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

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A R T I C L E I N F O

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A B S T R A C T

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

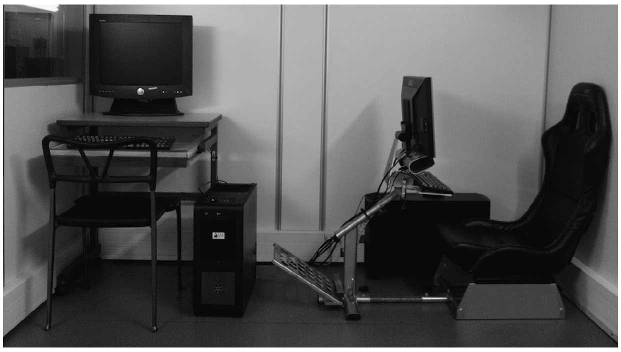

Fig. 1. Experimental setting. On the right-hand side, participants' seat with stimulus screen and embedded eye-tracker. On the left-hand side, experimenter's seat with eye-tracker control workstation.

amounts of light that impacted on participants' eyes for the combined levels of screen luminance and ambient illuminance are specified in Table 1.

Ambient lighting was provided by four TL 84 fluorescent lamps. TL 84 lamps are characterized by high amounts of green energy, with a color temperature of approximately 4000 K.

2.4. Experimental design and procedure

A 2 × 2 between-subjects design, where participants were randomly assigned to four experimental conditions (one for each combined level of luminance and illuminance), was employed. Text material was a novel in French language (Maupassant, 2004), the mother tongue of all participants. The test was performed in a controlled experimental room at CHART/LUTIN – Paris (www.lutin-userlab.fr). After having been explained the basic principles of the experiment, participants signed an informed consent, performed a visual screening test aimed at quantifying some basic visual functions, and filled in a subjective visual fatigue scale (VFS – Heuer, Hollendiek, Kröger, & Römer, 1989). Next, they sat on a comfortable chair at a fixed distance of approximately 60 cm from the screen, and the eye tracker was calibrated. They were then required to silently read the novel for one hour with one of the randomly assigned screen brightness and ambient illuminance levels, while their eye movements were recorded. During the reading session they were also asked to perform an auditory reaction time test (beep-task), which consisted of clicking the left button of a computer mouse as soon as a beep sound was heard (beep-task). At the end of each reading session, participants performed a memory awareness test (R/K – Tulving, 1985), underwent for the second time the VFS and finally a comprehension test (Benedetto, Drai-Zerbib, Pedrotti, Tissier, & Baccino, 2013). A schematic representation of the procedure is provided in Fig. 2.

2.5. Dependent variables

The multidimensional approach based on eye, performance, and subjective measures includes two groups of variables selected according to their sensitivity and reliability in detecting changes in visual fatigue (eye blinks, visual fatigue scale) and arousal (fixations, saccades, pupil diameter, microsaccades, reaction time, reading speed), and one variable aimed at verifying the nature and quality of the recall (R/K test).

2.5.1. Eye blinks

The quick closing and reopening of the eyelid, i.e. eye blink, is a well-known indicator of both visual fatigue (Benedetto et al. 2013) and drowsiness (Schleicher, Galley, Briest, & Galley, 2008). As to visual fatigue, a large body of literature suggests that blinks decrease when luminance increases; such a reduction contributes to a poor tear film quality and temporary stresses the cornea, causing dry eye (for a review see Blehm et al., 2005; Rosenfield, 2011). To verify this hypothesis, we calculated the blink rate (BR) as the number of eye blink events that take place in each experimental run. Blinks lasting less than 80 ms and more than 500 ms were excluded from the analysis (Benedetto Pedrotti, Minin, Baccino, Re & Montanari, 2011). As to drowsiness, eyelid closures longer than 500 ms were defined as microsleep episodes. The rate of microsleep (MSR) was defined as the number of microsleep events that take place in each experimental run (Wang, Toor, Gautam, & Henson, 2011).

Table 1
The total amounts of light that impacted on participants' eyes for the combined levels of screen luminance (low, high) and ambient illuminance (low, high).

