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Short-term effects of text-background color combinations on the dynamics of the accommodative response

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ABSTRACT

The purpose of the present study was to assess the accommodative response and pupillary dynamics while reading passages with different text-background color combinations on an LCD screen. Twenty healthy young adults read fourteen 2-min passages designed with fourteen different color combinations between text and background, while the accommodative and pupil responses were continuously measured with a binocular open-field autorefractometer. Our results revealed that the text-background color combination modulates the accommodative and pupillary dynamics during a 2-minutes reading task. The blue-red combination induced a heightened accommodative response, whereas positive polarities were associated with more variability of the accommodative response and smaller pupil sizes. Participants reported lower perceived ratings of legibility for text-background color combination with lower luminance contrast (white-yellow). The manipulation of text-background color did not have a significant effect on reading speed. These results may have important applications in the design of digital visual interfaces.

1. Introduction

The emergence of new technologies in the area of information and communication has radically changed the social interaction, communication and behaviour habits worldwide (Misra, Cheng, Genevie, & Yuan, 2016). Despite the numerous advantages that they offer to modern society, there are also some potential negative effects on peoplés physical, cognitive, emotional, and social wellbeing (Guedes, Sancassiani, Carta, Campos, Machado, King, & Nardi, 2016; Gutiïerrez, de Fonseca, & Rubio, 2016; Kuss et al., 2018). Notably, the use of electronic visual displays causes a wide range of visual symptoms such as blurred vision, eye strain, irritation, burning and dry eye sensation, redness, headache and double vision (Hayes, Sheedy, Stelmack, & Heaney, 2007; Sheppard & Wolffsohn, 2018), which are commonly termed as computer vision syndrome (Rosenfield, 2016).

Leaving aside the functional visual anomalies (e.g., refractive error, accommodative or binocular anomalies) as possible causes of visual discomfort in computer users (Gowrisankaran & Sheedy, 2015), numerous researches have sought to elucidate whether these visual symptoms and signs are mostly due to prolonged near work with electronic devices (Portello, Rosenfield, Bababekova, Estrada, & Leon, 2012), reduced viewing distances (Rempel, Willms, Anshel, Jaschinski, & Sheedy, 2007; Rosenfield, 2011), inadequate lighting (Sheedy, Subbaram, Zimmerman, & Hayes, 2005), technical characteristics of the screen or readability of the text displayed on the screen (see review Gowrisankaran & Sheedy, 2015).

The text-background color combination constitutes a usual and effective resource to draw the attention of the users on websites and social networks, since the desired impact of the message is highly dependent on its visibility and legibility (Hall & Hanna, 2004; Humar, Gradisar, Turk, & Erjavec, 2014). An inappropriate choice of color may result in poor visual performance and a higher incidence of eye strain (Lawoyin, Fei, Bai, & Liu, 2015; Luria, Neri, & Schlichting, 1989; Matthews, 1987; Shieh & Chen, 1997), affecting even cognitive performance (Bhattacharyya, Chowdhury, Chatterjee, Pal, & Majumdar, 2014). In this sense, luminance contrast ratio (i.e., the luminance ratio between stimulus and background), polarity (i.e., dark or light text on dark or light background) and chromaticity contrast (i.e., difference between background and stimulus colors with the same luminance) are considered as the most relevant factors that may alter the visibility and legibility of multichromatic stimuli (Shieh and Lin, 2000; Wang & Chen, 2000)

It is well-known that the accommodative response is sensitive to the chromatic components of the stimulus (Rucker & Kruger, 2004, 2006),

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and also, there is evidence that longitudinal chromatic aberration provides directional information to the accommodation control system (Lee, Stark, Cohen, & Kruger, 1999). As stated by Atchison, Strang, and Stark (2004), the impact of color combination on the accommodative response will occur especially when the two colors are sufficiently saturated and the dioptric interval between their dominant wavelengths was larger than the eye's depth of focus. Also, changes in pupil size affect the magnitude of specific ocular aberrations and the depth of focus, which have a predominant effect on retinal image quality (Artal & Navarro, 1994; B. Wang & Ciuffreda, 2006). The role of ocular aberrations on retinal image quality becomes negligible for pupil diameters lower than 2–3 mm, when the retinal image is diffraction-limited (Howland & Howland, 1977; Thibos, Hong, Bradley, & Cheng, 2002). Regarding the association between pupil size and accommodative response, it should be noted that a reduction in the accommodative response only occurs with pupil diameters lower than 3 mm (Ward & Charman, 1985). There are studies that have shown that greater luminance and positive polarity (dark text on light background), which reduce pupil size, lead to a sharper retinal image and better perception of details, and therefore a higher preference for these type of stimuli has been established (Buchner & Baumgartner, 2007; Piepenbrock, Mayr, Mund, & Buchner, 2013). As indicated by Piepenbrock, Mayr, and Buchner (2014), pupillary constriction would permit better reading performance, and hence, bright positive polarity displays are recommended. There are multiple factors that play an important role on the pupillary response, including light, target size and distance, apparent lateral or vertical displacement, fusional vergence, or stimulus contrast among others (Kasthurirangan & Glasser, 2006; Myers, Barez, Krenz, & Stark, 1990; Phillips, Winn, & Gilmartin, 1992; Wang & Munoz, 2014). Notably, there is scientific evidence that the pupil dynamics is sensitive to chromatic stimuli, with color signals inducing a greater pupillary response than luminance signals (Tsujimura, Wolffsohn, & Gilmartin, 2006; Tsujimura, Wolffsohn, & Gilmartin, 2001).

