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RESEARCH ARTICLE

A Review of Pupillometry for Human-computer Interaction Studies

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Abstract
The most commonly used methods in human-computer interaction (HCI) are based on behavioral data, interviews and questionnaires. While these practices are able to provide reliable results, they are influenced by subjective factors arising both from the experimenter's and the user's side. Many of these methods also have poor temporal resolution, limiting their range of use. Approaches based on physiological responses should not have these inherent shortcomings. Although there exist many methods based on different signals (EEG, ECG, EDA), pupillometry has its distinct advantages. The basic set of devices needed is cheap compared to most other methods and it is also the least intrusive option. It is well established that cognitive and affective processes can be monitored by recording changes in pupil dilation. While emotions are an important aspect of HCI and overall user experience, changes in mental effort levels are easier to interpret in case of software and webpage evaluation or interactions with automated systems. As a result, the present paper will focus on the measurement of mental effort, only mentioning other possible uses briefly. The goal of this review is to provide a brief insight on the issues that might arise during HCI studies and factors that should be controlled to gather valid data for mental effort calculations.

Keywords
human-computer interaction, pupillometry, mental effort, pupillary light response

1 Introduction

The measurement of pupil diameter to infer mental state changes is not a new topic. The most widely cited, earliest studies using pupillometry were conducted by Hess and Polt [1-2]. They have reported that when people view stimuli that is interesting, confusing or contains emotional tones, their pupils will dilate more compared to visually similar, but otherwise neutral stimuli. They also observed that changes in task difficulty also had an effect on pupil size. As the difficulty of a mental arithmetic task increased, so did the average pupil diameter. These findings have benne replicated many times since then [3–6] and pupillometry is used to achieve a wide variety of goals.

It can be used as a tool for medical and psychological diagnostics. Apart from localizing lesions that affect the Nervous System, certain parameters of pupil responsivity can also help diagnose disorders. Even at the early age of 2, children diagnosed with Autism Spectrum Disorder show increased baseline pupil diameter values [7] and diminished reactivity to simple visual stimuli [8].

Pupillometry also offers the promise of automated evaluation methods in many settings. Kaklauskas et al. [9] proposed a system that can track distant learning students' concentration level and provide feedback to both the student and the tutor. Based on the magnitude of change in pupil dilation when answering a question online (and also factoring in other behavioral variables), the system can flag too difficult tasks. Students are provided with a list of recommended learning materials based on their responses and pupil activity. Another avenue of research is intention detection in HCI. Jang et al. [10] proposed a method to separate implicit navigational and informational intent based on simple measures of fixation length, fixation count and pupil diameter. They used both a Nearest Neighbor and a Support Vector Machine (SVM) classifier. They report classification accuracy around 0.8-0.89 with the SVM providing slightly better results. However, it is difficult to judge these classifiers without additional measures of goodness (e.g. specificity, precision, etc.). They also report, that classifiers might not be necessary for their goals, as mean values were also significantly different for the two types of intentions.

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Another important aspect of HCI outside of mental effort changes, are user intentions. A recent paper [11] aims to predict user click intentions on webpages based on pupil dilation and EEG data. They extracted 15 features from the pupil and EEG data. In case of the pupil data, the z transformed dilation curves showed a difference in fixations that were followed by intentional clicking on a link vs. not clicked objects. On average, pupil diameter was greater for clicked objects. All 15 features were used as input for 7 different classifier. The best accuracy (0.7109) and precision (0.5449) values were achieved with Logistic Regression while the best recall (0.3566) and overall F-measure (0.4066) was attained by a Neural Network approach.

The purpose of this paper is to give a basic introduction about pupillometry especially focusing on information relevant when studying HCI. It is nowhere near a concise manual for pupillometic studies, its aim is to highlight considerations and solutions for those interested in the topic. The following section will briefly describe the neural basis of pupillary control followed by a summary of internal and external effects that have consequential influence on pupil reactivity and diameter. In the second part of this review, I will highlight methods and metrics most accepted in the field, describing their domain of use.

2 Basic mechanisms and pupillary responses

There are many organs (mostly visceral) in the human body that are not under conscious control; most of them are innervated through the Autonomic Nervous System (ANS). Organs under ANS control include: heart, bladder, kidney, sweat glands and the muscles responsible for changes in pupil size [12]. The ANS has two branches: the sympathetic and parasympathetic pathways. The function of the sympathetic pathway is to mobilize the body for activity. Conversely, the function of the parasympathetic pathway is to conserve energy and restore a resting state. They exhibit this type of reciprocal control in case of the pupil as well. The sphincter muscle of the pupil is under parasympathetic control and is responsible for constricting the pupil, while the dilator iris muscle is under sympathetic control which is responsible for dilating the pupil [13].

