Pupillary Response: Removing Screen Luminosity Effects for Clearer Implicit Feedback

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ABSTRACT
Pupillary dilation measured by eye-tracking can be useful source of implicit feedback for system adaptation and personalization. For example, cognitive load or emotional excitation can be inferred from it. However, practical exploitation of this phenomenon (e.g., in adaptive systems or user studies) has been limited due to other factors that influence pupillary dilation, namely changing luminosity of device screen. In this work, we present a personalized pupillary dilation model, which is able to predict the effects of screen luminosity on participant's pupil diameter. This information is useful for tracking true effects of cognitive load or emotional excitation of users. We demonstrate our model in a controlled eye-tracking study with 73 participants.

CCS Concepts
• **Human-centered computing~User models** • *Human-centered computing~Web-based interaction* • Information systems~ Personalization.

Keywords
Pupillary response; personalized model; luminosity; cognitive load.

1. INTRODUCTION
The collection of implicit feedback is a necessary precursor to user modelling, adaptation, and personalization. Implicit feedback streams are, however, influenced by multiple factors that obfuscate the information we seek. One such case is eye-tracked pupillary response (dilation) measurement. It is often done to measure user's *cognitive load* [1] and *emotional excitation* [6], both of which are useful in adaptation and personalization scenarios.

Unfortunately, pupil diameter is also influenced by other important factor: luminosity of environment surrounding the user, especially the stimulus that user is perceiving on the screen. Untracked changes in environment luminosity may completely disable any tracking of cognitive load or emotional excitation. In practical scenarios, stimulus luminosity cannot be kept stable and changes with every new screen. When the screen content is heterochromous, even the changes in gaze fixations may trigger pupillary dilations.

Only few solutions exist to this problem. Simple, but impractical, is to restrict the task design. By keeping the stimuli roughly on the same luminosity level throughout the experiment, one can attribute any pupillary response to cognitive load or emotional excitation [1]. A more sophisticated method of Xu et al. [5] measures mean pupillary diameters for time segments with constant stimuli luminosity and bases the cognitive load detection on dilation deviation. Another method tries to distinguish between abrupt (mental-state-caused) and moderate (luminosity-caused) pupillary responses [3]. These methods allow more variety in stimulus luminosity, but are still hindered when used for complex scenarios.

If we want to successfully filter out luminosity effects on pupillary dilation, we need to predict them for arbitrary, heterogeneous stimuli, accounting also for exact fixation points.

2. PERSONALIZED MODEL OF PUPILLARY RESPONSE
The contribution of this work is the *personalized model of pupillary response* (PMPR). Given the screen bitmap, the model is able to predict pupil diameter of the user in non-excited and non-loaded mental state. The model also takes into account the position of user's gaze fixations (e.g., when user focus to darker area, the predicted diameter increases). The model expects that the environment luminosity is invariant.

PMPR needs to be calibrated to each user, as diameter range of the pupil is a personal physiological trait. During calibration, user focuses on the center of the screen while he is presented with a sequence of defined stimuli, each with different color, visual structure and luminosity values (see figure 1). After the calibration, the user can work with any stimulus required and the model will predict pupillary responses caused by the stimuli luminosity changes, which can be then used to correct the overall measured pupillary response.

Figure 1. Evaluation experiments at UXI@FIIT STU labs. The users are calibrating the pupillary response model.

PMPR is based on two main concepts: (*i*) pupil reference curve and (*ii*) model of fixation-based image luminosity. The *pupil reference curve* models the user-specific behavior of the pupil with the changing luminosity of the stimuli. It is based on the work of Ellis [2] and assumes that the pupil diameter linearly increases with the decreasing luminosity of the stimulus. Therefore, it can be modelled as:

$$d_p = a \times (1 - lum) + b \qquad (2)$$

where d_p is the pupil diameter, lum is the stimulus luminosity from the interval $\langle 0,1 \rangle$, b is the value of pupil diameter for the white stimulus ($lum = 1$), and a is the slope of the reference curve.

