Vision Research 137 (2017) 24–28

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Effects of photopic and cirtopic illumination on steady state pupil sizes

Feng Rao [a,b], A.H.S. Chan [b], Xi-fang Zhu [a,*]

[a] School of Electrical and Optoelectronic Engineering, Changzhou Institute of Technology, Changzhou, Jiangsu 213002, PR China
[b] Department of Systems Engineering and Engineering Management, City University of Hong Kong, Kowloon Tong, Hong Kong, China

ARTICLE INFO

Article history:
Received 19 August 2016
Received in revised form 14 February 2017
Accepted 24 February 2017

Keywords:
Pupil size
ipRGC
Pupil light reflex
Cirtopic

ABSTRACT

The conventional view was that cones are responsible for pupil constriction in photopic lighting conditions. With the discovery of intrinsically photosensitive retinal ganglion cells (ipRGC), it was found that signals from ipRGCs along with cones mediated the pupil light reflex in photopic lighting conditions. Although both signals contributed, it was unclear how these signals were summed. In the work reported here, steady-state pupil size was measured with an infrared camera under LED lighting conditions with different color temperatures and luminance. A formula was then derived for pupil size according to the linear summation of cirtopic and photopic luminance. This formula allowed direct calculations to predict pupil size well when LED photopic luminance ranged from about 50 cd/m^2 to 300 cd/m^2, which is the general luminance level range for computer and smartphone screens.

1. Introduction

Pupil diameter of the human eye ranges from approximately 2 to 8 mm. Pupil size changes have a large effect on visual performance and depth of focus (Rao, Wang, Liu, & Wan, 2011). Pupil size is also an important factor to consider in the design of vision correcting lenses worn by ametropics (Madrid-Costa, Ruiz-Alcocer, García-Lázaro, Ferrer-Blasco, & Montés-Micó, 2015). Therefore, it is very important to monitor pupil size.

A number of studies have been conducted to develop equations to predict pupil sizes at different luminances. The first formula was developed in 1926 by Holladay for an average healthy young eye (Crawford, 1926), the data was collected from three observers binocularly viewing a large adapting area. Subsequently, a large amount of research was performed to refine such equations (Watson & Yellott, 2012), such as Crawford in 1936, Mono and Spencer in 1944, De Groot and Gebhard in 1952, Winn, Whitaker, Elliott, and Philips in 1994, Stanley and Davies in 1995 and Barten, Blackie and Howland in 1999. In 2012, Yellott reviewed the proposed formulas and developed a newly unified formula that incorporated the effects of luminance, size of adapting field, age and whether one or both eyes were adapted (Watson & Yellott, 2012). However, all these formulas only show the relationships between pupil size and photopic luminance.

With the discovery of a new class of photosentive cells in the retina, the intrinsically photosensitive retinal ganglion cells (ipRGCs), which send retinal information to the brain center for partly controlling the steady state pupil size (Adhikari, Zele, & Feigl, 2015; Berman, 2008; Dacey, Liao, & Peterson, 2005) it becomes important to understand how they interact with the pupil responses. Melanopsin containing retinal ganglions cells have been found to represent an input to the circadian system and are most sensitive to blue light (Oh, Yoo, Park, & Do, 2015). ipRGC-mediated vision has been termed "cirtopic vision", and represents a third visual input in addition to photopic and scotopic vision (Yao, Yuan, & Bian, 2016). However, the mechanisms for rod, cone, and ipRGC contributions to the pupil control pathway in humans are not well understood. It has been reported that cones are more important than ipRGCs in the control of pupil size at high luminances (Xu, 2011; Barrrionuevo, Nicandro, McAnany, Zele, & Gamlin, 2014). Tsujimura et al. reported that the ipRGC signals contribute to the pupillary response by a factor of three times more than the classic photoreceptor cells (Tsujimura, Ukai, Ohama, Nuruki, & Yunokuchi, 2010). Barrrionuevo et al. found the summation of the excitation of rods, cones and ipRGCs showed linear relationship with pupil phase response (Barrrionuevo et al., 2014). Pupil phase response is defined as the elapsed time between the light stimulus and the subsequent pupil constriction. Young and Kimura (2008) and McDougal and Gamlin (2010) found that different photoreceptors had different action thresholds and delay times to pupil reactions. Viénot et al. found that there was no difference in pupil response with rods, cones or ipRGCs alone (Viénot, Bailacq, & Rohellec, 2010). It seems that pupil size is determined by a complex mixture of rod, cone and ipRGC sensitivities. To date, no reported studies have provided a mathematical description of

* Corresponding author.
E-mail address: 1270437521@qq.com (X.-f. Zhu).

http://dx.doi.org/10.1016/j.visres.2017.02.010
0042-6989/

pupil size with the combined contributions of the different photoreceptor types. Therefore, this study was designed and conducted to explore these relationships.