Most of the studies that have assessed the effects of text-background color combinations in computer users have been based on subjective responses by using different questionnaires and rating scales, or by recording the reading speed (Hall & Hanna, 2004; Humar et al., 2014; Shieh and Lin, 2000; Wang & Chen, 2000). However, the short-term effects of color combinations on ocular accommodation and pupillary dynamics remain unknown. In this study, we aimed (1) to assess the effect of different text-background color combinations on the magnitude and variability of the accommodative response, and (2) to explore the impact of different text-background color combinations on the pupillary dynamics (magnitude and variability). Complementarily, we tested the effects of manipulating the text-background color on subjective ratings of perceived legibility and reading speed. For this purpose, accommodative response was objectively monitored by a binocular open-field autorefractometer, while participants read text passages with different text-background color combinations on an LCD visual display terminal. Additionally, subjective perceptions of legibility and reading speed were also recorded after each task. Specifically, we hypothesized that (1) those color combinations with more longitudinal chromatic aberration demand (larger difference in refractive error between their dominant wavelengths) will destabilize the neural mechanisms driving accommodation and they will alter the magnitude and variability of accommodative response during reading (Atchison et al., 2004), and (2) similarly, these color combinations as well as those with lower luminance contrast will reflect a lower subjective preference and worst recording of reading speed (Shieh and Lin, 2000).

2. Methods

2.1. Participants and ethical approval

Twenty healthy young adults (13 women; average age [mean ± standard deviation]: 24.5 ± 3.3 years; refractive error: −0.11 ± 1.31 D) participated in this study. The experimental sample was formed by eight myopes (mean spherical equivalent > −0.50 D, maximum value −2.00 D), six hyperopes (mean spherical equivalent > +0.75 D, maximum value +1.75 D), and six emmetropes (mean spherical equivalent between −0.50 D and +0.75 D). At the initial visit, all participants were required to pass an optometric evaluation in order to discard any visual symptomatology or sign that could affect to the experimental measurements. The inclusion criteria were:

a. Not suffering any systemic disease or being under pharmacological treatment.
b. No history of refractive surgery, orthokeratology, strabismus or amblyopia.
c. Normal or corrected-to-normal visual acuity, using an endpoint criterion of maximum plus consistent with best vision, of ≤0.00 log MAR in each eye. All participants were optically corrected with soft contact lenses when necessary, and they had at least one year of experience using contact lenses. The refractive power was lower or equal than 2 D and 0.75 D for the spherical and astigmatic components respectively.
d. Not presenting color vision deficiency as assessed by the Ishihara plates (Ishihara 2013, second edition, Handaya, Tokyo, Japan).
e. Have stereoacuity ≤50 s arc at 40 cm with the Randot stereotest (Scheiman & Wick, 2008).
f. Have an amplitude of accommodation (push-up method with accommodative target) within the normal range using the Hofstetter's equation (Hofstetter, 1950).
g. Present an accommodative lag within the normal range at 20 cm (lower than 1.55 D) (Wang & Ciuffreda, 2004), as measured in binocular conditions with the WAM-5500 autorefractometer.
h. Have a near point of convergence ≤7 cm using the push-up method with accommodative target (Scheiman & Wick, 2008).
i. Be free of symptomatology related to visual discomfort based on the scores of the Conlon visual discomfort survey (Conlon, Lovegrove, Chekaluk, & Pattison, 1999).
j. Below to the asymptomatic group of convergence insufficiency according to the Convergence Insufficiency Symptom Survey (Borsting et al., 2003).

Also, participants were asked to abstain from alcohol-based beverages for 24 h, and to get at least 7 h of sleep before each experimental session. This study followed the recommendations of the Declaration of Helsinki, was approved by the University Institutional Review Board (438/CEIH/2017).

2.2. Experimental conditions

This study examined the accommodative response behaviour and pupillary dynamics while participants read a 2-min text passage displayed on an LCD screen at a viewing distance of 50 cm, and under fourteen text-background color combinations. The 50 cm distance was based on the study of Shieh and Lee (2007), who found that the preferred viewing distance for electronic paper displays and visual display terminals was ~50 cm. For the experiment we choose six colors from a number of suitable colors from a non-dithering color palette: 1) white, 2) black, 3) yellow, 4) blue, 5) green, and 6) red (Lehn & Stern, 2000), which were detailed with RGB triplets, chromaticity coordinates (x, y), and luminance (L) (Ohta & Robertson, 2006) (Table 1).

The radiance spectra of the six color stimuli were measured using a

Table 1
CIE L*a*b* and x y chromaticity coordinates, luminance (L), hue (H), saturation (S), and dominant wavelength (λ_d) of the six colors used in this study.

Color	White	Blue	Green	Yellow	Red	Black
L*	57.16	22.60	45.72	53.28	28.84	5.73
a*	−13.59	5.36	−56.83	−19.34	40.53	−0.14
b*	12.68	−39.35	45.66	56.06	40.80	4.14
x	0.34	0.18	0.29	0.42	0.62	0.39
y	0.38	0.16	0.60	0.51	0.35	0.39
L (cd/m^2)	160.21	23.54	96.21	136.05	36.90	4.05
H	106.24	210.71	127.75	66.31	14.51	43.60
S	0.2	1	1	0.94	0.99	0.49
λ_d (nm)	555.5	475.6	544.4	567.6	602.5	575.7

Table 2
Luminance contrast, CIEDE 2000 color difference, and chromatic difference of refraction of the fourteen color combinations used in the study.

Text/background	Luminance contrast	ΔE00	R_E (D)
Black/White (K-W)	0.82	42.86	0.237
Black/ Yellow (K-Y)	0.81	43.22	0.04
Blue/White (BL-W)	0.43	46.45	0.567
Blue/Green (BL-G)	0.34	53.85	0.504
Red/Green (R-G)	0.23	60.95	0.287
Blue/Red (BL-R)	0.12	42.52	0.791
Yellow/White (Y-W)	0.04	18.01	0.063

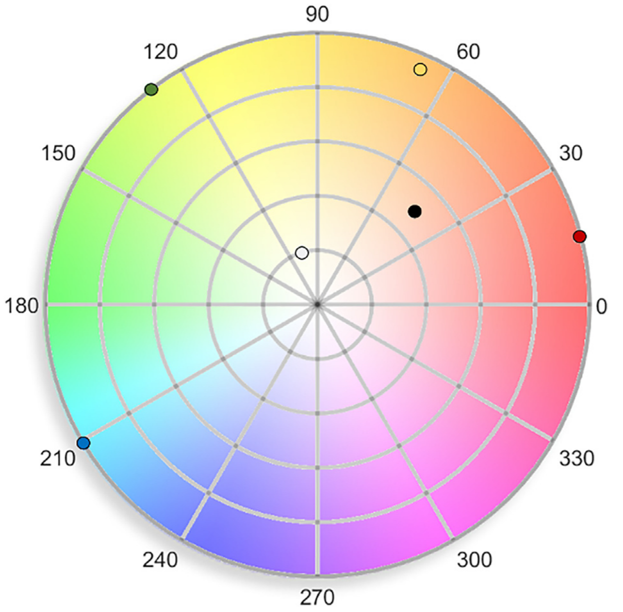

Fig. 2. Studied colors on a polar hue and saturation plot. Angle represents hue and radius saturation.

