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Density of gaze points within a fixation and information processing behavior

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Abstract. The use of eye movements to study cognitive effort is becoming increasingly important in HCI research. Eye movements are natural and frequently occurring human behavior. In particular fixations represent attention; people look at something when they want to acquire information from it. Users also tend to cluster their attention on informative regions of a visual stimulus. Thus, fixation duration is often used to measure attention and cognitive processing. Additionally, parameters such as pupil dilation and fixation durations have also been shown to be representative of information processing. In this study we argue that fixation density, defined as the number of gaze points divided by the total area of a fixation event, can serve as a proxy for information processing. As such, fixation density has a significant relationship with pupil data and fixation duration, which have been shown to be representative of cognitive effort and information processing.

Keywords: Eye Tracking, Cognitive Effort, Information Processing, Pupil Dilation, Pupil Dilation Variation, Fixation Density

1 Introduction

Eye movements can provide valuable data about a user's viewing behavior, and as such, the analysis of eye-movement data is becoming increasingly popular in human computer interaction (HCI) research [1, 2]. For example, fixations can provide invaluable data about a person's attention, awareness, and information processing behavior [1], [3]. Fixations refer to relatively stationary gazes during which we take "foveal snapshots" of interesting stimuli. These foveal snapshots are then sent to our brain for processing [1]. Thus, fixations form a fundamental unit of analysis in examinations of eye-movement data [3]. In this study, we examine one particular property of this important eye-tracking metric, namely its dispersion, or the density of the individual gaze points that form a fixation event. Because fixations are reliable indicators of cognitive processing [4], the distribution of gaze points within a fixation unit is likely to carry information about the intensity of cognitive processing. Fixation density represents both the number of gaze points, as well as their dispersion, during a certain

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fixation event. In this study, fixation density is computed as the number of gaze points within a fixation unit (event) divided by the area of the minimal bounding rectangle. A dense fixation unit is likely to represent more intense cognitive processing. Given this point of view, we expect to observe that gaze point density in a fixation is related to a number of known eye-movement metrics that represent cognitive processing, namely fixation duration, pupil dilation [5], and pupil dilation variation [6, 7].

2 Theoretical Background

Recent developments in eye-tracking technology have made it possible to capture a user's experience of a system through the analysis of eye movement data. Researchers in the field of Information Systems, Psychology, and Human Computer Interaction have been using eye-movement data to investigate users' attention, awareness, search behavior and preferences in a variety of ways [8, 9].

Eye-tracking data have also been used to discover user's cognitive states [10, 11, 12]. Understanding the relations between eye movements and human cognition has been useful in many domains such as studies of visual working memory [13]. Poole and Ball [3] identified different categories of eye-movement metrics, each reflecting the action of specific cognitive processes in the brain. These metrics include fixations, saccades, and pupil dilation. Fixations are defined as relatively stable gazes between saccades, and their interpretations differ depending on the context. Saccades are rapid movements of the eye when moving from one fixation to another [14]. There is evidence that cognitive load is likely to impact the length of fixation. A previous study using fixation data to find the correlation between a user's gaze and difficulty of the task shows a positive correlation between fixation duration and cognitive load [15]. Building on Just and Carpenter's [17] work, analyses based on the eye-mind assumption suggest that eye fixations can be used as a window into instances of effortful cognitive processing.

Fixations and saccades reflect very different types of eye movements. Fixations are related to information processing, whereas during saccades, visual information is not processed. Grounded in this distinction, a recent study discriminates between pupil data during fixations and saccades [7]. Because visual information is not processed during a saccadic event, in this paper, we focus on pupillary information during fixations only. Table 1 summarizes the eye-movement types and their respective metrics that were considered in this study.

Table 1 – Definition and application of different eye-tracking metrics used in this study as a representative of cognitive processing

Fixation ***Steady gazes with a minimum duration on a specific area of a stimulus***	Fixation Duration: High fixation duration indicates high cognitive workload [15], and higher cognitive effort [1],[3],[18] Fixation Density: Total number of gaze points divided by the total minimal area to encapsulate all the gaze points [16]
Pupil Dilation ***Changes in pupil size***	Changes in the pupil diameter represents cognitive and mental workload [19, 20, 21]
Pupil Dilation Variation ***Variation of changes in pupil size***	Standard deviation of pupil diameter [6]: Related to both cognitive processing [7] and the characterization of differences between neutral and arousal elicitation [22,23]

2.1 Hypotheses

As shown in Table 1, longer fixations have been associated with a greater degree of attention, and thus more intense processing. Therefore, we expect to see that denser fixations have a significant relationship with fixation duration:

H1) Denser fixations are significantly correlated with fixation duration.

Pupillary data are known to serve as reliable proxies of cognitive processing [5], thus it is reasonable to argue that a fixations' gaze density and its corresponding pupillary data have a strong correlation. Thus, we assert:

H2) Denser fixations have a significant relationship with pupil dilation during fixations.

H3) Denser fixations have a significant relationship with pupil dilation variation during fixations.

3 Methodology

The following sections provide a brief review of the laboratory experiments that were conducted to test our hypotheses.

