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Demonstrator for Extracting Cognitive Load from Pupil Dilation for Attention Management Services

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Abstract
Attention Management has become a fundamental requirement in interaction design of information systems, considering the information overload distributed by omnipresent wearable devices. This implies the management of notifications and interruptions according to current user activities, context and especially cognitive load and perception capabilities. This paper presents a demonstrator designed towards the real-time assessment of cognitive load from pupil dilation as a somatic indicator of attention, which can be exploited as input for the control of future attention-aware interaction designs. Cognitive Load is modeled from pupil dilation via exploiting the task-evoked pupil response while considering disturbances of illumination and blink activities.

Author Keywords
Cognitive Load; Attention Estimation; Pupillometry; Attention & Interruption Management

ACM Classification Keywords
H.1.2 [User / Machine Systems]: Human Factors, Human Information Processing; H.5.2 [User Interfaces]: User-centered Design

Introduction
Our society has been experiencing a massive evolution from the early 1990s, when information represented one of

the most valuable goods, to a society, in which information has become available anytime and anywhere to a point of annoying excess. The phenomenon of information overload is defined in the business dictionary as 'Stress induced by reception of more information than is necessary to make a decision (or that can be understood and digested in the time available)', originating from the conflict between the natural urge of making well-informed decisions and the massive amounts of information which can never be adequately processed.

This gap between available and processable information can be expected to be ever-increasing and it represents a trend which already has transformed people from 'searching' to 'filtering' instead of 'finding' beings, a trend which threatens to drown us in data, which needs to make us rethink the basic underlying concept of information and communication technologies. The orientation of interaction design along an optimal management of user attention represents a counterpoint to current ICT paradigms. This goal can be achieved via (i) connecting devices to an overall unified, personalized information system to avoid unnecessary redundancy in information and interruption management, as well as (ii) by making automatic information systems adaptive to human perception resources via awareness of current activities, context and especially attention distributions, cognitive load and perception capabilities.

Sensing Attention

Enabling Attention-Awareness in interactive systems requires an understanding or estimation of current activities as well as of underlying intentions, motivations, levels of engagement and associated cognitive load to allow for the adaptation of e.g. notification services to current levels of interruptibility of the user. Such an adaptivity needs to be based on the assessment of psycho-physiologic expressions of attention indicate current cognitive activities and cognitive load, e.g. pupil dilation [1], heart-rate variability, galvanic skin response, etc.

Pupil Dilation as Indicator of Cognitive Load

Pupil dilation has been established in the literature as an expressive, reliable and quantifiable indicator of attention which shows promising potential to serve as an input parameter in the development of future attention-aware ICT systems [9][7]. Besides light incidence control, the pupil is also sensitive to psychological and cognitive activities and mechanisms, as the musculus dilatator pupillae is directly connected to the limbic system in via sympathetic control [5]. Since the 1960's and 70's, pupil dilation has been investigated as an indicator of cognitive activities, emotion and decision making in academic research. These research activities triggered the start of the so-called *cognitive pupillometry* focused on these *small but ubiquitous pupillary fluctuations ... providing a unique psychophysiological index of dynamic brain activity in cognition* [1].

As the pupil diameter is not under voluntary control, it represents a promising indicator and psychological reporter variable of internal cognitive processes. Pomplun and Sunkara [15] identified pupil dilation as a highly relevant indicator of occupied workload capacity and apply a neural-network based calibration interface and comparison of effects from cognitive workload and display brightness on pupil dilation. Bijleveld et al. [2] explored pupil dilation regarding strategic resource recruitment adjacent to subliminal reward cues and found that resources recruitment is independent from conscious or unconscious perception of the respective reward cue. Kang et al. [11] continued Smallwood's research [18] regarding pupil dilation as an index of overall attentional effort by controlling luminance changes, thus ruling out disturbing influences of brightness on the study results.

