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A CALIBRATION AND ADJUSTMENT METHOD FOR A DYNAMIC VISUAL COMFORT ASSESSMENT

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ABSTRACT

Glare is known as one of the main causes of visual discomfort in office space and yet remains difficult to evaluate quantitatively. Most discomfort glare models have limitations when attempting to represent the reality of user behaviour. One reason is that models are developed based only on subjective surveys. This research aims to probe the influence of experiencing glare on user ocular and dynamic gaze behaviour as an objective response. To do so, an experimental study was conducted utilizing an eye-tracking device to record user's gaze responses to the surrounding environment. High dynamic range imaging was also used to record luminance distribution. This paper documents the calibration process for the variety of equipment utilized in this research.

INTRODUCTION

In the contemporary workplace, productivity (Abdou, 1997), satisfaction (Galasiu & Veitch, 2006) and comfort (Iwata, Hatao, Shukuya, & Kimura, 1994) are highly contingent upon the visual environment. However, glare as one of the principal reasons for visual discomfort (CIE, S, ILV: International Lighting Vocabulary. Vienna, & 2011:203., 2011), gives rise to such unexpected experiences as early fatigue, headache and so on (Boyce, 2014). Additionally, owing to various human tolerances and attitudes towards glare, evaluating discomfort glare has been controversial (Rea, 2000).

The existing glare models are driven by photometric measurements in the field-of-view (FOV), visibility, and subjective evaluation have been utilized to quantify the perceived glare (Hopkinson, 1950). The influential factors on glare are known to be as formulated below:

$$G = \left(\frac{L_s^e \cdot \omega_s^f}{L_b^g \cdot f(P)} \right) \quad (1)$$

In this equation, L_S accounts for the luminance of the glare source which is received by the user's eye from a specific viewpoint; ω_s is the solid angle subtended by the source with respect to the eye of the observer; L_b is the adaptation luminance; P is the position index, and stands for the discomfort perceived depending on the location of the glare source in the FOV with respect to the line of sight (view direction); the exponents (e, f and g) are weight factors for each parameter which vary in different glare formulae. The empirical correlation between these photometric quantities and subjective responses through different studies on discomfort glare has resulted in several prediction models. The prevalent quantitative subjective assessments such as the de Boer (1967) scale, which is a category rating scale to evaluate glare, are, however, susceptible to significant bias (Fotios, 2015). Another limitation that the existing models have is making certain assumptions about user behaviour such as fixed-view direction assumption.

Physiological involuntary responses, which are now easier to record on account of novel advanced technologies, have been considered in a few studies in order to overcome uncertainties about category rating scale assessment methods that have so far been used to quantify glare. The pupillary response has been the main objective feature investigated by researchers to address light-induced physiological reflexes. There is a consensus that the pupil diameter itself cannot be used as an indicator of experiencing glare whereas the fluctuations and irregularity of pupil dilation and constriction should be considered (Berman, Bullimore, Jacobs, Bailey, & Gandhi, 1994; Fry & King, 1975; Hopkinson, 1956; Howarth, Heron, Greenhouse, Bailey, & Berman, 1993; Lin et al., 2015; Murray, Plainis, & Carden, 2002). The inclusion of involuntary user ocular behaviour, which includes but is not limited to user physiological responses such as pupillary oscillation, has proven to be an alternative and complementary objective assessment of the discomfort glare.

The fixed-view assumption deficiency has been addressed through arbitrary predefined orientations for view direction (Jakubiec & Reinhart, 2012) without considering user natural behaviour. This issue has been addressed more rigorously in a series of experimental studies where the effect of different lighting conditions on view direction orientation and the actual perceived visual comfort was investigated, which resulted in a gaze-driven model (Amundadottir, Rockcastle, Sarey Khanie, & Andersen, 2017). Sarey Khanie et al. (Mandana Sarey Khanie, 2015; M Sarey Khanie, Stoll, Einhäuser, Wienold, & Andersen, 2016) through use of a head-mount mobile head and eye-tracking device, conducted these experiments to assess the impact of luminance distribution and outside view in a daylight office on view direction behaviour.