spectroradiometer model PR-745 (Photo Research Inc. USA) with 2 degrees aperture in the same exact conditions as the observers were doing the experiment. In order to completely characterize the perceived colors, their *x* and *y*, and CIE *L*a*b** color coordinates were calculated, as well as their hue (H), saturation (S), luminance (L) and dominant wavelength (λ_d) (Ohta & Robertson, 2006). Also CIEDE 2000 color differences were calculated for the color combinations studied, as well as luminance contrast ratios (Sharma, Wu, & Dalal, 2005) (Table 2).

In Fig. 1, three projections of the six studied colors are plotted in the CIE L*a*b* color space. Fig. 2 shows the same colors on a polar plot, where the angle corresponds to hue value and the radius to saturation value.

Note that, as shown in table 1 and Figs. 1 and 2, the chromaticities of black and white colours are different. This is indeed a qualitative difference that occurs in most consumer level LCD displays (in our study we used a fluorescent backlighted LCD monitor), where reducing the output signal, not only impacts the luminance but also the chromaticity of the stimulus. Fig. 3 shows the spectral radiance emitted by the monitor for the six considered color stimuli. As expected for a fluorescent backlighted LCD monitor, these spectra have spiky shapes, generated by the fluorescent lamps and modulated by the LCD light modulator.

A total of seven color pairs (Black-White [K-W], Black-Yellow [K-Y], Blue-White [BL-W], Blue-Green [BL-G], Red-Green [R-G], Blue-Red [BL-R], and Yellow-White [Y-W]) and two polarities (positive and negative) were chosen to design the text-background of the passages. In total, fourteen color combinations of text and background were used (see Fig. 4 for a schematic illustration), and they were classified as positive and negative polarities depending on the luminance values. Their luminance contrast, CIEDE 2000 color difference, and chromatic difference of refraction are shown in table 2 (Thibos, Ye, Zhang, & Bradley, 1992).

All sessions were conducted on the same equipment, a 15.35-inch LCD screen with a resolution of 1360 × 768 pixels without interpolation, placed at 50 cm distance from the participants' eyes. Following the methodology of other studies, a monitor inclination of 105° was fixed, and participants' eyes height was slightly above the screen center, forming a viewing angle of 15° (Shieh and Lin, 2000). The ambient illumination in the room was kept constant at ~150 lx (T-10 Konica Minolta Inc., Tokyo, Japan).

For the reading task design, the PsychoPy2 (V.1.85.4) software library written in Phyton 3.6.3 was used (Peirce, 2009). Fourteen different passages written in the participant's native language (Spanish) were chosen from different web-pages with a similar legibility

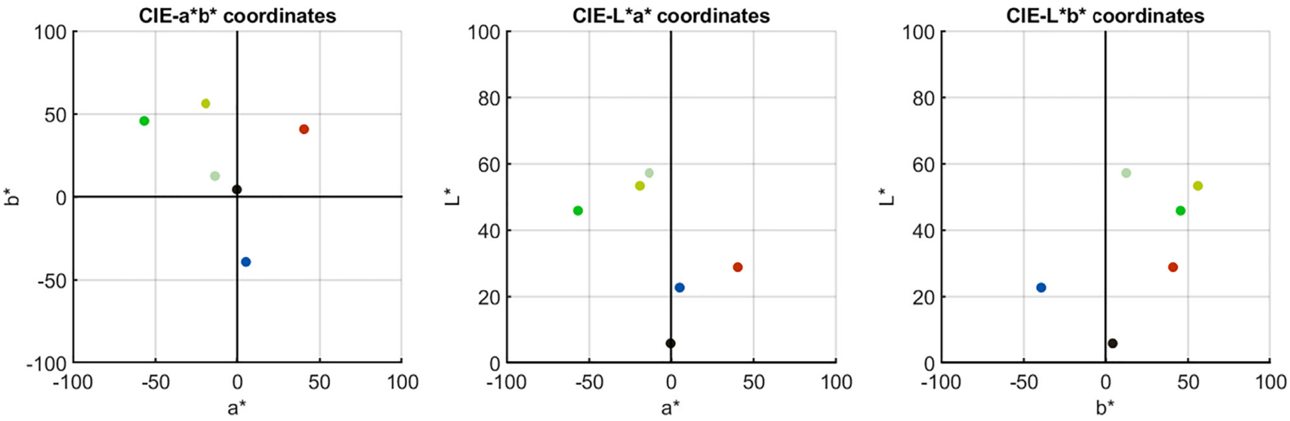

Fig. 1. Studied colors over the three projections of CIE L*a*b* color space.

