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Effects of luminance and illuminance on visual fatigue and arousal during digital reading

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ABSTRACT

We investigated the conjoint effect of screen luminance and ambient illuminance on visual fatigue and arousal during prolonged digital reading (one hour) by means of a multidimensional approach based on eye, performance and subjective measures. Two levels of screen luminance (low, high) and two levels of ambient illuminance (low, high) were tested in a 2 × 2 between-subjects design in which participants were arbitrarily allocated to four groups, one for each combined level of luminance and illuminance. Results showed that reading under high levels of screen luminance increases visual fatigue, as reflected by a decrease of eye blinks. Concerning arousal, exposure to higher levels of either luminance or illuminance increased alertness and performance. Faster saccades, increased reading speed and less microsaccades were found under high screen luminance. Fewer regressive saccades and shorter reaction times were observed under high ambient illuminance. However, the reason why some of these measures are sensitive to screen luminance while other to ambient illuminance remains unknown. These findings might have practical implications for the implementation of adaptive brightness solutions and for the online detection of both visual fatigue and arousal levels during digital reading.

1. Introduction

Computers have revolutionized the world in many ways, and will continue to do so in the future. Computer workstations are usually made by a central unit and several peripheral devices. While human inputs are usually performed with keyboard and mouse, computer outputs take place on electronic visual displays (EVD). Nowadays, EVDs are no longer restricted to desktop computers but are everywhere. Many studies have been conducted to address questions concerning safety and health for EVDs' users, and it has been shown that eye-related symptoms are the most frequently occurring problems (Blehm, Vishnu, Khattak, Mitra, & Yee, 2005; Dillon & Emurian 1995; Dillon & Emurian 1996; Rosenfield, 2011; Sheedy, 1992; Sheedy & Parsons, 1990). These symptoms can be assimilated to a larger concept called visual fatigue (sometimes referred to as asthenopia or eye strain), which has been classified by the World Health Organization (WHO) as a subjective visual disturbance (ICD-10, H53.1), manifested by a high degree of visual discomfort typically occurring after prolonged visual activity, and characterized by fatigue, pain around the eyes, blurred vision or headache. Usually, visual fatigue results from visual inefficiencies or from eye-related symptoms caused by a combination of individual visual anomalies and poor visual ergonomics (Gangamma & Rajagopala, 2010). According to the American Optometric Association, when these symptoms are associated to the use of computers, we should refer to computer vision syndrome (CVS). In this paper – in order to avoid confusion – we prefer to use the expression *visual fatigue* rather than the acronym *CVS*. According to Sheedy, Hayes, and Engle (2003) two broad categories of visual fatigue symptoms can be identified, i.e. internal and external. Internal symptoms are commonly caused by refractive, accommodative or vergence individual anomalies. External symptoms are attributable to dry eye (also known as keratoconjunctivitis sicca, or xerophthalmia), an eye disease caused by either decreased tear production or reduced blinking, which in turn increases tear film evaporation (Tsubota & Nakamori, 1993). According to a large body of literature an increase of light intensity is usually associated with dry eye, which can easily detected by observing changes in eye blink rate (for a review see Rosenfield, 2011). While the study of

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internal symptomatology refers to clinical populations, the study of external symptoms usually adverts to normal populations. In this respect, our investigation focuses on the latter. An important element in the design of EVDs seems to be the effect of light intensity on arousal – the psycho-physiological state of being awake or reactive to stimuli – that involves the activation of the reticular activating system, the autonomic nervous system and the endocrine system. Many studies have shown that exposure to higher levels of light intensity can result in increased alertness and better performance (Badia, Myers, Boecker, Culpepper, & Harsh, 1991; Cajochen, Zeitzer, Czeisler, & Dijk, 2000; Campbell & Dawson, 1990; de Kort & Smolders, 2010; Gifford, Hine, & Veitch, 1997; Lowden, Åkerstedt, & Wibom, 2004; Myers & Badia, 1993; Partonen & Lönnqvist, 2000; Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003; Rüger, Gordijn, Beersma, de Vries, & Daan, 2006; Smolders, de Kort, & Cluitmans, 2012).