To date, the spatial frequency of user view directions based on different lighting distributions and office task types has been investigated. However, adjusting view direction is a user adaption behaviour. Thus, to have a profound understanding of user behaviour regarding glare, and to see how they can affect glare predictive models, differing ways of evaluation and individual preferences, as they reveal rather than report, should be considered. It is worthwhile therefore to delve into the influence of experiencing glare on user ocular and gaze behaviour in addition to their visual performance.

In order to explore further the gaze and ocular behaviour as involuntary physiological responses to glare, this experimental study, by means of an eye-tracking device and High Dynamic Range (HDR) imaging for luminance mapping, aims to tackle the mentioned limitations in studies to date in relation to discomfort glare. A vital sensitive step in this study was the calibration phase to produce accurate results. The key challenge of this method was in translating acquired data from the eye-tracker to useful data for glare analysis.

This method consisted of three phases: the calibration process for the eye-tracking device; the calibration process for HDR imaging and finally processing the acquired data. In this paper, the calibration phase and data processing are described in detail.

METHODOLOGY

Each device used in the experimental set up required a sensitive calibration procedure in order to obtain accurate data. The first instrument to be calibrated was the eye-tracking device, the aim being to interpret various ocular data and translate its inertial measurements into spatial coordinates and vectors. Calibrations included adjusting for drift and mapping the data-stream with task activity.

The second calibration pertains to creating HDR images as a record of the luminance distribution in the room. HDR imaging is a well-known technique for obtaining a larger spectrum of luminance values than standard imaging. Several calibration studies on HDR imaging have been published, including (M. Hirning, Coyne, & Cowling, 2010; M. B. Hirning, 2014; MN Inanici, 2006; Mehlika Inanici & Galvin, 2004; A. Jacobs, 2012; Jakubiec, Van Den Wymelenberg, Inanici, & Mahic, 2016; Pierson, Bodart, Wienold, & Jacobs, 2017). Devebec and Malik (Debevec & Malik, 2008) present one of the best-known approaches for recovering radiance data from HDR images. Although the various details and options in creating HDR images were recorded, problems included calculating the response curve of the camera, accounting for the vignetting effect of a Fisheye lens, and adjusting the luminance scale to a measured point in the image.

The final step in calibration dealt with understanding the recorded gaze data. The gaze data can be categorised into 4 types of eye movement: small rapid (*saccadic),* smooth tracking *(pursuit),* focusing *(fixation),* and rapid corrective (*vestibule-ocular*) (Purves D, 2001). Recognising these subtle behaviour 'features' and processing the data will provide a deeper understanding of user physiological behaviour and visual performance. In his study, to classify eye movements from the raw data, a Velocity-Threshold Identification (I-VT) fixation classification algorithm was adopted, which is a velocity based classification algorithm (Salvucci & Goldberg, 2000).

The calibration process for the eye-tracking device

The Tobii eye-tracking glasses are wearable, lightweight, discreet binocular eye trackers, which work based on the corneal reflection eye-tracking technique ("Tobii Pro Glasses 2,"). Using this device, gaze data including but not limited to head-referenced gaze direction and pupil diameter can be recorded on a 100 Hz sampling rate. This device has an integrated micro-electro-mechanical system (MEMs) incorporated in the eye-tracker, which aggregates translational acceleration and rotational velocity, demonstrating body movements. The adopted eye-tracking glasses utilize one-point calibration method. In this type of calibration, only one calibration marker is required for personal calibration (Common calibration methods require the user looks at nine to twenty calibration markers in succession) (Ohno, 2006). The calibration needs to be performed just once, before commencing the data recording.

Figure 1 A participant wearing an eye-tracker and the calibration process

In this research, the calibration process was integrated into the visual tasks of the experiment. It was used at the beginning of the experiment task sequences to calibrate the eye-tracker which is normally required for recording gaze data. The calibration marker was also added to the end of the experiment tasks for two reasons. Firstly, to validate the captured data during the experiment, and estimating accuracy and precision of the acquired data. Secondly, to utilize the calibration marker as a measure for visual discomfort experienced by the user at the end of the experiment.