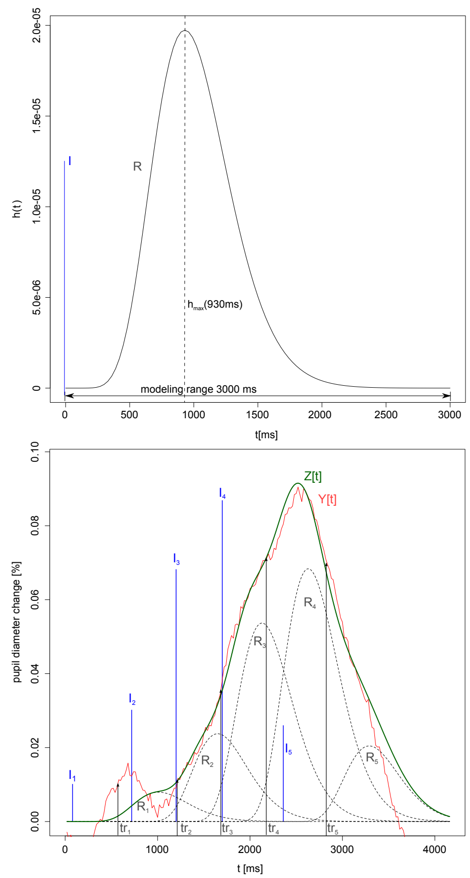

Figure 1: (a) left: Task-evoked pupil impulse response $h[t]$, (b) right: Modeling of pupil curve via task-evoked pupillary response (TEPR) via a linear combination of scaled and positioned attention impulse responses R_k resulting in modeling curve $Z[t]$. The impulse responses are the result of a convolution operation of instantiated impulses I_k with the impulse response h.

Kang et al. successfully verified synchronized behavior in conscious versus unconscious perception of stimuli. Pflleging et al. [14] employed a remote eyetracker to analyze cognitive load from pupil dilation and analyzed the impact of illumination changes.

Besides Cognitive workload and attentional effort, the so-called task-evoked pupil response (TEPR) has found application in various other cognitive disciplines: (i) emotion & arousal [5][3][17][10] (ii) task switching: Katidioti et al. [12] and (iii) decision making [4][16].

In this paper
In this workshop paper, we will present a demonstrator prototype tpwards the estimation of cognitive load from pupil dilation in near real-world conditions, based on a commercially available eye tracker. The demonstrator realizes the pupil analysis algorithm published in [6] and provides a graphical user interface which allows to experience the functionality of real-time tracking and analysis of pupillary data.

Modeling Cognitive Load from Pupil Dilation

This work is substantially based on research by Hoeks et al. [8], who created a computational model of cognition-related pupillary behavior by modeling the TEPR as a linear input/output system whereas attentional input is represented as a sequence of attentional impulses (Figure 1), which are associated to pupillary output via a characteristic pupil impulse response $h[t]$ (Figure 1). Hoeks empirically identified the pupil impulse response $h[t]$ (Figure 1.a) to reversely compute the initial attention impulses that trigger the detected pupillary output. The position and scale of the calculated impulses represent temporal onset and amount of cognitive load whereas the distribution of the pupil dilation curve represents the respective temporal course.

Mathematically, the relation between $i \leq j$ input impulses $I_i = s_i \cdot \delta[k_i]$ with scale s_i, onset time k_i and modeled pupillary output $Z[t]$ is represented via the time-discrete convolution operation, which, due to the impulse character of the input, modeling can be simplified to the following:

$$Z[t] = \sum_{i=1}^{j} (I_i * h)[t] = \sum_{i=1}^{j} s_i \cdot h[k_i - t] \quad (1)$$

$$h[t] = t^{10.1} \cdot e^{-\frac{10.1t}{930\,ms}} \quad (2)$$

The proposed system represents an iterative (frame-wise) optimization algorithm which is capable of modeling continuous data-streams of pupil dilation for online analysis of cognitive load. In [6], the authors developed a curve matching optimization algorithm in the time domain, enabling real-time processing and analysis with dynamic detection of the position and scale of attention impulses, optimized to best possibly match the measured pupil curve. For a detailed description of the optimization and filtering approaches, please refer to [6].

Demonstrator Description

The proposed demonstrator for real-time assessment of cognitive load implements the iterative process as displayed in Figure 2. A core optimization algorithm for modeling pupil dilation and thus inferring cognitive load is preceded by modules which aim at compensating the traditional challenges of pupillometry in real-world settings: (i) illumination, (ii) blinks, (iii) determination of the required reference baseline as well as (iv) on- and offset detection of significant cognitive activities.