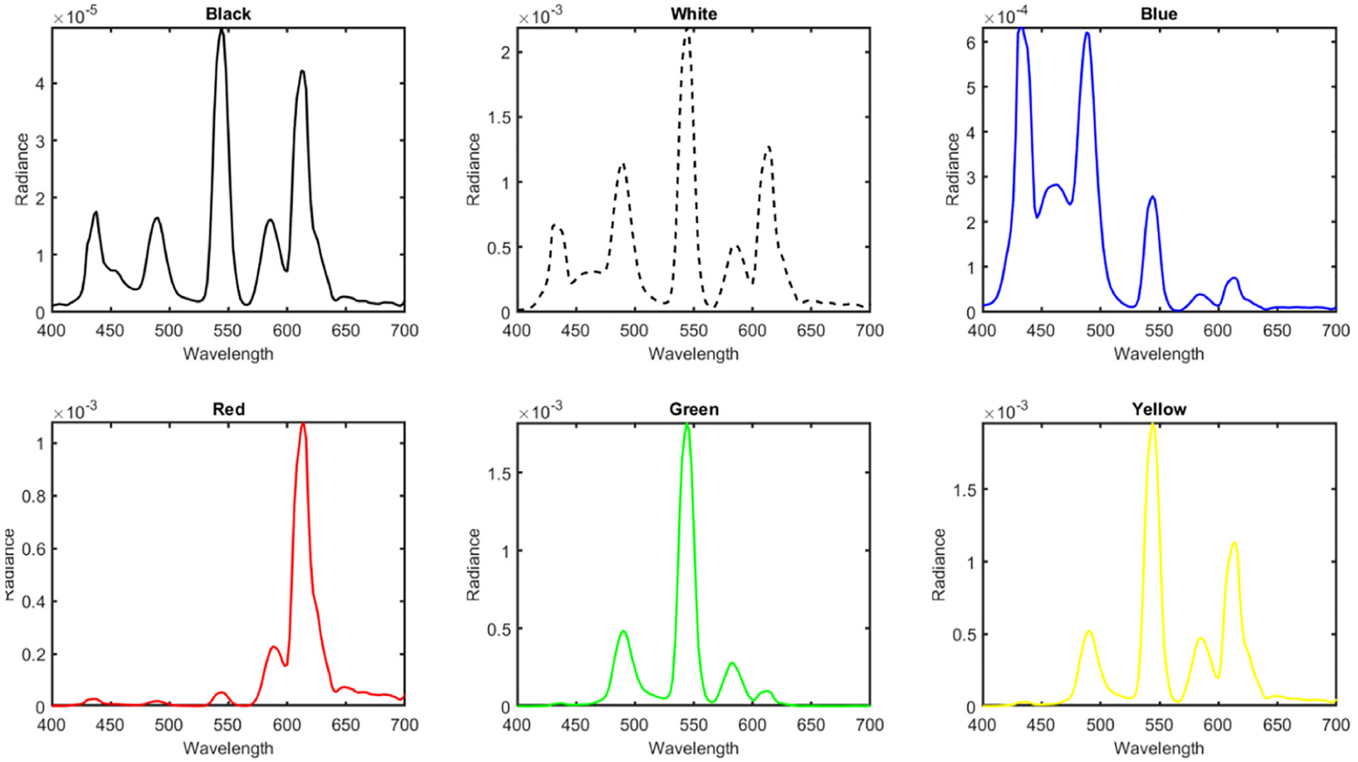

Fig. 3. Spectral radiances emitted by the monitor for the six color stimuli considered.

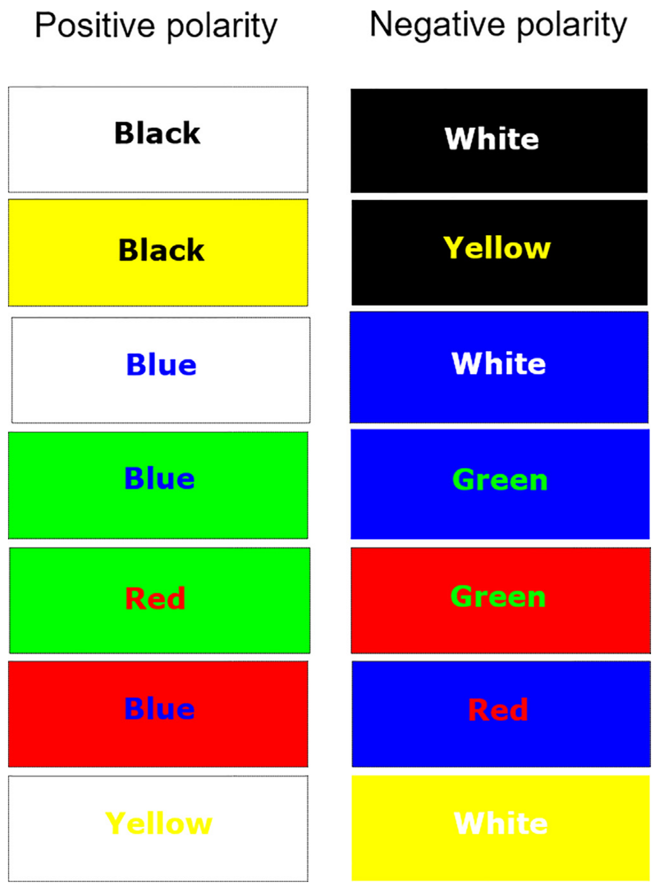

Fig. 4. Schematic illustration of the fourteen color combinations used in this study. The left panel displays the seven combinations with positive polarities, whereas the right panel shows the seven combinations with negative polarities.

according to the INFLESZ scale, with all the passages belonging to the category of "somewhat difficult" (48.75 ± 4.30) based on the classification of Barrio-Cantalejo et al. (2008). For all the passages, the Verdana font type was used as recommended by Sheedy, Smith, and Hayes (2005). During each presentation, and in order to maintain a correct alignment of the instrument with the visual axis of the eye, the passages were left-justified in a format of 40 characters per full width line and shown on a 10-text line window height of 15° placed on the screen center (Kundart, Tai, Hayes, Gietzen, & Sheedy, 2010). Each character sustained a visual x-high angle of 0.22° in order to permit an optimal reading speed (Legge & Bigelow, 2011). The initial velocity of text appearance was adjusted to 0.25 cm/s, although throughout the reading of each passage, participants were allowed to set the rate at which the text was vertically scrolled on the screen by adjusting the arrows cursor of the computer keyboard.

2.3. Assessment of accommodative response and pupillary dynamics

The assessment of magnitude and variability of both accommodative response and pupil size was carried out in binocular conditions using the WAM-5500 open field autorefractometer (Grand Seiko Co. Ltd., Hiroshima, Japan) in HI-SPEED mode, which continuously records the accommodative response and pupil size (apparent pupil) at a rate of ~5 Hz. The sensitivity of this instrument is 0.01 D and 0.1 mm for the accommodative response and pupil size, respectively (Sheppard & Davies, 2010).