The calibration process for HDR imaging

High dynamic range (HDR) imaging allows for capturing luminance values over a wide range, with accuracies in the range of 10% (Mehlika Inanici & Galvin, 2004). However, creating HDR images with reasonably affordable equipment requires an extensive calibration process to ensure that luminance data and derived spatial information is correct (Pierson et al., 2017). The most common HDR calibration process steps determined in the literature (Coyne, Isoardi, Luther, & Hirning, 2008; M. B. Hirning, 2014; Jakubiec, Van Den Wymelenberg, Inanici, & Mahić, 2016; Pierson et al., 2017) are:

- capture of multiple exposure images,
- camera response curve derivation,
- HDR image generation,
- calibration adjustment by spot luminance measurement and geometrical re-projection

The luminance maps acquired during the research were captured using a Canon EOS 5D MARK III digital camera with Full Frame CMOS (36.0x24.0) sensor fitted with the EF 8-15mm f/4L Fisheye USM lens.

In acquiring luminance maps, a sequence of multiple exposure LDR images is required. In this study, thirteen RAW images (A. Jacobs, 2012) were captured with exposure time ranging from 1/1000s - 4s. A sequence of multiple exposure images has to be taken by varying the exposure time between photographs, since changing the aperture would increase the problem associated with vignetting, which is a light fall-off at the periphery of the captured image (Reinhard et al., 2010); therefore, shutter speed is a more reliable measure than aperture size (MN Inanici, 2006). Small aperture sizes are correlated with greater potential for lens flare (Jakubiec, Van Den Wymelenberg, Inanici, & Mahic, 2016), and large aperture sizes suffer from a low maximum captured luminance value (Jakubiec, Van Den Wymelenberg, Inanici, & Mahić, 2016) and a large vignetting effect (Cauwerts & Deneyer, 2012). For this reason, the aperture of the lens was kept constant at a mid-range aperture size, F/11(Jakubiec, Van Den Wymelenberg, Inanici, & Mahić, 2016; Pierson et al., 2017).

The camera response function relates pixel values to relative radiance (M. B. Hirning, 2014) and is specific for each camera, even if they are the same model (Axel Jacobs, 2007). There are several algorithms to estimate the camera response function. In this research, the software Photosphere has been implemented, which uses Mitsunaga and Nayar's method to approximate the response factor. To retrieve the real luminance values from HDR images, the centre of the target (Figure 3) was measured with the Minolta luminance meter (Figure 2) before and after the multiple exposure photographs were taken.

Having achieved the map of the individual radiance values at each pixel, the next step was to create an HDR image. The largest available bracketed sequence was then selected to ensure that over- and under-exposed photographs were captured. In order to select the sequence of useful exposures, a mask file was applied to set all pixels outside the LDR Fisheye view images to a neutral colour (such as black) (Van Den Wymelenberg, 2012). A script was then used to automatically count the pixels in the usable area of the LDR images and then select the right sequence. After selecting appropriate LDR images and the derivation of camera response function, HDR images were generated using Photosphere.

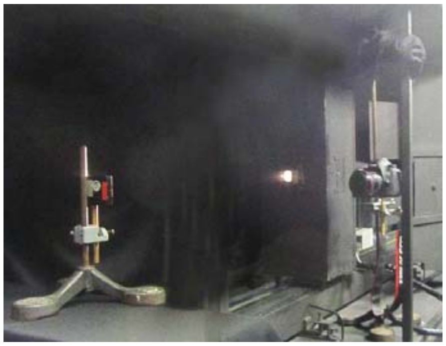
(a)  (b) 

Figure 2 (a)The position of the camera, the target and the light source with constant luminous flux; (b) The position of the target, camera and the luminance meter