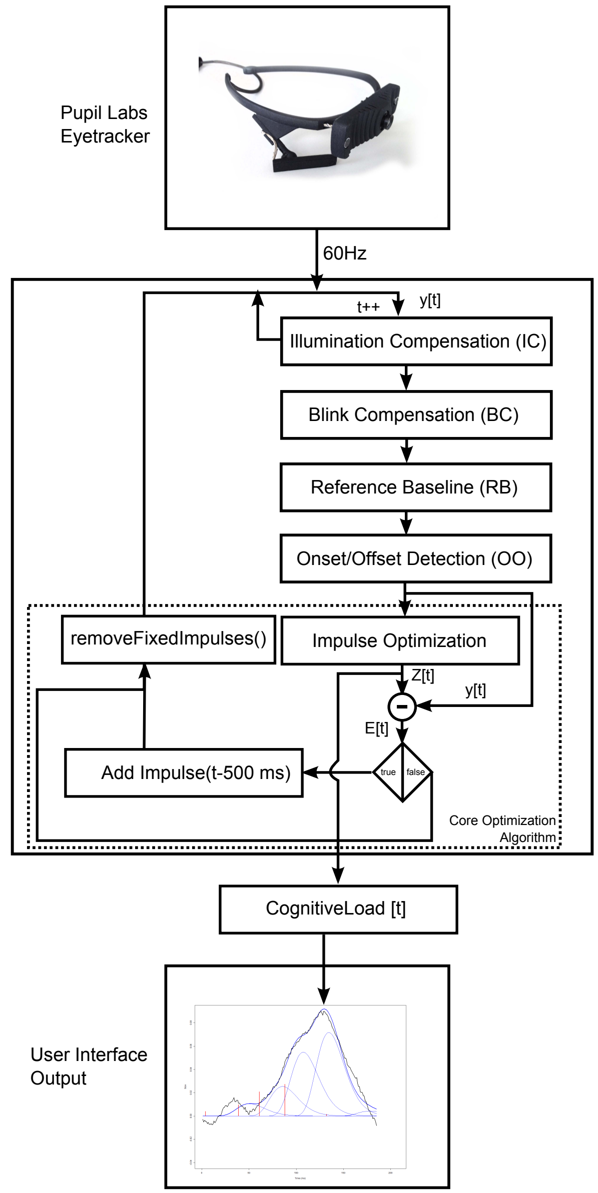

Figure 2: Structure of proposed algorithm for online analysis of pupil dilation for dynamic input for interactive systems.

Technical Description

The employed Pupil Labs eye tracker [13] provides pupillary dilation in mm at a frequency of 60 Hz, as well as world camera footage resembling the current field of view of the user in 720p resolution. The pupil dilation data rate is sufficient to model cognitive load, whereas the world camera video data is used to analyze the brightness of the situation to detect illumination changes which might interfere with reliable pupil analysis. The demonstrator, including sensor integration, data filtering and processing as well as the actual pupil modeling, is implemented in a JAVA application.

Functional Description

This demonstrator provides a graphical user interface in which (i) current pupil data and the modeled cognitive load data is visualized in real-time and (ii) mathematical problems of differing complexity (traditional multiplication problems, confer Figure 3) are presented to enable to experience the assessment of cognitive load engaged in the respective task. The timing of the presentation of the mathematical problems is synchronized with pupillary response data and is visualized, to not distract the proband from the mathematical problem, for a posteriori analysis (Figure 3).

Conclusion & Future Work

In this work, we present a demonstrator which is supposed to enable to experience the real-time assessment, and thus the potentials, of inferring cognitive load from pupil dilation. The underlying algorithm modeling cognitive load based on the task-evoked pupil response has been presented in [6].

We are convinced, that pupil dilation provides a very valuable indicator of attention as input for the control of information and notification systems, making these interactions adaptive to human cognitive states and thus creating truly user-centered applications.

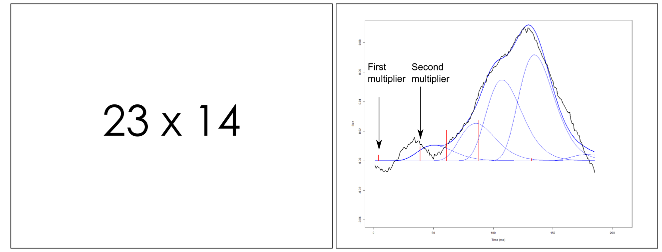

Figure 3: Screenshots of graphical user interface, left: Mathematical problem presentation, right: subsequent alignment of pupil curve, cognitive load and temporal events of multiplier presentation.

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