		Screen Luminance (cd/m^2)	
		Low (20 cd/m^2)	High (140 cd/m^2)
Ambient Illuminance (lx)	Low (5 lx)	10 lx	40 lx
	High (85 lx)	90 lx	120 lx

2.5.2. Fixations

Fixation is the maintaining of the gaze on a single location. It has been shown that physical characteristics such as contrast font characteristics and resolution have an influence on both fixation duration and rate (Just & Carpenter, 1980; Rayner, 1998, 2009; Reingold & Rayner, 2006; Ziefle, 1998). According to Siegenthaler, Wurtz, Bergamin, and Groner (2011), fixations can be used as a measure of legibility, where longer fixations might indicate issues in extracting visual and/or linguistic information (i.e. reduced legibility). However, if we consider fixations as a reading performance measure (Rayner, 1998), they might also reflect changes in the levels of arousal. Fixation rate (FR) was defined as the number of fixations that take place in each experimental run, whereas fixation duration (FD) as the average duration (ms) of fixations occurring in each experimental run.

2.5.3. Saccades

Saccades are fast eye movements occurring between fixations. In reading, three types of saccades are relevant: (a) progressive, i.e. saccades in the direction of the text, (b) regressive, i.e. saccades opposite to the direction of the text, (c) line return sweeps, connecting the end of a line with the beginning of the next one. Regressive saccades are backward moves within a line, produced to re-examine material not clearly perceived or understood (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981). Regressive saccades depend on text difficulty, on readers' skills, and on the physical characteristics of the text (Rayner, 2009; Siegenthaler et al., 2011). Usually, an increase in regressive saccades indicates reduced legibility (Javal, Ciuffreda, & Bassil, 1990; Tinker, 1958), but it might also indicate low levels of arousal. Regressive saccade rate (RSR) was defined as the number of regressive saccades that take place in each experimental trial.

Recent studies suggest saccadic velocity to be a good indicator of arousal, with increased speed as arousal or activation increases (Di Stasi, Catena, Cañas, Macknik, & Martinez-Conde, 2013; Di Stasi, Marchitto, Antolí, Baccino, & Cañas, 2010). Saccadic velocity (SV) was defined as the average velocity of saccades (°/s) occurring in each experimental run.

2.5.4. Microsaccades

Microsaccades are involuntary saccade-like fixational eye movements (Ratliff & Riggs, 1950) typically occurring at rates of one to two per second, and having amplitudes that are usually smaller than 1° of visual angle. While saccades alternate with fixations, microsaccades occur within fixations. Lower microsaccade rates are usually associated with increased levels of arousal (Benedetto, Pedrotti, Bridgeman, 2011; Betta & Turatto, 2006; Engbert & Mergenthaler, 2006; Honda, Kohama, Tanaka, & Yoshida, 2013; Martinez-Conde, Macknik, Troncoso, & Dyar, 2006). Microsaccades were defined in our data set as main-sequence binocular events having amplitudes of 1° or less and velocity of 100°/s or less. Binocular microsaccades correspond to left and right saccadic events whose onsets occur within a four-millisecond window. According to Otero-Millan, Troncoso, Macknik, et al. (2008) microsaccade rate (MR) was calculated taking into account only the time spent in binocular fixation: the total number of microsaccades for each trial was hence divided by the total time spent fixating during that trial.

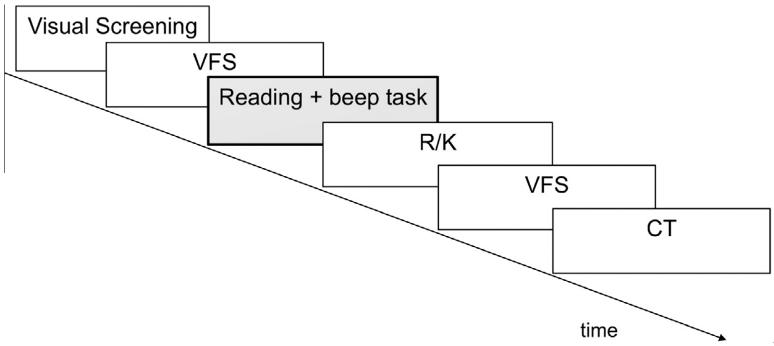

Fig. 2. Experimental procedure.

