper we focus on the third task, that of visual tracking: participants were instructed to follow a visual target which switched location between the trucks (Figure 1). The light reaching the participant's eye varied as the participant's gaze moved from one truck to another. 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 (50% brightness, 31.6 lux), while the right truck was nearly white (90% brightness, 193.1 lux). The environment was naturally colored. The target was white on the black and gray trucks, and gray on the white truck. The image was projected on the front screen of the simulator, with all other screens turned off.

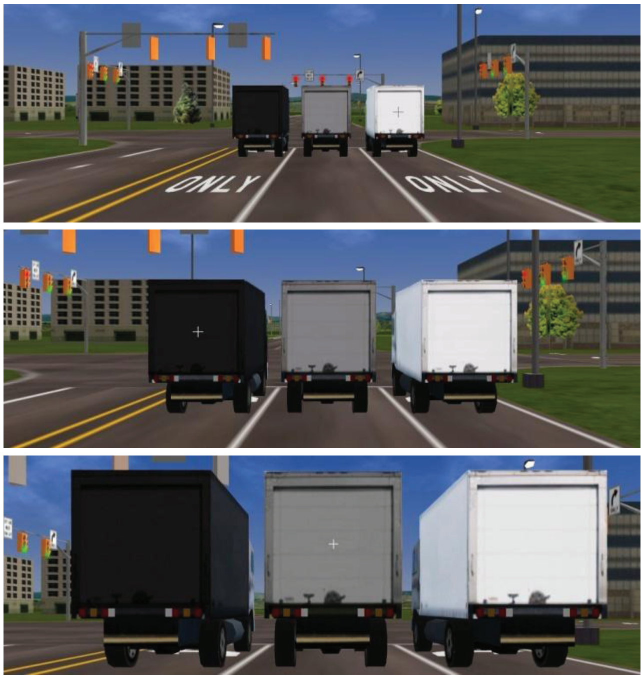

Figure 1. Small, medium and large trucks (top to bottom).

The task started with the target on the 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.

3.2.3 Experiment design

We conducted a 3x3 study, with *Size* and *Luminance* as independent variables. *Size* was a between-subjects variable with three levels (large, medium, small). *Luminance* was a within-subjects variable, also with three levels (black, gray, white).

We had a single dependent variable, namely the mean pupil diameter change (MPDC). MPDC for a subject is defined as the average of the left pupil diameter in a given time period minus the mean value of the pupil diameter in the whole experimental run.

Figure 2. Eye tracker on dashboard.

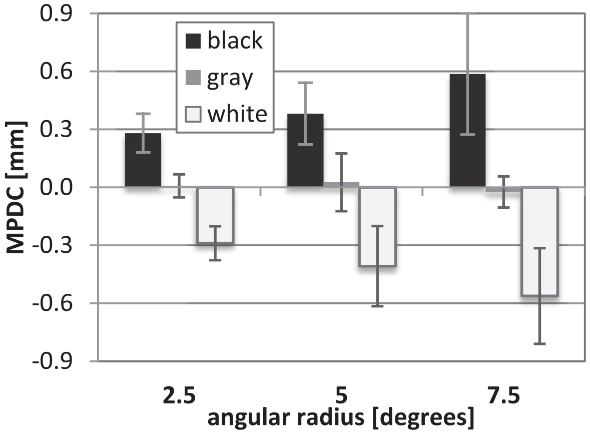

Figure 3. Pupil diameter for all trucks grouped by angular radius (that is size). The approximate angular radius is 2.5° for small, 5° for medium and 7.5° for large trucks.

The averaged time periods were the 9 second intervals of looking at different trucks. The overall mean is subtracted because people's pupils are of different sizes. We then averaged the MPDC over all periods when looking at the white, gray and black truck, thus ending up with three values for each subject.

4. RESULTS

Figure 3 shows the average MPDC values over all participants for each *size* and *luminance*. The x-axis represents size in angular radius, with 0° representing the direction of the participant's fixation. We conducted a two-way ANOVA, with *Size* and *Luminance* as independent variables. The analysis revealed a significant main effect for *Luminance* ($p<0.001$). We also found a significant interaction between S*ize* and *Luminance* ($p<0.005$).