Baseline pupil diameter shows great interindividual variation which has its implications for HCI evaluation. The normal range of pupil diameter is between 2 and 8 mm [14] but resting values are not simply a consequence of lighting condition and eyeball size [15]. There can be considerable difference between users based on their baseline ANS activity balance.

Influence on pupil dilation can arise from multiple sources. Changes in lighting intensity produces the most profound effect through the phenomena called the Pupillary Light Response (PLR). Because of its impact on pupil recordings, PLR will be discussed in greater detail in the next section of the paper. Another response is called the Pupillary Near Response. When an object in the frontal, foveal field of vision decreases its distance, the eyes converge and accommodate while the pupil also reacts by constriction [16]. However this reaction is quite transient, as dilation starts to occur even before accommodation of the eyes is complete. Any type of psychological state change or reaction also causes a pupillary response. This small, but in some cases quite preserved [13], effect caused by stress, fear, general arousal or mental load increase is called the Psychosensory reaction. This reaction has the greatest importance when it comes to human-computer interaction evaluation, albeit it requires strict control over experimental conditions. As a result of this response being a mix of many influences, factors that are of no interest should be controlled as well as possible. If mental effort is the focus of the study, emotional influences or probable sources of stress and anxiety should be minimized.

Apart from the previously mentioned phenomena, that are mostly event-related, there is also a constant, very small, but detectable oscillation of the pupil [17]. The amplitude and frequency of these oscillations are influenced by a number of factors, lighting levels and drowsiness being the most influential. This change in oscillation parameters can be used as a measure of user fatigue in human-computer interaction studies. This will be discussed in greater detail in the next section.

2.1 The Pupillary Light Response

Pupilary Light Response (PLR) is the phenomena when the sphincter muscle constricts in response to a sudden increase in photonic intensity [18]. The reaction happens with a latency of roughly 200-450 ms. The time it takes to reach minimum pupil diameter is in the magnitude of the latency (Fig. 1). After the minimum is reached, the pupil redilates with constantly decreasing velocity. All parameters of the PLN are tied to stimulus intensity. There is a logarithmic relation between stimulus intensity and constriction amplitude, constriction time, constriction speed and the inverse of latency time [19].

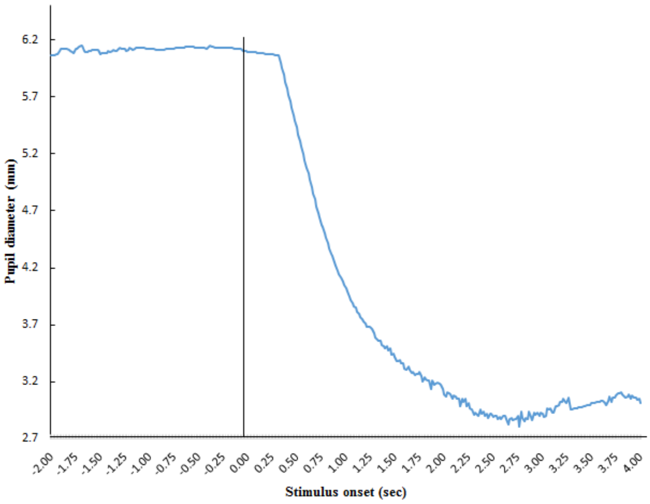

Fig. 1 Pupillary Light Response of a 30 year old participant to a blank, white monitor screen after a minute of dark adaptation. The vertical line shows the offset of the bright stimulus. (source: Author's own recording)

Light adapted pupil size can be estimated before running any participants. Watson and Yellott [14] propose a formula that integrates all other attempts at pupil size estimation, given a number of factors. Their solution factors in age, luminance, adapted field size (the size of the illumination source in degrees) and monocular vs. binocular adaptation. Of course, this only provides a rough estimate, as individual ANS baseline activity level is not part of the formula. However, it can still be of use to guide the experimenters' expectations about the users' pupillary reactions to avoid ceiling effects.

In most cases, PLR is elicited with the use of white light therefore there are not too many studies that explore how the wavelength of light might influence PLR parameters. One such study used [20] isoluminant (5 lux at the cornea) white, blue (450 nm), green (510 nm) and red (600 nm) light. They reported that the white and green light conditions had the greatest amplitude and shortest latency times. The red light condition had the smallest amplitude and highest latency, while blue was in the middle. These findings show that in order to elicit a large enough PLR, stimulus parameters should be designed accordingly.