2.5.5. Pupil diameter

The human pupil primarily constricts as light intensity increases, and dilates for opposite reasons (Beatty, 1982; Beatty & Lucero-Wagoner, 2000; Loewenfeld & Lowenstein, 1993). At the same time pupil fluctuations indicate changes of arousal level, namely reduced sizes as arousal decreases. These fluctuations are very characteristic for sleepiness (Honda et al., 2013; Lowenstein, Feinberg, & Loewenfeld, 1963; Newman & Broughton, 1991; Wilhelm, Giedke, Lüdtke, et al., 2001; Schmidt & Fortin 1982; Yoss, Moyer, & Hollenhorst, 1970). With the aim of verifying the effects of the manipulation of luminance and illuminance on pupil diameter, the average pupil diameter (PD) – i.e. the mean of all pupil diameter values (mm) collected during each trial – was employed. Concerning pupil fluctuation over time, average pupil diameter data were broken down into 12 time-blocks of 5 min each for analysis against time. A linear regression coefficient (RC-PD) was then calculated for each participant on the 12 pupil diameter values. A negative RC-PD would be indicative of reduced PD as time spent reading increases, possibly indicating a decrease in the level of arousal.

2.5.6. Reading speed

Reading speed (RS) – i.e. the number of read words per minute (wpm) – has been largely employed for comparing paper reading and digital reading (for a review see Dillon, 1992), and for evaluating different types of displays (Siegenthaler, Bochud, Bergamin, & Wurtz, 2012; Siegenthaler, Wurtz, & Groner, 2010). It is generally recognized that higher luminance contrasts (perhaps leading to higher levels of arousal) enhance legibility and reading speed (Knoblauch, Arditi, & Szlyka, 1991; Legge, Parish, Luebker, & Wurm, 1990; Legge & Rubin, 1986).

2.5.7. Reaction time (beep-task)

During reading, participants were asked to perform a concurrent beep-task, which consisted of 20 auditory stimuli, appearing every 3 ± 1 min within the whole reading session. Since it is well known that reaction times associated to beep-tasks are affected either by internal (i.e. arousal) and external (number of stimulus–response) factors (for a review see Kosinski, 2008), the average reaction time (RT) was calculated as the average of the 20 reaction times. The beep-task was used as a measure of changes in attention during reading.

2.5.8. Memory awareness (R/K test)

At the end of each reading session, participants were also asked to complete a tailor-made version of the Remember/Know test (R/K – Tulving, 1985), a largely employed tool for gauging the nature and quality of recall and – by implication – learning. The R/K test is based on two main types of retrieval response, namely "Remember" and "Know". While the recollection of episodic details (R) belongs to episodic memory, the familiarity in the absence of recollection (K) refers to semantic memory. Garland and Noyes (2004) suggested that the cognitive processing taking place when learning from EVDs and paper is different, mainly because the characteristics of the computer screen might interfere with cognitive processing for long-term memory, causing a larger employ of episodic memory. To this end thirty words – of which only fifteen effectively appeared in the text – were selected. The proportion of recognized items (R/K) was calculated as the ratio between the recognized items (either R or K) and the number of words that really appeared in the text (i.e. 15). These words were chosen according to three main criteria, i.e. one-single presentation in the text, no proper names, and homogeneous distribution within the text.

2.5.9. Visual fatigue scale

A six-item rating scale of visual fatigue (VFS – Heuer et al., 1989) was administered before and after each reading session. Each item was rated on a 10-point Likert scale and an average VFS score on the six items was computed.