4.1 The effect of luminance

Pair-wise comparisons indicated that for every truck size MPDC is significantly different between every level of *Luminance*. For small trucks the difference was significant with at least $p<0.008$. Furthermore, Figure 3 shows that, even for small trucks, the MPDC changes by around 0.3 mm between gray and black/white trucks. Such changes have the potential to obscure the effects of the TEPR (e.g. in [5] we identified the TEPR based on changes in pupil diameter of about 0.1 mm). This result supports our first hypothesis, which proposed that changes in luminance for small targets can result in a PLR that obscures the TEPR.

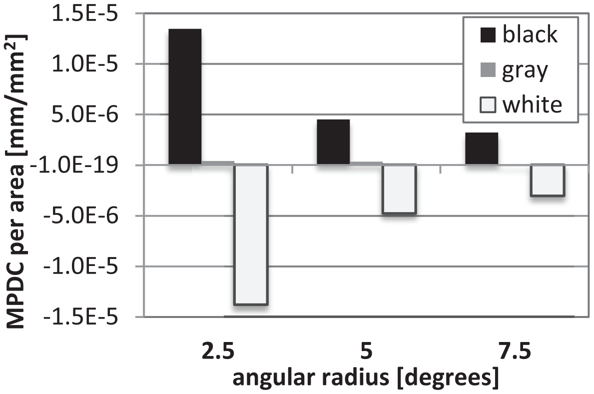

Figure 4. Mean pupil diameter change in mm, per unit truck area in mm^2. Truck area is shown in terms of angular radius.

4.2 The effect of size

To explore the S*ize* x *Luminance* interaction further, we used a one-way ANOVA to compare MPDC for large, medium and small black trucks (black bars in Figure 3). The effect of size was marginally significant ($F(2,15)=3.46$, $p<0.058$). Pair-wise comparison showed significant difference in MPDC for large and small black trucks ($p<0.02$). For white trucks the main effect was not significant ($F(2,15)=2.87$, $p<0.088$), however pair-wise comparisons showed a significant difference in MPDC between large and small white trucks ($p<0.031$). For both black and white trucks the difference in MPDC between large and small trucks was about 0.3 mm. This result supports our second hypothesis that small changes in target size can result in large-enough PLR changes to obscure the TEPR.

Further exploring the implications of *size*, we divided the MPDC for different trucks with the areas of those trucks, expressed in square millimeters on the projection surface. The results in Figure 4 reveal that the smaller the trucks, the larger the pupil reactions (in mm) per unit truck area (in mm^2). This indicates that the image area closer to the point of regard (fixation) of the eye has a greater influence on the size of the PLR than areas further away. This result is in agreement with prior work in ophthalmology [3] [9].

5. WEIGHTING FUNCTION

Our results suggest that we could use a weighting function in estimating the PLR based on the visual scene. This estimate could be subtracted from the change in pupil diameter, ideally revealing the TEPR. The luminance of those areas that are close to the point of regard would be weighted more heavily than the luminance of those areas that are further away.

We used the data from the above experiment to create a weighting function (Figure 5). It divides the visual field into three nested square regions, with angular radii of 2.5°, 5°, and 7.5°. Within each of these three regions the value of the function is uniform, and it is calculated by dividing the contribution of that region to the change in MPDC (from Figure 3) by the area of the region (indicated in Figure 5). For simplicity, we used MPDC data for white trucks only to calculate the weights and assumed that the same weights can be applied for both light and dark regions.

We evaluated the weighting function using data collected in an experiment with 4 students from our lab. Our participants were seated in the driving simulator and viewed an image of a white

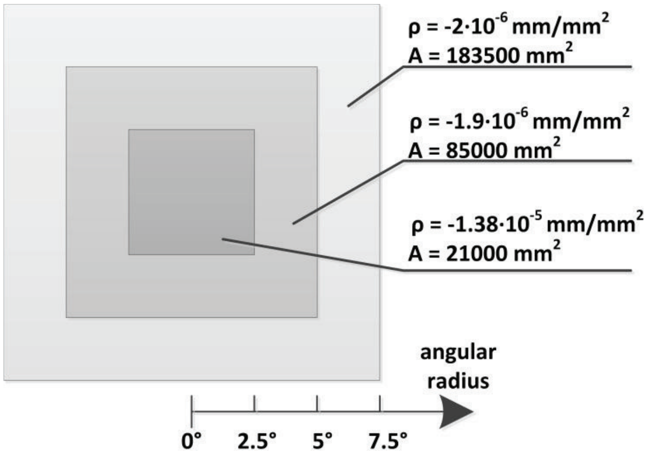

Figure 5. Weighting function with three nested squares. The value of the function (ρ) is uniform within each nested region (function values and approximate region areas shown above).