2.2 Factors influencing pupil reactivity

There are numerous factors that influence the different parameters of pupillary responses. In the previous section about PLR, some were already mentioned (such as age). In the following paragraphs, I will highlight the major influences on pupil reactivity that are relevant when conducting HCI studies. As already mentioned, age is a major factor in many parameters of the PLR and should be accounted for in all studies [14]. Older participants show decreased amplitude of response [21], increased latency and in some cases decreased velocity [20] as well.

Emotional changes are another important influence on pupil reactivity [19, 22]. According to the latest studies, the valence of the emotion (pleasant or unpleasant stimulus) is not important only the intensity is [23]. Pupil dilation amplitude depended on the affective intensity of the viewed stimuli; the higher the arousing level of a picture, the greater the following dilation was. This was also confirmed in case of auditory stimuli as well [24].

Laeng and Falkenberg [25] reported that women in their fertile phase had significantly greater average pupil diameters for sexually significant stimuli. However it is not clear if it is a general effect or is it specifically tied to sexual stimuli. Also, this effect was only observable for women not using oral contraceptives. In case of gender, there seems to be a consensus about it not having an effect either on reactivity or baseline pupil diameter values [26, 27].

PLR parameters are also influenced by ongoing cognitive processing. Compared to no task, performing difficult mental arithmetic will result in reduced amplitude of response [28]. Another major factor influencing PLR is fatigue. When sleepy, participants tend to produce smaller dilation changes compared to an alert state [29]. Sleepiness is also accompanied by relatively smaller pupil diameters. In a dark environment, an alert person will have oscillations in pupil diameter with around 1 Hz and amplitude below 0.3 mm [30]. This can be defined as a stable state of the pupil. If that person is drowsy, the amplitude of these oscillations will increase, hence the so called "sleepiness waves" or "fatigue waves" will appear. This instability can be measured and used as a measure of fatigue. The most well-known of these measures is the Pupillary Unrest Index (PUI) which is best measured by the Pupillographic Sleepiness Test procedure [31]. PUI is correlated with most subjective measures of fatigue and the power of certain (delta, theta and alpha 1) waking EEG frequency bands [31].

PUI is defined as the sum of absolute differences between each data point over a 1 minute time period. In order to reduce noise, the standard method is to average 16 consecutive data points (and perform this calculation for all data points). Then sum up the absolute differences between these averages for 1 minute long periods [32]. PUI is reported in mm/min. Although it is highly correlated with drowsiness and fatigue, it requires special conditions to be valid. It requires a dark room to rule out any light induced fluctuations that are very similar to the PUI [33]. Consequently it needs an infrared based measuring system. Gathering sufficient amount of data is also necessary; pupillary instability usually occurs only after about an accommodation period of 1 minutes in the dark. The standard recording time for PUI is between 10-12 minutes which in turn will presumably contain 10 minutes of higher amplitude oscillations in case of drowsiness.

Another line of research have found, that there is a connection between baseline pupil diameter and intelligence and working memory. Tsukahara, Harrison and Engle [34] reported that baseline pupil size (while controlling for most factors) was predictive of participant scores on tests measuring fluid intelligence and working memory. Those who were categorized as higher working memory capacity (upper quartile) individuals, had significantly greater baseline pupil diameter values compared to low working memory capacity (lower quartile) individuals. The same relation was found for groups created based on fluid intelligence scores as well. The average difference was 0.65 and 1.04 mm respectively. Hierarchical regression analysis revealed that, when put in a single model, only fluid intelligence scores retained a significant relationship with pupil size. Among the controlled variables that also significantly influenced baseline pupil size were age (-), being a college student vs. not (+), nicotine consumption in the last 10 hours (-), and medication that affects memory or attention vs. no such medication (+). Since there are no more published finding on this topic (to the authors knowledge), this effect should be viewed with care. Nonetheless the baseline difference would not cause any issues for most studies since pupil diameter data should always be transformed for each participant to control for more basic, organic differences (will be discussed in more detail in a later section of the paper).

Drugs and medication can have a varied effect on pupil diameter and reactivity both in duration and in their exact influence on reactivity. However, covering this topic with all of its implications is beyond the scope of this review. For a concise description of this topic along with organic disorders concerning the pupil, see [13].

In sum, there are numerous factors that should be accounted for in a study using pupillometry to ensure reliable results. Age, recent stimulant use, medication and fatigue should always be measured in some way for each participant. These are the factors that have the greatest impact on pupil parameters. Also, a baseline pupil dilation value should be acquired for each participant. This can be done with the presentation of a simple blank screen. It is preferable not to use black or white screens as they can induce extreme dilation or constriction. Illumination levels for baseline recordings should be set to best match the ones encountered in the experiment. Individual reactivity measures (mainly average amplitude and latency) to a standard stimuli, such as a flash of light, can also prove useful later on for removing participants with extreme values.