3. Results

The significance level α was set at .05 for all statistical analyses. Dependent variables (DVs) were firstly analyzed with a multivariate analysis of variance (MANOVA) where luminance and illuminance were used as categorical predictors. Univariate results were also provided for each of the DVs. Means and standard deviations for each of the dependent variables are reported in Table 2. Correlation matrix is provided in Table 3. The first requirement for proceeding further into the analysis was to make sure that participants had effectively read and understood the book. The absence of wrong answers to the comprehension test (CT) validated this prerequisite.

As to luminance, a main effect was found (*Wilks'* $\lambda = .29$, $F(12, 33) = 6.72$, $p < .001$). Univariate results revealed increased frequencies of eye blinks (BR – $F(1,44) = 13.79$, $p < .001$, $\eta^2_p = .24$, Fig. 3), fixations (FR – $F(1,44) = 4.88$, $p < .05$, $\eta^2_p = .10$, Fig. 3), and microsaccades (MR – $F(1,44) = 6.15$, $p < .05$, $\eta^2_p = .12$, Fig. 3), and larger pupil diameters (PD – $F(1,44) = 47.29$, $p < .001$, $\eta^2_p = .52$, Fig. 3) under low screen luminance. At the same time results revealed faster reading times (RS – $F(1,44) = 9.65$, $p < .005$, $\eta^2_p = .18$, Fig. 3) and saccades (SV – $F(1,44) = 9.05$, $p < .005$, $\eta^2_p = .17$, Fig. 3), and flatter slopes of pupil diameter regression coefficient (RC-PD – $F(1,44) = 8.97$, $p < .005$, $\eta^2_p = .17$, Fig. 3) under high screen luminance.

As to illuminance, a main effect was found (*Wilks'* $\lambda = .38$, $F(12, 33) = 4.38$, $p < .001$). Univariate results revealed increased

Table 2
Means and standard deviations (italic) for each of the dependent variables and experimental conditions.

Dependent variables		Independent variables			
		Screen luminance High / Ambient illuminance High	Screen luminance High / Ambient illuminance Low	Screen luminance Low / Ambient illuminance High	Screen luminance Low / Ambient illuminance Low
BR		86 (*64*)	77 (*35*)	297 (*247*)	167 (*108*)
MSR		9 (*7*)	6 (*3*)	9 (*6*)	14 (*13*)
FR		2460 (*354*)	2245 (*368*)	2485 (*370*)	2736 (*493*)
FD (ms)		227 (*26*)	215 (*21*)	212 (*4*)	238 (*31*)
SV (°/s)		96 (*9*)	93 (*2*)	88 (*11*)	86 (*10*)
RSR		411 (*150*)	442 (*118*)	406 (*117*)	583 (*200*)
MR		0.41 (*0.09*)	0.40 (*0.14*)	0.46 (*0.13*)	0.61 (*0.27*)
PD (mm)		3.03 (*0.32*)	3.33 (*0.35*)	3.94 (*0.62*)	4.24 (*0.47*)
RC-PD		−0.008 (*0.008*)	−0.005 (*0.01*)	−0.022 (*0.017*)	−0.019 (*0.022*)
RS (wpm)		256 (*61*)	275 (*59*)	228 (*59*)	202 (*47*)
RT (ms)		1090 (*101*)	1202 (*99*)	1092 (*84*)	1166 (*53*)
R/K (%)	R	39 (*20*)	39 (*12*)	33 (*18*)	35 (*12*)
	K	16 (*15*)	19 (*10*)	15 (*6*)	16 (*9*)
VFS (1–10)	Before	1.25 (*0.32*)	1.90 (*1.03*)	2 (*1.28*)	1.74 (*0.56*)
	After	2.44 (*1.39*)	3.55 (*1.98*)	3.53 (*1.70*)	3.66 (*1.54*)

Table 3
Correlation matrix for study variables. Marked correlations (*) are significant at $p < .05$; $N = 48$.