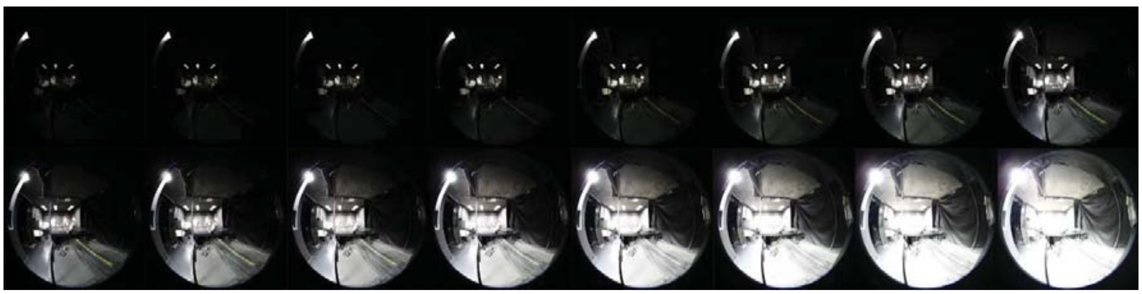


Figure 3 A range of LDR images was used to calculate the camera response factor

Figure 4 The captured LDR image and the usable area for making the HDR image

The Canon EF 8-15mm f/4L Fisheye USM lens uses equidistant projection to produce an image. There is a phenomenon known as vignetting in Fisheye lenses which refers to light fall-off at the periphery of an image (Reinhard et al., 2010). Subsequently, a deviation from the real-world luminance value will occur which needs to be addressed and corrected. Vignetting is strongly dependent on the aperture size (or F-number) of the lens and increases with larger apertures (Mehlika Inanici & Galvin, 2004). The fall-off of light from the optical axis of the Fisheye lens was measured in laboratory conditions for an aperture size of f/11, and a digital correction filter was created (M. B. Hirning, 2014; Jakubiec, Van Den Wymelenberg, Inanici, & Mahic, 2016; Van Den Wymelenberg, 2012).

Glare source detection

Regarding glare source detection, the *Evalglare* program was used which is part of Radiance (Al-Rahayfeh & Faezipour, 2013). It is a command-line program with the purpose of identifying sources of glare in a given HDR image. For VDT (visual display terminal) tasks, it is recommended to use the average task-zone luminance as a threshold luminance (Wienold & Christoffersen, 2006). Therefore, a target task-zone with an opening angle of about 0.9sr was used so that it covered most parts of the computer screen and parts of the desk. Pixels with a luminance value four times higher than the average task-zone luminance were detected as a glare source.

Data processing

In each experimental trial, three different sets of data were acquired from the eye-tracking device (ocular and inertial); luminance camera and the light sensors which were used due to their potential for investigating physical and physiological responses, along with user visual performance. Figure 5 illustrates Research scheme for the data stream and data processing.