3 Recording pupil diameter data

A very important property that makes pupillometry an outstanding candidate for a physiology based monitoring, feedback or automation system design is the fact that it is non-intrusive. Of course the most precise measurements require restriction of head movements but no sensors or electrodes have to be attached to the user. This makes it easier to implement outside of a lab environment, compared to EEG, ECG or EDA based methods. With a head mounted setup, it can be readily available for outdoor use.

Pupil dilation is measured through video-oculography (VOG) as it is impossible to measure with high precision, contact techniques used in eye-tracking such as scleral coils [35]. Identification of the pupil is required in most commercially available eye-tracking devices to estimate gaze direction. Therefore they generally log some form of pupil diameter or area data as well. Pupil size can be calculated based on simple video recording such as a high definition webcam zoomed in on the region of the eyes [36], but most systems use infrared light as well. The advantage of using infrared illumination is that it can provide image processing algorithms higher contrasts which makes accurate identification easier. It also enables higher quality, self-tuning identification methods [37].

There are three approaches (Fig. 2) that are used in most cases for pupil dilation measurement [38]. Horizontal pupil diameter is the least complex form of measurement. The reason behind horizontal and not vertical diameter being the standard is that it is less influenced by eyelid closure. However, horizontal measurement can be vulnerable to extreme gaze directions, because of the distorted image of the pupil in these situations (called the pupil foreshortening error). This type of error can be reduced by another approach which is to identify the greatest diameter value regardless of its orientation. This will provide a better estimate of pupil size even in extreme gaze direction situations. The third method is to measure the area of the pupil, but that is vulnerable to both eyelid closure and the pupil foreshortening error. There are attempts to attenuate these sources of error: the pupil foreshortening error can be lessened by using a geometric eye model based correction routine [39].

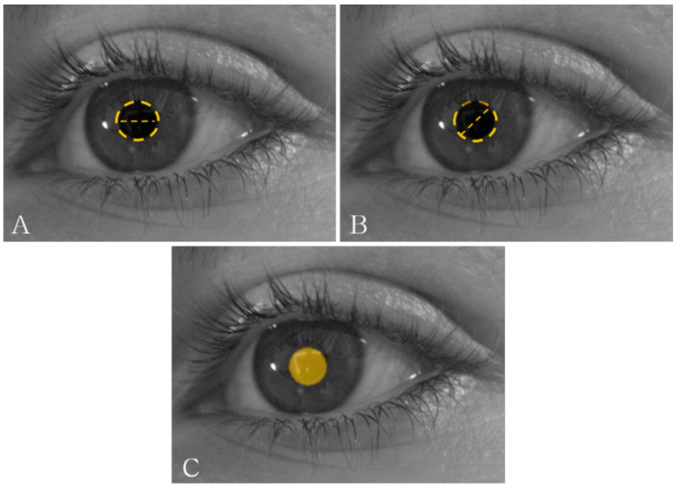

Fig. 2 the most commonly used approaches to measuring pupil dilation. A: horizontal pupil diameter, which is vulnerable to extreme gaze directions B: greatest pupil diameter regardless of orientation which is less vulnerable to extreme gaze directions C: area of the pupil which is vulnerable to both extreme gaze directions and eyelid closure

4 Metrics derived from pupil diameter

Some form of transformation of the raw data is necessary to compare pupil dilation data because of great interindividual variation. This can be done by simply subtracting the average value for each participant from all data points [40], performing a z-transformation [30] or providing the percentage of change compared to a baseline value[1]. This latter practice is prone to producing misleading results because it is greatly influenced by the chosen baseline value [41] and should be avoided.

Even though there are a number of methods that try to differentiate between lighting and task induced responses, simple pupil diameter and diameter change data can still be a valuable indicator of mental effort or emotional changes. The exact method of calculation is dependent upon the paradigm. Both event related (phasic) and longer lasting (tonic) changes can be described using these simple metrics. The following are the most often used and simplest measures of pupillary changes:

- *Pupil diameter*. Measured in mm or pixels. For most studies, some form of normalization is required because of the individual differences. A variation of this metric is pupil diameter change. It eliminates some of the differences between participants but still best to normalize
- *Pupil area*. Some eye-tracking devices output area values in pixels instead of diameter. The same principles apply as in the case of pupil diameter. Change in pupil area is also used

- *Event related response latency or response velocity*. Mostly useful for diagnostic purposes, but increased levels of mental load are able to influence these parameters [42]

Although PLR is diminished under high levels of cognitive load [28] it can be still a serious liability when it comes to reliable data acquisition. One way to counteract this is to create highly controlled conditions for data recording. By keeping both background and stimuli luminance at a constant level during data acquisition, factors from lighting changes should be eliminated. This approach also necessitates constriction of head movements, otherwise lighting can still influence the data. If the paradigm allows these restrictions, then this is the faster and most reliable approach. However, it is also the most confining when it comes to possible research topics. In case of a real-world like activity such as driving [43] or other simulated activities [44, 45], it is not feasible to apply all restrictions without risking the validity of the study.