Subjects, when necessary, wore their soft contact lenses during the task. Subjects were seated at the autorefractometer, using the corresponding chin and forehead supports, and were aligned with the distance fixation target to ensure on-axis measurements. First, we measured the monocular refractive state at far distance using the WAM-5500 in its static mode (i.e., baseline refractive value), which was used for the lag of accommodation calculation (see below). After it, participants read, in binocular viewing conditions, the different passages during a time period of 2 min for each one, and with 5-min breaks between two successive passages in order to avoid accommodative adaptation (Lin, Lin, Chen, & Chen, 2016). At each 2-minute reading task, the accommodative response and pupillary dynamics were continuously recorded from the sighting dominant eye (Momeni-Moghaddam, McAlinden, Azimi, Sobhani, & Skiadaresi, 2014).

Following previous recommendations (Tosha, Borsting, Ridder, & Chase, 2009), data points varying > 3 standard deviations from the mean spherical refraction value were removed, since they are considered blinks or recording errors. The remaining data (91% of the recorded values) were considered for further statistical analyses. The lag of accommodation was calculated as the difference between mean spherical refraction value of the dynamic measures and the stimulus vergence adjusted by the subject́s refraction (Poltavski, Biberdorf, & Petros, 2012). Additionally, the standard deviations of the continuous recordings of accommodative response and pupil size were considered as the variability of accommodation and pupil size, respectively.

2.4. Subjective ratings of legibility, perceived performance and reading speed

At the completion of each reading task, the reading speed (number of words per minute) was automatically registered by the Psychopy software. Additionally, the comprehension of the text was checked by a set of 3 questions for each passage, which were answerable as true or false on the basis of the information into the passage (Mills & Weldon, 1987). Two correct answers were considered to ensure an adequate comprehension of the passage.

Additionally, subjective ratings of legibility (ease of identification of text items) were recorded. For it, participants were asked to respond one same question for each of 14 color combinations: “How legible do you find the characters presented?” on a ten-point Likert scale anchored by 1 “very poor legibility” and 10 “excellent legibility” (Humar et al., 2014).

2.5. Procedure

In the first session and prior to the main experimental session, we performed an optometric examination in order to check that the inclusion criteria were met. During the second visit, subjects wore their habitual soft contact lenses, when necessary, and we obtained a baseline measurement of the refractive state through this correction using the WAM-5500. After it, participants read a practice passage, so that they could familiarize themselves with the operation of the computer cursors and the appearance of the display. The subjects were free to adjust the scrolling rate throughout the reading of each passage. Then, we performed the measurement of accommodative response and pupillary dynamics for each color combination. All participants attended the laboratory at the same time of day (± 1 h), and each subject read a total of 14 passages (each measurement lasted 2-minutes), in randomized order, and with breaks of about 5 min between passages. Immediately after each passage the perceived ratings of legibility and comprehension questionnaire were assessed, and the reading speed was obtained.

2.6. Experimental design and statistical analysis

A Shapiro-Wilk and Levene’s tests were performed to assess the normality of data and the equality of variance, respectively (p 0.05). A randomized repeated measures design was carried out to assess the effects of manipulating the text-background color during 2 min reading-time on ocular accommodation, pupil size, reading speed and perceived legibility. For this purpose, we performed separate repeated measures ANOVAs, with the color pairs (K-W, K-Y, BL-W, BL-G, R-G, BL-R, and Y-W) and polarity (positive and negative) as the within-participants factors, and considering the magnitude and variability of the accommodative response, magnitude and variability of pupil diameter, perceived levels of legibility, and reading speed (words per minute) as the dependent variables. We used the partial eta squared (ηp2) for Fs and Cohen’s effect size (ES) for t-tests as indices of the magnitude of the differences. The level of statistical significance was set set at 0.05, and the Holm-Bonferroni correction was applied for multiple comparisons.

3. Results

3.1. Effects of text-background color manipulation on accommodative response

The magnitude of the accommodative response showed statistically significant differences for the color combination ($F_{6,114} = 3.614$, $p = 0.003$, $\eta p^2 = 0.160$) and the interaction *color combination × polarity* ($F_{6,114} = 2.720$, $p = 0.017$, $\eta p^2 = 0.125$), whereas no significant differences were found for the polarity ($F_{1,19} = 0.265$, $p = 0.612$). Subsequently, in order to analyse the effect of polarity in each color combination, we performed paired samples T-tests. We found statistically significant differences between both polarities only in the blue-red color combination (corrected p-value < 0.001, $d = 0.966$), with the positive polarity (BL-R) showing a lower lag of accommodation (0.63 ± 0.47 D) when compared to the negative polarity (R-BL) (0.80 ± 0.42 D) (Fig. 5, panel A).

For its part, the variability of the accommodative response evidenced statistically significant differences for the polarity ($F_{1,19} = 17.349$, $p < 0.001$, $\eta p^2 = 0.323$), whereas the color combination ($F_{6,114} = 0.891$, $p = 0.504$) and interaction *color combination × polarity* ($F_{6,114} = 1.499$, $p = 0.185$) did not reach statistical significance. Post-hoc comparison evidenced that the polarity did not promote any statistically significant effect on the variability of accommodative response (all corrected p-values > 0.05) (Fig. 5, panel B).

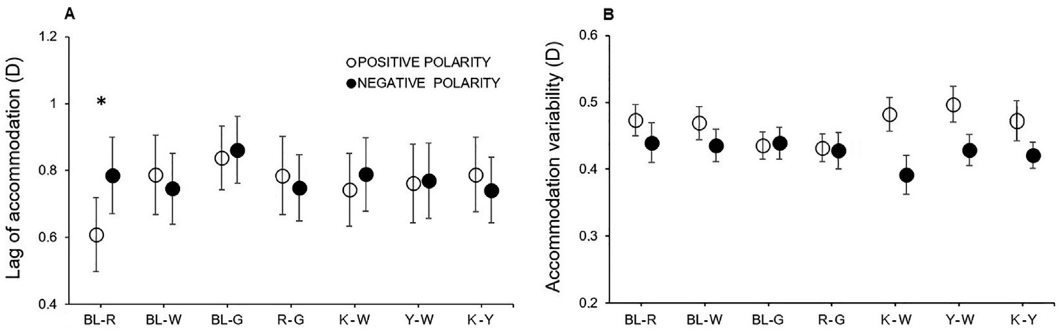

Fig. 5. Accommodative response under different text-background color combination. Panel A displays the lag of accommodation, and panel B the variability of accommodation. * denotes statistically significant differences between the positive and negative polarities of each color pair (corrected p-value < 0.05). Error bars show the standard error (SE). BL-R = Blue-Red, BL-W = Blue-White, BL-G = Blue-Green, R-G = Red-Green, K-W = Black-White, Y-W = Yellow-White, K-Y = Black-Yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