From the review of the existing literature and ISO standards, two factors – i.e. screen luminance and ambient illuminance – seem to mostly influence visual fatigue and arousal when interacting with EVD (Blehm et al., 2005; ISO 9241-303, 2011; Rosenfield, 2011). In this study we refer to luminance – measured in candelas per square meter (cd/m^2) – as the amount of light emitted by a display, and to illuminance – measured in lux (lx) – as the incident light on a surface. In our measurement conditions, the surface corresponds to participants' eyes (see Section 2). As to screen luminance, both performance (e.g. reading speed, search accuracy) and visual fatigue increase as the level of luminance rises (Chang, Chou, & Shieh, 2013; Lee, Ko, Shen, & Chao, 2011; Rosenfield, 2011). Such a direct relationship leads to a forced compromise where these elements should coexist. In this respect several recommendations can be found. For example, ISO 9241-303 (2011) recommends that the luminance emitted by the screen be in the range of 100–150 cd/m^2, when the horizontal illuminance is 500 lx. With regard to ambient illumination, its choice greatly depends upon the task (Helander & Rupp, 1984), and many recommendations exist within both the scientific literature and ISO standards (ISO 9241-303, 2011). For cathode ray tube (CRT) and liquid crystal display (LCD) workstations, an ambient lighting of 200–500 lx is generally suggested. Higher levels of ambient illumination can wash out the images on the screen and possibly cause glares that interfere with visual tasks, impairing performance and increasing visual fatigue (Chen & Lin, 2004; ISO 9241-303, 2011; Shieh & Lin, 2000; Xu & Zhu, 1990). Unfortunately, none of the aforementioned studies and standards provides information about the ideal amount of light – i.e. luminance and illuminance – that should impact on participants' eyes, leaving some sort of missing perspective of the real influence of such levels of light during a specific task. The literature on this topic is rather focused on the light emitted by the light source, which makes these recommendations quite limited and not completely applicable to real situations. In such a framework, the aim of our intervention is to study the conjoint impact of luminance and illuminance on visual fatigue and arousal during prolonged digital reading (Baccino, 2004; Dillon, 1992) using a multidimensional approach based on eye, performance and subjective measures. To this end, two levels of screen luminance (low and high) and two levels of ambient illuminance (low and high) were tested in a 2 × 2 between-subjects design.

2. Materials and methods

2.1. Participants

Fifty participants (33 females, mean age = 27 years, SD = 7) took part in the experiment and gave written informed consent before participation. Two participants over fifty were rejected from all the analyses because of poor recording quality. Forty-eight participants were then allocated to four equinumerous groups, one for each combined level of luminance and illuminance. All of them were naïve as to the aims and the expected outcomes of the experiment, and had normal or corrected-to-normal vision, as assessed by automatic visual displaying test (Ergovision; www.essilor.com). The study was performed in keeping with the declaration of Helsinki. A financial compensation (10 €) was offered to participants.

2.2. Apparatus

Eye movements were recorded with an infrared video-based eye tracker (SMI RED 5; www.smivision.com). Sampling rate was set to 250 Hz, and a 9-point calibration was made for each participant at the beginning of each reading trial. The whole experiment was carried out under constant artificial illumination, as assessed by an Extech 403,125 digital light meter (www.extech.com) pointed toward the screen and placed 5 cm above participants' head and laterally centered with respect to their head. The average distance between participants and the 22″ LCD stimulus screen (Dell P2210; www.dell.com) was 60 cm. A picture of the experimental setting is provided in Fig. 1.

2.3. Stimuli

Screen luminance and ambient illuminance were chosen as independent variables. Two levels of screen luminance (*Low*; *High*) and two levels of ambient illuminance (*Low*; *High*) were selected. As to luminance, contrast ratios were calculated according to the Michelson definition of contrast (Michelson, 1927): [$C = (L_{max} - L_{min})/(L_{max} + L_{min})$] where C = contrast, L_{max} = maximal luminance, L_{min} = minimal luminance. By means of a digital luminance meter for contact measurements (Mavo-Monitor; www.gossen-photo.de), we measured luminance for black (L_{min}) and white (L_{max}) screen for the two experimental conditions (*Low*, *High*). For screen luminance, contrast ratios were as follows:

Low: $C = 0.998$ (L_{max}: 20 cd/m^2; L_{min}: 0.02 cd/m^2).
High: $C = 0.997$ (L_{max}: 140 cd/m^2; L_{min}: 0.2 cd/m^2).

As to illuminance, we measured *screen off* the amount of light that impacted on participants' eyes for the two levels of ambient illuminance:

Low: 5 lx.
High: 85 lx.

The same measurement was also taken *screen on* using a random page of the novel employed in the experiment. The total

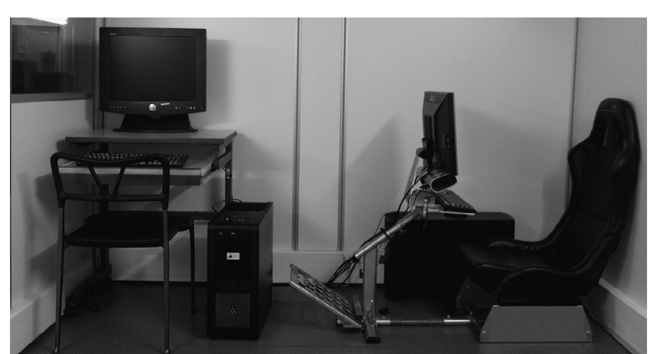

Fig. 1. Experimental setting. On the right-hand side, participants' seat with stimulus screen and embedded eye-tracker. On the left-hand side, experimenter's seat with eye-tracker control workstation.