Generally, photopic vision is determined by the combined inputs of rods, cones, and ipRGCs, based on cirtopic luminance, which is the summation of spectral irradiance of the light weighted cirtopic spectral sensitivity (Oh et al., 2015). The cirtopic action factor of luminous radiation, also called c/p value or a_{cv}, has been defined as the ratio between cirtopic luminance and photopic luminance (Rebec & Gunde, 2014). Nowadays, smartphone and computer with LED screens are used extensively. Screen luminances typically range was from 50 cd/m^2 to 300 cd/m^2. Therefore, in this research, LED light with a similar luminance range was selected for this study. Color temperatures of 3000 K, 4500 K and 6500 K, as in common daily use, were selected for testing. Pupil diameters of 40 students were recorded with an infrared camera under different LED lighting conditions and a formula developed describing pupil size during the combined input of photopic and cirtopic luminance.

2. Method

2.1. Participants

Twenty male and twenty female students, ranging in age from 18 to 23 years (average 19.5) voluntarily participated in this study. None of the participants had eye problems or general health complaints. All participants were fully informed of the purpose of the experiments and took part under the ethical guidelines of City University of Hong Kong.

2.2. Apparatus

An integrating sphere (Everfine Instrument Co. Ltd) was used which diffused light rays equally inside a sphere with a diameter of 50 cm. The set-up is schematically illustrated in Fig. 1. The voltage of a power supply could be regulated by three adjustable resistors for each of the three high power LEDs, which produced color temperatures of 3000 K, 4500 K and 6500 K. A color luminance meter (Everfine Instrument Co. Ltd, BM-9) was used to measure luminances and color temperatures in the integrating sphere. The subject looked at the opening of the sphere which had a diameter of 10 cm. Viewing distance was 25 cm, resulting in an angular extense of the illuminated circular field of 20 deg. Participants were asked to keep their chin on the chin rest to avoid head movements and to look at the target for the duration of the experiment. An infrared camera was used to capture videos of participant right pupil at 30-frames-per-second. The lab was dark during the tests, and the illuminace was lower than 0.5 lx.

Six levels of luminance, from 50 cd/m^2 to 300 cd/m^2, at intervals of 50 cd/m^2 were selected for testing at each color temperature in this study, providing a total of 18 lighting conditions for the tests in each participant.

2.3. Procedure

Before all the test sessions, a calibration was necessary to transform pixel values to linear values in millimeters by taking a photograph of ruler in front of eye, i.e. 12 cm above the chin rest.

In each experiment, the head of subject was placed in the chin rest. Then the LED was switched on. The subject had to look into the opening with both eyes for 1 min. While the subject was asked to maintain fixation to the opening in the sphere, pupil size of the right eye was recorded with the infrared camera for another 20 s.

The protocol of each test is shown in Fig. 2. The sequence of the 18 test conditions was randomized for each participant.

2.4. Analysis

The relationship between pixel values and linear values in millimeters was obtained from the calibration. During each test, the right eye was selected as the object of study, the pupil size in pixels were obtained from the digital pictures from the infrared videos. Therefore, pupil diameter (D) in millimeters can also be calculated from mathematic analysis.

After adaptation, although fixation remained stable, pupil sizes may have changed slightly during the test time. The mean value of the pupil sizes at the fifth, tenth and fifteenth second during the test time was used as representative values for pupil sizes at the respective lighting condition.

Average pupil sizes of all participants at each lighting condition were determined. A formula combining the photopic and cirtopic effects for light-adapted pupil size was then derived.

3. Results

Fig. 3 shows the normalized spectra of LEDs with color temperatures of 3000 K, 4500 K and 6500 K. It is clear that with the decrease of color temperature, the proportion of blue light in the spectra decreased and that of the yellow light increased.The cirtopic action factor (a_{cv}) of luminous radiation, is an important factor corresponding to cirtopic activity, and is calculated with the following formula (Rebec & Gunde, 2014).

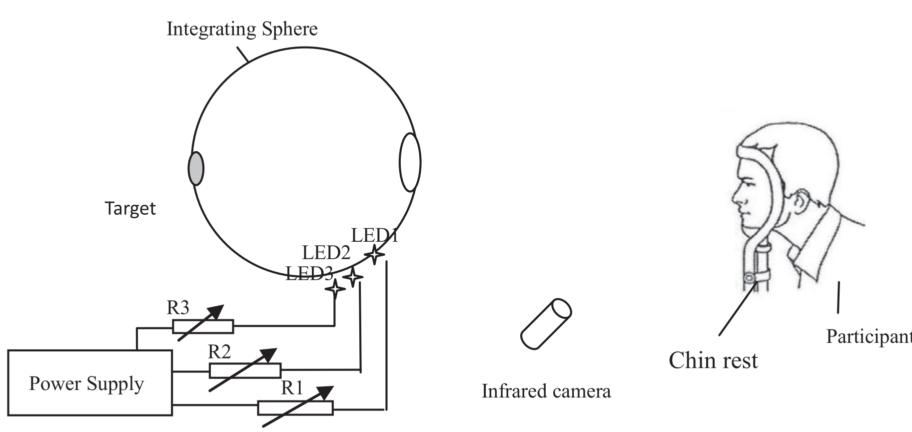

Fig. 1. Schematic diagram of the test system; LED1:3000 K, LED2:4500 K, LED3:6500 K.