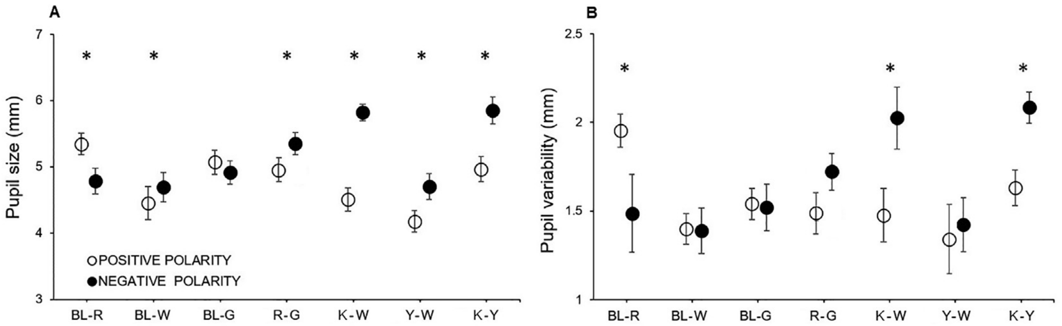

Fig. 6. Pupil size under different text-background color combination. Panel A displays the magnitude of pupil diameter, and panel B the variability of pupil diameter. *Denotes statistically significant differences between the positive and negative polarities of each color pair (corrected p-value < 0.05). Error bars show the standard error (SE). BL-R = Blue-Red, BL-W = Blue-White, BL-G = Blue-Green, R-G = Red-Green, K-W = Black-White, Y-W = Yellow-White, K-Y = Black-Yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. *Effects of letter-background color manipulation on pupil size*

There was a statistically significant effect for the color combination ($F_{6,114} = 25.28$, $p < 0.001$, $\eta p^2 = 0.571$) polarity ($F_{1,19} = 51.36$, $p < 0.001$; $\eta p^2 = 0.730$) and interaction *color combination* × *polarity* ($F_{6,114} = 32.96$, $p < 0.001$; $\eta p^2 = 0.634$) on pupil size. Post-hoc comparisons showed that the positive polarity was associated with smaller pupil sizes: B-W (corrected p-value = 0.007, d = 1.48), B-Y (corrected p-value = 0.007, d = 1.05), BL-W (corrected p-value = 0.014, d = 1.60), R-G (corrected p-value = 0.019, d = 0.44), and Y-W (corrected p-value = 0.007, d = 0.84) text-background color-combinations, with the exception of the BL-R (corrected p-value = 0.007, d = 0.69) color pair for which the positive polarity induced larger pupil sizes (Fig. 6, panel A).

The variability of the pupil size reached statistical significance for the color combination ($F_{6,114} = 9.80$, $p < 0.001$, $\eta p^2 = 0.340$), polarity ($F_{1,19} = 6.76$, $p < 0.001$; $\eta p^2 = 0.263$) and interaction *color combination* × *polarity* ($F_{6,114} = 8.76$, $p < 0.001$; $\eta p^2 = 0.316$). Post-hoc comparisons evidenced that the negative polarity induced only a heightened variability of the pupil size for the B-W (corrected p-value = 0.015, d = 0.83) and B-Y (corrected p-value = 0.014, d = 0.54), whereas the positive polarity lead to a larger variability of pupil size for the BL-R color combination (corrected p-value = 0.014, d = 0.82) (Fig. 6, panel B).

3.3. *Effects of letter-background color manipulation on reading speed and legibility rating*

There was a significant effect of polarity on reading speed, showing a higher reading speed for positive polarities ($F_{1,19} = 4.537$, $p = 0.046$; $\eta p^2 = 0.193$). However, no effects were observed for the color combination ($F_{6,114} = 0.681$, $p = 0.666$; $\eta p^2 = 0.035$) and interaction *color combination* × *polarity* ($F_{6,114} = 1.362$, $p = 0.236$; $\eta p^2 = 0.067$). Post-hoc comparisons did not evidence significant differences between the positive and negative polarities for any color combination (all corrected p-values > 0.05) (Fig. 7, panel A).

Regarding perceived levels of legibility, our data showed a main effect of the color combination ($F_{6,132} = 37.37$, $p < 0.001$, $\eta p^2 = 0.629$), polarity ($F_{1,22} = 21.05$, $p < 0.001$, $\eta p^2 = 0.489$) and interaction *color combination* × *polarity* ($F_{6,132} = 4.89$, $p < 0.001$, $\eta p^2 = 0.182$). Post-hoc tests demonstrated a reduced legibility for the Y-W color combination (corrected p-value = 0.007, d = 1.38), with a greater rating of perceived legibility in the positive polarity (Y-W [text-background]) (Fig. 7, panel B).

4. Discussion

This study assessed the impact of different chromatic combinations between text and background on the accommodative response and pupillary dynamics during a 2-min reading task displayed on an LCD screen. Our data evidenced that the accommodative response (magnitude and variability) was sensitive to the color combination, obtaining a greater accommodative response for the BL-R text-background combination. Also, the pupillary dynamics were modulated as a function of the text-background color combination, showing smaller pupil sizes when the positive polarity was present, except for the BL-R text-background color combination. Furthermore, and as expected, the Y-W text-background color combination provoked a decrease in subjective ratings of legibility. However, the reading speed did not show any statistically significant change as a result of manipulating text-background color.