Dependent variables	Correlations matrix								
	BR	FR	FD	SV	RSR	MR	PD	RC-PD	RS
BR									
FR	0.16								
FD	−0.20	0.09							
SV	−0.49*	−0.42*	0.01						
RSR	0.14	−0.04	0.03	−0.04					
MR	0.24	0.35*	−0.15	−0.28	0.37*				
PD	0.30*	0.23	0.09	−0.34*	0.19	0.35*			
RC-PD	−0.08	−0.50*	0.19	0.21	0.12	−0.37*	−0.21		
RS	−0.25	−0.22	−0.47*	0.39*	−0.21	−0.32*	−0.40*	0.11	
RT	0.13	−0.03	−0.25	−0.13	0.13	0.13	0.16	−0.03	−0.08

frequencies of regressive saccades (RSR – $F(1,44) = 5.68$, $p < .05$, $\eta^2_p = .11$, Fig. 3), larger pupil diameters (PD – $F(1,44) = 5.30$, $p < .05$, $\eta^2_p = .11$, Fig. 3), and longer reaction times (RT – $F(1,44) = 14.30$, $p < .001$, $\eta^2_p = .25$, Fig. 3) under low ambient illuminance.

Concerning the interaction luminance ∗ illuminance, a main effect was found (*Wilks'* $\lambda = .55$, $F(12, 33) = 2.21$, $p < .05$). Univariate results revealed a nearly-significant interaction on fixation rate (FR – $F(1,44) = 4$, $p = .05$, $\eta^2_p = .08$, Fig. 3) and a significant interaction on fixation duration (FD – $F(1,44) = 8.62$, $p < .01$, $\eta^2_p = .16$, Fig. 3). As to fixation rate, the Tukey HSD post hoc test showed that only under low ambient illuminance FR is significantly lower ($p < .05$) when the screen luminance is high ($M = 2245$; $SD = 368$) with respect to low ($M = 2736$; $SD = 493$). The Tukey HSD post hoc test on FD revealed that – only when reading with low screen luminance – the duration of fixations is significantly shorter ($p < .05$) when ambient illuminance is high ($M = 211$; $SD = 2$) with respect to low ($M = 238$; $SD = 31$).

Finally, no effects of both screen luminance and ambient illuminance were found (All *F*s n.s.) on microsleep rate (MSR), proportion of R/K (R/K), and subjective visual fatigue scale (VFS). However, other effects were found on R/K and VFS, independently from luminance and illuminance. A larger number of "R" rates with respect to "K" was observed ($Z = 4.99$, $p < .001$) on the R/K, and higher scores were found *after* reading ($Z = 5.26$, $p < .001$) with respect to *before* on the VFS.

4. Discussion

The aim of the present study was to investigate the conjoint impact of luminance and illuminance on visual fatigue and arousal during prolonged digital reading (one hour) using a multidimensional approach based on eye, performance and subjective measures. Results showed that some of these measures were sensitive to luminance, others to illuminance, and others again to specific combinations of luminance and illuminance levels. Two groups of variables were selected according to their sensitivity and reliability in detecting changes in visual fatigue and arousal, and one variable aimed at verifying the nature and quality of recall.

Concerning visual fatigue, results on BR indicated that reading under high screen luminance leads to a decrease in the frequency of blinks with respect to low screen luminance. This result is in line with a large number of studies (for a review see Rosenfield, 2011) wherein higher levels of light intensity are usually associated with a decreased frequency of blinking and an increased rate of tear evaporation, each of which contributes to dry eyes, one of the main factors for visual fatigue (Benedetto et al., 2013). Results on VFS revealed that subjective visual fatigue significantly increased after reading. However, no effects of either luminance or illuminance were found. This absence of effects is in line with previous studies that employed this measure for quite similar purposes (e.g. Buchner & Baumgartner, 2007; Lee et al., 2011). Furthermore, it