The idea behind the *model of fixation-based image luminosity* is based on the anatomical distribution of the rods and cones in the eye [4], which makes our vision sharpest at the foveal area (2° to 3° of visual angle) with the visual acuity steeply decreasing the farther from the center towards parafoveal and peripheral area (by 90% at 40° of visual angle) [7]. This means that the perceived luminosity of the image is influenced the most by the luminosity of the part of the image that is in the center of the visual attention, i.e., it is fixated by the user. The further the area of the image is from the fixation point, the lower is its addition to the overall luminosity perceived by the user. Therefore, when computing perceived luminosity of the stimulus bitmap, we modify each pixel's luminosity with *2D Gaussian kernel* centered at fixation point.

Thus, we can formally define the *personalized model of pupillary response* as the following triple:

$$PMPR = (a, b, \sigma) \quad (6)$$

where and a and b are the parameters from the reference curve and σ is a parameter of the 2D Gaussian kernel. During the calibration, these parameters are trained on various abstract colored and shaped stimuli (e.g. planes, circles, diagonal splits).

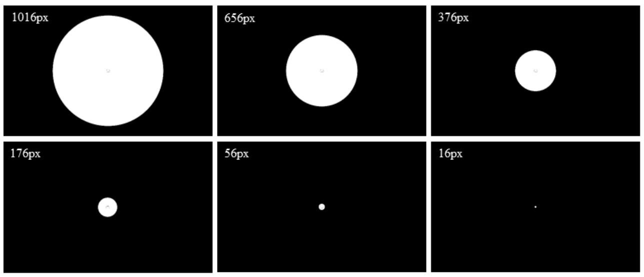

Figure 2. The calibration images for the training of σ parameter of the 2D Gaussian kernel.

The first part of calibration serves to *calibrate the reference curve* (parameters a and b). All of the desired luminosity levels are projected with the help of the plain monochromatic stimuli, in several iterations with brightening and blanking phases through the spectrum of gray. In second part of the calibration procedure, the *σ parameter of the 2D Gaussian kernel* is trained. We project to the users white circles on a black background with different diameters (ranging from 1016px to 16px), while the calibrated person is looking at their center (see Figure 2) and record the actual pupil diameters. The numeric optimization method (quasi-newton BFGS algorithm) is then used to find the optimal value of σ. The whole calibration procedure takes about four minutes, which makes it feasible to use before a user study that uses cognitive load or emotional excitation as an indicator of implicit feedback.

3. EVALUATION

We have done a preliminary evaluation of our model. We invited 73 participants to participate in approximately four minute eye-tracking experiment. Each participant looked at a series of stimuli which were expected to yield changes in the pupil diameter due to changing luminosity. The stimuli series consisted of a set of plain color images, two-color images and real web pages. During the exposure, participants were asked to focus their sight on a cross in the middle of the screen. We focused on the evaluation of the precision of the pupil diameter predictions of the model.

The experiment was carried out in the *UX Group* laboratory (see figure 1) of the *User Experience and Interactions Research Center*[1] at our university, which contains 20 working stations each equipped with Tobii X2-60 eye-tracker with 60Hz sampling frequency.

For each participant, we have trained their PMPR model (over portion of plain color and two-color stimuli recordings) and tested the prediction on the rest (rest of plain color images and web pages). For both plain color stimuli and web pages, the relative prediction error of our model was up to 5% (of the total dilation range of participants). The highest error for plain color stimuli reached 10%, for web pages 15%. Furthermore, the success rate of prediction over web stimuli varied (for some participants, the model consistently predicted better than for others).

Importantly, the trained parameters of the model varied among the participants, which justifies the whole concept of the personalized model of pupillary response and our novel approach of the individually trained reference curve.

4. CONCLUSION

The contribution of this work is a personalized model of pupillary response (PMPR), which can predict changes of pupil diameter caused by screen stimulus luminosity. The relative errors of prediction reach about 5% of the total dilation range. We are confident that this makes the model usable for successfully separating effects of luminosity from overall pupillary dilation effects and thus enables to measure implicit feedback such as cognitive load or emotional excitation. Furthermore, PMPR works over any type of stimuli including real web pages, and does not need carefully crafted stimuli with constant luminosity. This eases the design of studies, which aim to measure cognitive load or emotional excitation using pupillary dilation tracking.

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