It has been demonstrated that longitudinal chromatic aberrations provide directional information for accommodation in order to regain sharp focus in the retina, in such a way that the contrast of spectral-wavebands of the retinal image mediate the signals that specify dioptric vergence (Kruger, Nowbotsing, & Aggarwala, 1995). Thus, the contrast of the retinal image would be maximum for the wavelength in focus and minimum for the farther wavelength of retina, and the three cone types would effectively sample this retinal contrast and therefore determinate the direction and magnitude of accommodative response (Aggarwala, Kruger, Mathews, & Kruger, 1995). In this sense, a greater long wavelength contrast than middle-wavelength contrast would lead to accommodative shift towards the visual far point (dis-accommodation), while a response towards near (accommodation) with a chromatic short-wavelength cone contrast would be expected (Rucker & Kruger, 2004, 2006). In this study, we found that the BL-R color pair, namely the color combination with the greatest difference in refractive error between their dominant wavelengths (0.79 D), induced a greater accommodative response in comparison to most other combinations. Also, our results showed that the positive polarity (BL-R text-background) induced a greater accommodative response than the negative polarity (R-BL text-background).

The influence of the text-background polarity on magnitude of accommodative response, using black and white color combination, has been extensively documented (Bernal-Molina, Esteve-Taboada, Ferrer-Blasco, & Montés-Micó, 2019; Ciuffreda, Rosenfield, Rosen, Azimi, & Ong, 1990), with most studies showing no significant differences between polarities. Here, we assessed the accommodative response under different chromatic combinations, and our findings converge with those previously mentioned, except for the blue-red color combination, in which the positive polarity (BL-R text-background) induced a greater accommodative response. Previous studies have investigated the role of isolated short-, middle- and long-wavelength sensitive cones in the control of accommodation (Rucker & Kruger, 2001, 2004), as well as its combinations (Kruger et al., 2005). These investigations have showed that the short-cones can drive accommodation, although the

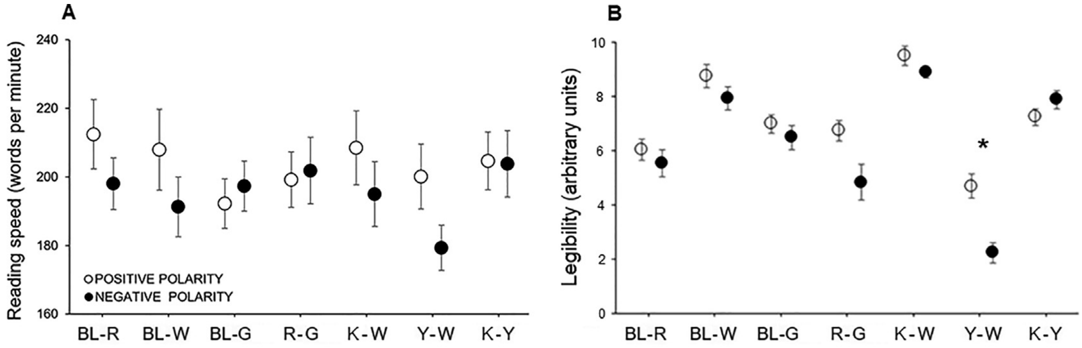

Fig. 7. Reading speed (panel A) and legibility (panel B) under different text-background color combination. * denotes statistically significant differences between the positive and negative polarities of each color pair (corrected p-value < 0.05). Error bars show the standard error (SE). BL-R = Blue-Red, BL-W = Blue-White, BL-G = Blue-Green, R-G = Red-Green, K-W = Black-White, Y-W = Yellow-White, K-Y = Black-Yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

accommodative gain from short-cones alone was small than for long- and mile-cones together. Nevertheless, the possible influence of each of the three cone types on the accommodative response to chromatic stimuli requires further investigation, since considerable individual differences in ocular accommodation to multicolored displays have been reported, and specially for the blue-red color pair (Atchison et al., 2004; Charman, 1989). Also, as indicated by Campbell (1957), the variation of retinal resolving power with wavelength could also modulate the dynamics of the accommodative response, since the visual acuity becomes worse for shorter wavelengths, and therefore, a blue text on red background could lead to more accommodation in order to obtain a maximum sharpness of the characters. Also, the magnitude of Stiles Crawford effect increases as the pupil dilates, which has demonstrated to be an important factor in the chromostereopsis phenomenon, and with the blue-red color combination, blue is perceived closer than red (Thompson, May, & Stone, 1993). Although in the present study, this phenomenon was not measured, a higher pupil dilatation was recorded with the positive polarity of the BL-R color combination in comparison with the positive polarities of other color pairs and its opposite polarity (red text on blue background). In view of this, the influence of negative chromostereopsis could be present, inducing a heightened accommodative response due to the proximity sensation of blue stimulus (text) in comparison to red background.

Additionally, it has been demonstrated that grating bars with different chromaticities presented on an LCD screen for 3-s induce discomfort, being the ratings of discomfort positively associated with the perceptual difference in the color of the component bars of the grating, however, it did not modify the magnitude or variability of the accommodative response (Haigh, Barningham et al., 2013). Accommodative variability has demonstrated to be an accurate measure of visual fatigue and stress (Jeng et al., 2014). However, regarding the effect of the target chromaticity on variability of accommodation, non-conclusive results have been reported in the scientific literature. To our knowledge, no text-background color combinations have been considered before (Denieul & Corno-Martin, 1994; Gray, Gilmartin, & Winn, 2000), or if they were, the statistical power was insufficient due to the considerable inter-individual differences (Atchison et al., 2004). Here, we used stimuli with higher accommodative demand (text-background color combinations) than those stationary stimuli used in previous investigations, and we also found no evidence about the influence of text-background color combination on the variability of accommodation, being this result in line with the abovementioned authors.

Regarding pupil dynamics, our findings showed that positive polarities induced smaller pupil sizes than negative polarities, with the exception of BL-R text-background color combination, in which the negative polarity was associated with a smaller pupil size. This result may be explained by the small luminance contrast of this color combination (see Table 2). As indicated above, a positive polarity would promote a larger depth of focus due to the reduced pupil size (Wang & Ciuffreda, 2006), however, pupil diameters lower than 3 mm are required to observe changes in the accommodative response (Ward & Charman, 1985). Therefore, no differences in the accommodative response may be expected due to pupil changes since our experimental manipulation induced pupil diameters ranging between 3.33 and 7.12 mm. Nevertheless, for the BL-R text-background combination a heightened accommodative response was found with larger pupil diameters. It may be consequence of the low luminance contrast (0.12) and the high chromatic difference of refraction (0.79), which also lead to higher variability of pupil size (1.98 ± 0.75 mm) in comparison to the majority of color combinations, and it could constitute a directional cue to accommodation.