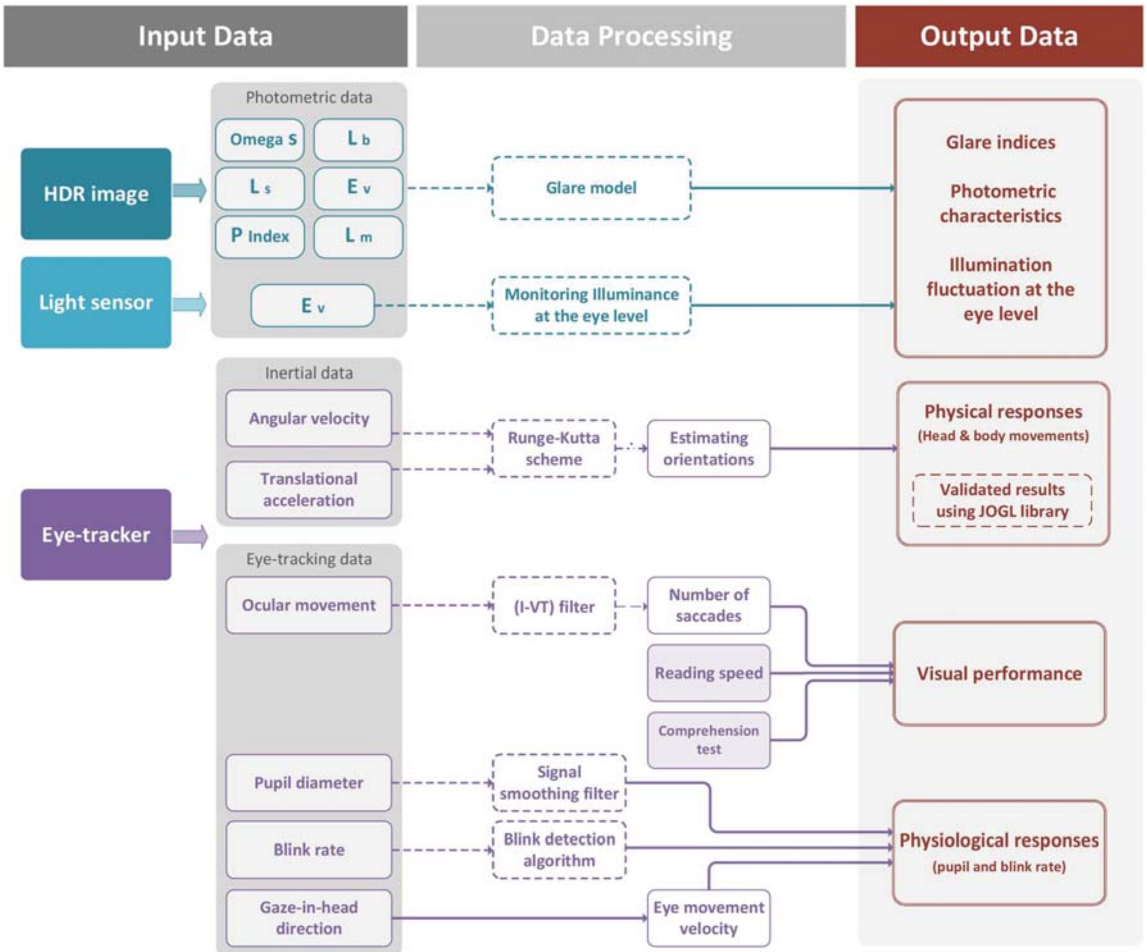


Figure 5 Research scheme for data stream and data processing

The eye-tracker, the gyroscope and the accelerometer are 3 different devices with different sampling rates, 100 Hz, 95 Hz and 100 Hz ("Tobii Pro Glasses 2,") respectively. Hence, they do not have the same periodicity; further actions are required to synchronize all data. The drift from the gyroscope and accelerometer were consistent enough to be expressed as a linear equation and adjusted.

Figure 6 Comparison between aye-tracker scene camera and simulated 3D model

The comparison between the captured video data and the visualization demonstrated (Figure 6) that this approximation encapsulates the recorded movement with the accuracy that is needed for this research. The interpolated data was visualized in a 3D model of the space and tested against the video recorded from the eye-tracking glasses. An application was made in Java using the JOGL library to create the visualization.

In order to address physiological responses as well as visual performance, the acquired data required extensive data processing. In this step, an intermediate calibration, matching the eye related data as recorded by the eye-tracker, with other data sets and task activities was performed. The first step was translating eye-tracking raw data into a useful set of information. For this purpose, pupil diameter signals are de-noised using a smoothing filter, as shown in Figure 7.

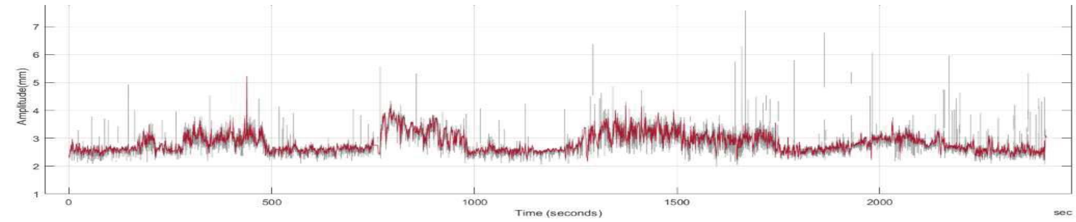


Figure 7 The frequency of pupil diameter: raw data (grey line) and de-noised data (red line)

In the next step, the eye-blink rate was provided by means of a novel algorithm was developed that detects the user's eye blinks from the raw data and analyzes the pattern and duration of the blinks. Figure 7 depicts the pupillary oscillation and blink rates during the entire experimental course and each visual task activity. In order to compare the frequency of pupil diameter oscillation for participants, the first derivative of pupil diameter is utilized. It is important to separate each task relative data since each type of experimental task differs in terms of required responses. Figure 8 shows the first derivative of the pupil diameter (blue line) added to the pupil diameter (dashed line) graph to demonstrate pupillary oscillation during each task activity (light grey horizontal bar indicates reading, medium grey horizontal bar indicates pause and dark grey horizontal bar indicates writing).