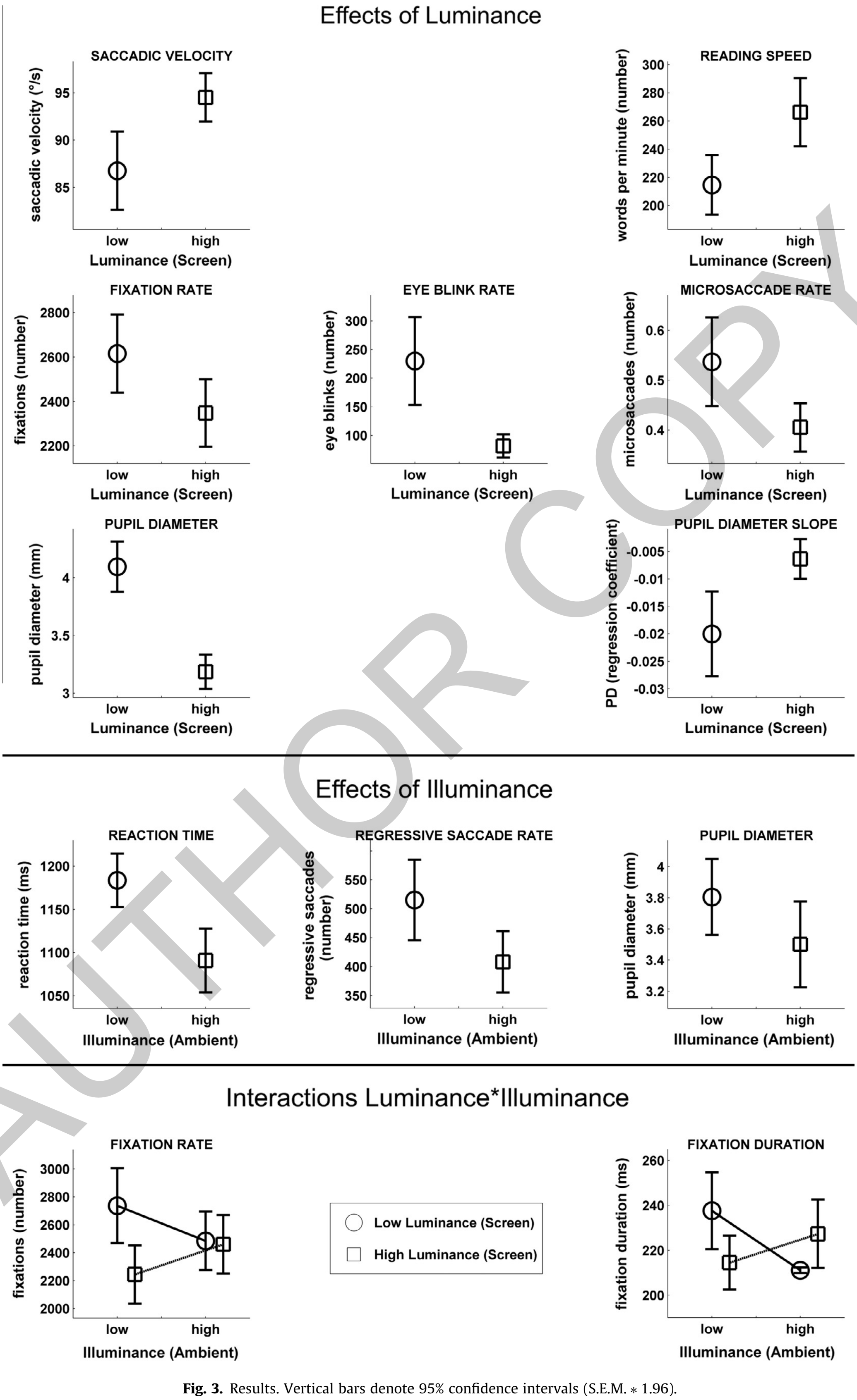

Fig. 3. Results. Vertical bars denote 95% confidence intervals (S.E.M. ∗ 1.96).

is interesting to notice that the highest difference between the measurements taken before and after (net score) occurs under low screen luminance and low ambient illuminance. This effect might be related to the fact that people usually give positive connotation to brighter stimuli, and bad connotation to darker ones (Meier, Robinson, & Clore, 2004).

Regarding arousal, results revealed some of the measures to be sensitive to screen luminance while other to ambient illuminance. Although many studies have shown that exposure to lower levels of light intensity can result in decreased alertness and performance (see Section 1), none of them made a clear distinction between screen luminance and ambient illuminance, nor explored their conjoint effect on visual fatigue and arousal during digital reading. Hence, the reason why some of the measures employed in our experiment respond to luminance while other to illuminance remains unknown.