Overall, our results evidenced a lower reading speed and legibility for negative in comparison to positive polarities. In this study, the ambient illumination was considerably high, and thus, a modest effect of manipulating the polarity on the pupil size may be expected. However, we found a significant pupil size reduction with the positive polarities. The higher luminance associated with positive polarity may be the more plausible explanation to greater reading speed found with these polarities, since a greater pupillary constriction has been associated with better reading performance (Piepenbrock et al., 2014, 2013). It has been stated that the greater depth of focus associated with positive polarities (smaller pupil sizes) may allow to reduce the accommodative efforts required to obtain a sharp image at near distances (López-Gil et al., 2013). The within-subject manipulation of polarity could have induced a higher effort for those combinations with negative polarity in order to obtain a similar performance to positive polarity conditions (Buchner & Baumgartner, 2007). In addition, a higher familiarity and experience of positive polarity text presentations could also influence reading speed (Hall & Hanna, 2004). Our findings agree with previous authors (Piepenbrock et al., 2014; Zuffi, Brambilla, & Beretta, 2009), with the Y-W text-background color combination, leading to the worst reading speed (number of words read per minute). The Y-W color combination has demonstrated to impose greater levels of cognitive effort in comparison to other color combinations, and thus, its use is discouraged (Bhattacharyya et al., 2014).

Numerous authors have argued that some color combinations constitute a conflicting stimuli and destabilize the neural control mechanisms of ocular accommodation, decreasing performance and probably increasing the risk of eye strain (Luria et al., 1989; Matthews, 1987; Shieh & Chen, 1997; Shieh & Lai, 2008). As indicated by Atchison et al. (2004), it will occur especially when the two colors are sufficiently saturated and the dioptric interval between their dominant wavelengths is larger than the eye's depth of focus (Allen, Hussain, Usherwood, & Wilkins, 2010). Based on this, it is plausible to think that the subjective preferences of color combination would be dependent on longitudinal chromatic aberration accommodative stimulus demand

(Drew, Borsting, Stark, & Chase, 2012), and therefore, a higher preference for color combinations with lower chromatic difference of refraction could be expected (i.e., K-Y and Y-W combinations). Similarly to reading speed, the Y-W text-background color combination offered a poor legibility (2.2 ± 1.6, ranged 1–10), being this result in agreement with the study of Humar et al. (2014). A lower luminance contrast between these colors (yellow and white) seems to be responsible of this subjective perception (Bhattacharyya et al., 2014).

4.1. Limitations and future research

Despite the relevance of our results, there are several limitations that must be acknowledged. First, the present study was limited to the use of fourteen text/background color combinations, and possibly, other color combinations may have different effects on accommodative and pupillary dynamics. The inclusion of color combinations frequently used in web-page designs would allow to discern which color combination promotes a better reading speed and visual comfort. In addition, we tried to mimic real-world conditions, and thus, the screen brightness was maintained constant across all the experimental conditions, and although the text window was relatively small, participants had to perform eye movements for reading. Nevertheless, future studies could explore the influence of manipulating the screen brightness on the dynamics of ocular accommodation, as well as the influence of eye movements during reading on the dynamics of the accommodative response. Second, our experimental sample was formed by healthy young individuals who had experience in the use of electronic visual displays. Future studies with visually symptomatic individuals and different ages may provide particular recommendations for each cohort. Third, the 2-minute task may not be long enough to test the time-on-task effects of text-background color combinations on visual discomfort and reading speed. The implementation of longer reading tasks could help to elucidate it. Also, previous studies have reported that the accommodative response and pupil size may vary in different refractive groups (Cakmak, Cagil, Simavli, Duzen, & Simsek, 2010; Harb, Thorn, & Troilo, 2006), and future studies should consider to explore the influence of refractive error on the dynamics of accommodative response and pupil while reading with different text-background color combinations. Fourth, we consider of interest to explore how the vergence system and accommodative convergence/accommodation ratio is altered by text-background color combination, aiming to discern the effects of manipulating the text-background color combinations on both accommodative and binocular function. Lastly, further research is necessary to identify the stimuli and mechanisms that subjects use to accommodate to multichromatic text-background in order to contribute to the understanding of the ease of reading on displays under standard viewing conditions.

5. Conclusions

The current results show that manipulating the text polarity was insufficient to induce significant changes in the accommodative response, however reading with the blue-red text-background color combination caused a heightened accommodative response in comparison to the rest of color combinations. For the variability of accommodation, the use of text-background color combinations with positive polarities was associated with a less stable accommodative response, which may be of relevance due to the association between accommodative stability and visual discomfort. Further analysis showed that positive polarity induced a greater pupil constriction and that it was an important factor of color combination for ratings of legibility, being the yellow-white text-background color combination the least preferred option. Taken together, our findings may be of relevance for designing visuals in webpages and multimedia digital resources in order to increase visual comfort and minimize the risk of visual fatigue. Nevertheless, our findings should be cautiously interpreted due to the multiple factors affecting the dynamics of the accommodative response, and the specific viewing conditions (headrest, scrolling text, unusual colors) used in this study.

CRediT authorship contribution statement

Raimundo Jiménez: Conceptualization, Methodology, Project administration, Resources, Writing - original draft. **Beatriz Redondo:** Conceptualization, Investigation, Writing - original draft. **Rubén Molina:** Data curation, Investigation, Writing - original draft. **Miguel Ángel Martínez-Domingo:** Formal analysis, Methodology, Software, Writing - original draft. **Javier Hernández-Andrés:** Funding acquisition, Methodology, Project administration, Resources, Writing - original draft. **Jesús Vera:** Conceptualization, Formal analysis, Resources, Supervision, Writing - original draft.

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