Because of these reasons, paradigms with higher ecological validity must rely on other methods to filter out changes attributed to lighting. There are a multitude of solutions proposed by different research groups. The following will contain a brief description of some of those approaches with the aim of highlighting a wide range of research questions and the proposed solutions.

The Index of Cognitive Activity (ICA) [46] is one of such methods, that attempts to differentiate between task and lighting change induced pupillary responses. Although the exact method of calculation is patented, so it is not freely accessible, the logic behind it is available. It uses wavelet analysis to disentangle light and task induced responses. It is based on the principle that lighting induced changes are gradual with greater amplitudes while task related changes have smaller amplitudes and shorter overall time. Although the domain specificity of ICA is unknown because of its limited availability and number of publications, it appears to be valid in many cases. ICA appears to be a reliable measure of increases in cognitive load during linguistic processing [47]. It also performs well in simulated driving scenarios [48] and visual search [46]. There is also a report about different types of loads being more significantly represented in one of the eyes when load is measured by ICA. Linguistic processing effects appeared stronger in the left eye while simulated driving dual-task effects appeared stronger in the right eye [49].

Spontaneous fluctuations of the pupil can also be used to measure ANS activity changes. In the same way as with hearth rate variability (HRV) [50] that can be used as a measure of mental effort, pupil size variability (PSV) can provide similar result. However, the fact that both organs are innervated by both sympathetic and parasympathetic branches, does not mean that exactly the same effects will appear. There is correlation but it is far from identical [51]. In order to use PSV to measure mental effort, power spectral density estimation has to be performed. Frequency bands are the same as in case of HRV: Low frequency (LF, 0.04-0.15) and High frequency (HF, 0.15-0.45). Both HF and LF band power is used to measure mental effort [50] and the low frequency-high frequency (LF/HF) ratio as a ANS activity balance measure (however, the validity of this latter measure came under question, see: Billman (2013)). The LF/HF ratio seems to be the best for identifying changes in mental effort levels independent of luminance changes [53], both in memory span and mental arithmetic tasks [54]. It also appear to be quite robust in virtual reality settings [55]. The exact algorithms vary, maximum entropy [54], Yule-Walker [56] and custom autoregressive models [57] are all used in the field.

Another approach that also tries to differentiate between the two main influences of mental effort and lighting is based on component analysis. Principal component analysis and Independent component analysis can be used to this end. In their study Jainta and Baccino [58] used both methods to compare their validity on pupil data. They used different difficulty levels of mental arithmetic tasks under time pressure. The Principle component analysis revealed three components that accounted for 81.3% of total variance. This was in line with previous findings [59], however based on the calculated factor scores showed no significant difference between conditions. After running two different algorithms for Independent component analysis, the authors described three components (based on their previous results). The first component peaked right after stimulus onset, the second during the first 2 seconds and the third near the end of each task. After calculating energy scores for each component, they examined their relation to behavioral data. They have found that the first and third component had no consistent relation to the data. However, the energy of the second component showed a similar pattern (non-significant) to error rate.

5 Discussion

Pupillometric data contains similar, yet different effects of ANS activity, compared to other methods. Because of this, recording multiple signals such as HRV and EDA at the same time with pupillometry is not redundant at all. Correlations are in the magnitude of 0.4-0.46 between certain HRV and pupil parameters [51]. As the same way as it is with usability studies of HCI, one method will provide only one part of the whole picture. The behavior of the user is a great source of information but without a post-task interview, it is easy to misinterpret the causes of actions. The same holds true for pupillometry; additional sources of information are always important.

Both hardware and software issues have to be resolved to create a method that is easier to use. With growing processing power, even long standing issues such as the pupil foreshortening error [39] are becoming feasible to solve even in real-time. The future of the field is in highly adaptable, self-correcting image processing algorithms, that work in tandem with other sources of information (heart rate, electrodermal activity changes and behavioral data), to identify problems in HCI or to provide feedback for both the users and the developers.

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