As to the effects of screen luminance on arousal, slower saccade velocities (SV) were found under low screen luminance, thus confirming previous studies employing this measure for studying arousal (e.g. Di Stasi et al., 2013). Similarly, results on microsaccade rate (MR) showed an increase under low screen luminance. This result is in line with a quite large body of literature that associates higher microsaccade rates with decreased levels of arousal (Betta & Turatto, 2006; Engbert & Mergenthaler, 2006; Honda et al., 2013; Martinez-Conde et al., 2006). Consistent with the hypothesis that lower luminance contrasts (perhaps leading to lower levels of arousal) reduce legibility and reading speed (Knoblauch et al., 1991; Legge & Rubin, 1986; Legge et al., 1990), lower reading speed (RS) was found under low screen luminance.

Concerning the effects of ambient illuminance on arousal, we found that reading under low ambient illuminance leads to an increase in the frequency of regressive saccades. Being saccades strongly connected to fixations, the interaction luminance $*$ illuminance revealed that under low ambient illuminance and low screen luminance fixations are longer (FD) and more frequent (FR). Finally, longer reaction times to the beep task (RT) were found under low ambient illuminance, thus confirming that exposure to lower levels of light intensity can result in decreased performance (for a review see Section 1).

The pupil diameter values resulting from our measurements confirmed the effective manipulation of light intensity: pupil diameter appeared to be mainly influenced by screen luminance (1 mm roughly) with respect to ambient illuminance (0.4 mm roughly), possibly because that light source (screen) was closer to participants' eyes, and also more intense. Concerning the evolution of pupil diameter over time, results confirmed earlier outcomes showing that reductions of arousal level can be associated with decreases of activity of the sympathetic nervous system which in turn makes the pupil diameter smaller (e.g. Wilhelm et al., 2001). Smaller and smaller pupil diameters were found as the time spent reading went on, as confirmed by the negative regression coefficients of average pupil diameter. As expected, the coefficients were lower under low luminance (−.02 roughly) with respect to high luminance (−.005), suggesting a steeper decrease in the level of arousal when the light is dim.

As to and the nature and quality of the recall and – by implication – learning, the R/K test showed no effects of both screen luminance and ambient illuminance. Nevertheless, a larger employ of episodic memory (reflected by a larger number of R frequencies, as opposed to K ones) was observed when reading from EVD. This result is in line with Garland and Noyes (2004), who suggested that the cognitive processing taking place when learning from EVDs and paper is different. According to these authors the characteristics of the computer screen (refresh rate, high levels of contrast and fluctuating luminance) might interfere with cognitive processing for long-term memory.

In conclusion, results showed a concurrent increase of both visual fatigue and arousal under high screen luminance. While an upsurge in visual fatigue – reflected by a reduction of the number of eye blinks – might be a bad news for our eyes, the rise of arousal – reflected by improved reading performance – has a quite good connotation. For example, the fact that participants showed faster reading times under high screen luminance without impairing comprehension is definitely good news. A thought-provoking finding, for which unfortunately we still do not have any explanation, concerns the effect of the light source (either screen or ambient) on arousal. Some of the measures employed in this experiment were found to be sensitive to screen luminance (saccade velocity, microsaccade rate, PD regression coefficient, reading speed) while other to ambient illuminance (regressive saccade rate, reaction time): future studies should examine the underlying reasons in depth. Many recommendations can be found in the literature regarding the optimal levels of ambient illuminance. In turn, the information regarding screen luminance as well as the interaction between luminance and illuminance is quite limited if not even missing. The results of this study provide an initial perspective on such an unexplored topic, which might have potential applications in real-world settings such as schools, workplaces and homes. For example, applications might involve the implementation of more efficient automatic solutions for adjusting both screen luminance and ambient illuminance, thus preventing visual fatigue, increasing performance while optimizing power consumption.

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