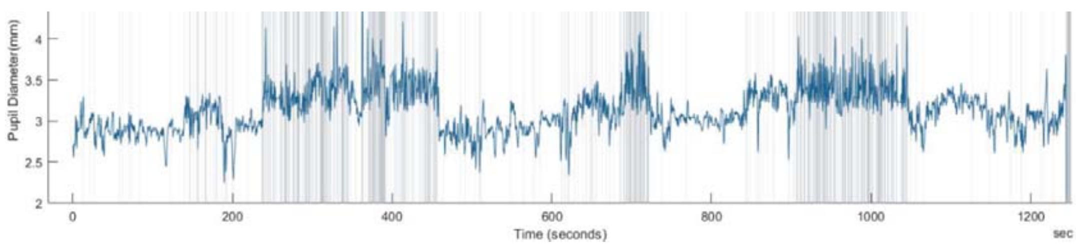


Figure 8The reflex of the pupil (blue line) to a light stimulus as well as blink rates (vertical lines)

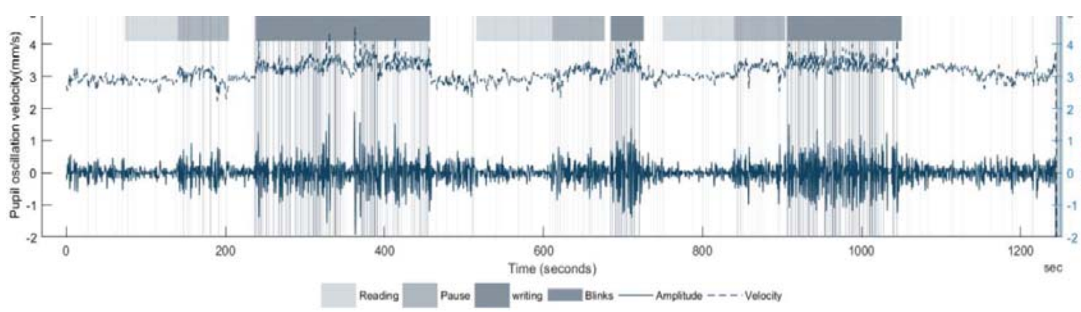


Figure 9 The first derivative of pupil diameter (blue line) and pupil diameter (dashed line) during each task activity

In this experiment to evaluate visual performance the total time spent on reading each passage was automatically recorded during the experiment. Fixations and saccades were also detected by applying a I-VT filter on eye-tracker raw data, and the accuracy was tested with a comprehension test at the end of each reading task. Figure 10 demonstrates gaze fixation points and their dwell time as the diameter of the circle. As a result, a new method for the future experimental research on glare evaluation and physiological response has been defined.

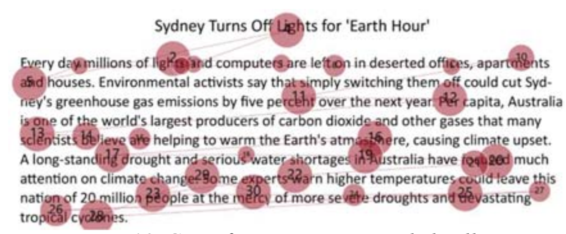


Figure 10 Gaze fixation points and dwell time as well as gaze trail and order for a reading task

CONCLUSION

An excessive calibration procedure was conducted in order to obtain accurate data for evaluation of human responsive behaviours in relation to glare. Moreover, a novel method was considered so as to study further the interrelations of glare, gaze and visual performance.

The calibration procedure was carried out in three major steps. Started with calibrating the eye-tracking device and then followed by the calibration process for HDR imaging. The final step described the method utilized for processing all captured data sets and how to translate them into the useful data for investigating the objectives of this research. As an immediate next step, the resultant data consistency with lighting conditions and subjective glare evaluations should be further examined.

The established method will be employed in an experiment, in which, four lighting conditions with different light distribution and glare level will be considered. Participants will be asked to perform different types of office tasks while their eye and gaze data are recording in conjunction with photometric measurements to provide a deeper analysis of light-induced user behaviour.

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NOMENCLATURE

L_b	Luminance of source
L_s	Adaptation luminance
P	Position factor of source
ω_s	Solid angle of source
E_V	Illuminance at the eye level
L_m	Average luminance

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