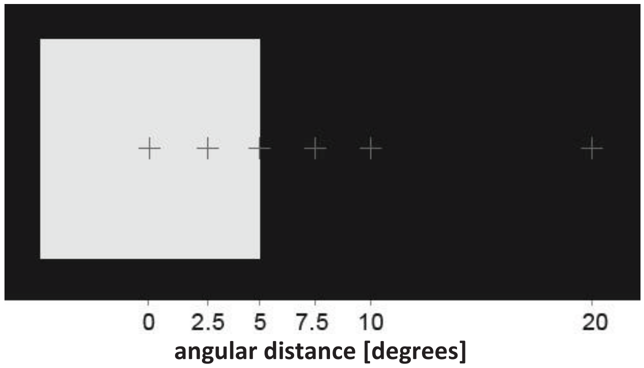

Figure 6. Visual targets for weighting function experiment.

square (90% of maximum projector brightness) on a black background (10% of brightness), as shown in Figure 6. The apparent angular radius of the square was around 5°. A gray target (plus sign) appeared first in the right part of the screen, at an angular distance of about 20° from the center of the white square. It then skipped to the middle of the square, where it remained for 9 seconds, after which it moved back to 20° for 5 seconds. Next, it moved left, to 2.5°, then back to 20°. It continued skipping from side to side until it reached 10° away from the center of the square. Skipping to 20° was introduced to "reset" the pupil size to a larger diameter and provide a consistent reference size for pupil size changes due to the PLR.. This sequence was repeated 3 times for each participant. For each participant we averaged the MPDC for the 3 runs for five locations: at 0°, 2.5°, 5°, 7.5° and 10°. The averaged MPDC for all subjects is shown in Figure 7.

We estimated the value for the MPDC due to the PLR by numerical integration of the product of the weighting function and the luminance (we used +1 for the luminance of the white square and -1 for the black areas). The result is shown in Figure 7 along with the error of the estimation, which is always less than 0.2 mm. While this error is still too large (the TEPR can have a similar magnitude), these results are encouraging. They indicate that a more advanced weighting function might be able to estimate experimental data accurately.

6. CONCLUSION AND FUTURE WORK

The practical implication of our work is that driving simulator experiments which utilize pupil diameter as a measure of cognitive load must be designed to either minimize, or account for, the influence of changes in target object size and luminance on pupil size. Our results indicate that even gazing at relatively small targets, such as distant vehicles, can result in PLR that can obscure the TEPR.

One approach to minimizing the effect would be to create driving simulator scenarios with small changes in target luminance (where the exact meaning of "small" has to be defined in future studies).

On the other hand, to account for the PLR we need to estimate the PLR based on where a participant is looking. Our work suggests that the estimation can take advantage of the non-uniform retinal sensitivity to light, which is manifested in small targets giving rise to larger PLR per unit area compared to larger targets. This means that the estimator can apply a weighting function to the visual scene in order to select areas that will influence the PLR the most.

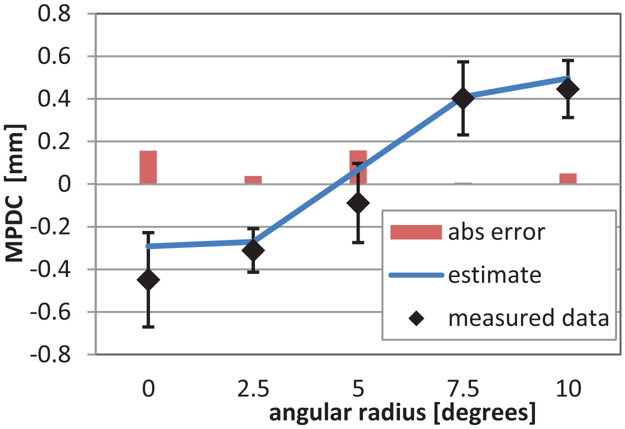

Figure 7. Measured and estimated MPDC due to the PLR in the weighting function experiment. Whiskers show +/- 1 SD of measurement. Also shown is the absolute value of estimation error for the 5 measured MPDC values.

While these conclusions are promising, they primarily *demonstrate* the effect of size and luminance on the PLR. Further studies are needed to systematically explore these effects, as well as the effects of individual differences. Also, work is needed to explore realistic gaze patterns in which participants switch from one visual target to another rapidly (such as in driving).

7. ACKNOWLEDGMENTS

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