3.1 Participants and Design

A total of 24 graduate students from various technical disciplines (e.g., computer science, electrical and computer engineering) in a northeastern university of the US were recruited for this study. Participants were assigned to complete a problem-solving cognitive task without any time limit. Because students are accustomed to taking timed tests, this setting was relevant and appropriate for manipulating cognitive load in our study.

We used the Tobii X300, a remote eye tracker with a sampling rate of 300 Hz and Tobii software version 3.2.3 to collect participant's eye-movements data. The I-VT filter was used with 30°/sec saccadic velocity threshold. To track eye movements, each participant completed a brief eye-calibration process. While seated, participants were asked to observe a moving dot on the eye-tracking monitor. This calibration process, which required participants to follow the moving dot on the screen, took less than one minute.

3.2 Task

The problem-solving task used in this study required participants to provide correct answers to a set of mathematical questions. A set of 10 math questions were manually selected from a pool of problem-solving practice tests for the GRE cite available at www.majortests.com. The questions were then used to develop an online multiple choice math test.

3.3 Data Processing

The eye-movement data of 24 participants acquired from the Tobii eye-tracking software were further analyzed using MATLAB 2014b to calculate the average and standard deviation of the metrics mentioned in Table 1 and to compute the area encapsulating each fixation event for each participant. In addition, normalized values of fixation duration as well as fixation density for each participant were computed. Normalized fixation duration was calculated by dividing the total fixation duration by the total completion time of the task. The average values were then used in regression analyses, which are reported in the next section.

4 Results

The basic mean and standard deviation statistics of the variables under study, namely fixation density, pupil dilation during fixation, pupil dilation variation during fixation, and normalized fixation are reported in Table 2.

Table 2. Mean and Standard deviation of variables under study

	Mean – [unit]	STD
Fixation Density	0.470 [mm^{-2}]	0.166
Pupil Dilation During Fixation	3.048 [mm]	0.385
Pupil Dilation Variation During Fixation	0.014 [mm]	0.009
Normalized Fixation Duration	0.399	0.160

To investigate the relationship between fixation density (FD) and pupil dilation (PD), pupil dilation variation (PDV) and normalized fixation duration (NFD), we used three different regression models as outlined below.

$$FD = \beta_0 + \beta_1 \times PD \qquad (1)$$

$$FD = \beta'_0 + \beta'_1 \times PDV \qquad (2)$$

$$FD = \beta''_0 + \beta''_1 \times NFD \qquad (3)$$

Unsurprisingly, the results of the regression analyses showed that fixation density is strongly (p-value = 0.004) and positively (β_1 = 0.481) correlated with normalized fixation duration. Twenty-three percent of the variation in model (3) was explained by normalized fixation duration, as displayed in Table 3. Our model (2) results showed that average pupil dilation *variation* was strongly (p-value = 0.001) correlated with fixation density. The relationship, however, was negative (β'_1 = -0.674), meaning that higher fixation density was correlated with larger pupil dilation variations during fixations. Contrary to our expectation, the results were not significant in model (1): that is, the results did not show a significant relationship between average pupil dilation during fixation and fixation density (p-value =0.953). These results together, which are displayed in Table 3, suggest that fixation density can be predicted by normalized fixation duration and average pupil dilation variation during fixation, but not average pupil dilation during fixation.

Table 3: Results of regression analysis for Fixation Density (FD) in terms of NFD, FD in terms of PD, and FD in terms of PDV

	R^2	P-value	β
Normalized Fixation Duration	0.231	0.004	0.481
Average Pupil Dilation during Fixation	0.009	0.953	-0.013
Average Pupil Dilation Variation during Fixation	0.454	0.001	-0.674

1 Discussion and Conclusion

Because fixations are a collection of gaze points that are close to each other in time and proximity, denser fixations represent a user's more focused attention, and thus a higher level of cognitive processing when viewing visual stimuli. Therefore, it is likely that fixation density is related to other eye movement metrics that are representative of a user's information processing behavior. In this paper, we investigated whether fixation density was correlated with three different eye metrics that are typically used to assess cognitive processing. Our results showed that fixation density was strongly correlated with pupil dilation variation and normalized fixation duration but not with pupil dilation. These results are consistent with prior research that indicates pupil dilation variation may be a more sensitive measure of information processing in HCI research [7]. Overall, the results provide evidence that fixation density, along with pupillary data, may also serve as an appropriate measure of information processing. These results have important implications because they provide a theoretical direction for incorporating fixation density in future HCI studies.

2 Limitations and Future Research

As with any experiment, our study had limitations, which we intend to address in follow-up studies. Our sample size was small, and the task was limited to a problem-solving cognitive task. Another limitation in our study was that the area for fixation was governed by a rectangle rather than a convex hull. Future studies are needed to replicate our analysis with larger sample sizes, different tasks, and convex hull as the area for fixation to increase confidence in the generalizability of our results.

3 Contribution

While there is evidence that fixations concentrated in a small area (fixation spatial density) is illustrative of focused and efficient searching [16], little work has been done to examine the relationship between fixation density and other eye movement measures that represent information processing. Our results show a strong positive relationship between fixation density and fixation duration and a strong negative relationship between fixation density and pupil dilation variation. These results contribute not only to HCI research but also to research in cognitive effort and information processing.

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