ORIGINAL ARTICLE

Influence of contrast polarity on the accommodative response[☆]

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Abstract
Purpose: To assess the changes in the accommodative response of the eye while reading a text under different contrast polarity conditions: black letters on white background (BoW condition) and white letters on black background (WoB condition).
Methods: Eighteen subjects with ages ranging from 21 to 41 years participated in this experimental study. The accommodative response (AR) of the eye while reading a text with BoW or WoB contrast polarity was obtained objectively with an adaptive optics system that corrected all aberrations but subject's own. Two different letter sizes (visual acuity conditions), shown on a microdisplay, were tested. The AR of each eye was measured with its natural pupil diameter at 0–3 D of accommodative demand from the far point of the eye, with a step of 0.5 D. The slope of the stimulus–response curve was calculated for each subject and condition.
Results: The averaged maximum pupil size was bigger for reverse (WoB) than for normal (BoW) contrast with statistical significance. The slopes for the ARs of the four conditions were not significantly different from each other.
Conclusions: Contrast polarity does not seem to influence the accommodative response when reading text from an electronic microdisplay.
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Influencia de la polaridad de contraste en la respuesta acomodativa

Resumen

Objetivo: Evaluar los cambios de la respuesta acomodativa del ojo al leer un texto en diferentes condiciones de polaridad de contraste: letras negras sobre fondo blanco (condición BoW) y letras blancas sobre fondo negro (condición WoB).

Métodos: En este estudio experimental participaron dieciocho sujetos de edades comprendidas entre 21 y 41 años. Se obtuvo objetivamente la respuesta acomodativa (AR) del ojo al leer un texto con polaridad de contraste BoW o WoB con un sistema de óptica adaptativa que corregía todas las aberraciones salvo las propias del sujeto. Se estudiaron dos tamaños de letra diferentes (condiciones de agudeza visual), mostrados en una micropantalla. Se midió la AR de cada ojo con su diámetro de pupila natural con 0 a 3 D de demanda acomodativa desde el punto remoto del ojo, en intervalos de 0,5 D. Se calculó la pendiente de la curva estímulo-respuesta para cada sujeto y condición.

Resultados: El tamaño máximo medio de la pupila fue mayor para el contraste inverso (WoB) que para el normal (BoW), con significación estadística. Las pendientes de las AR para las cuatro condiciones no difirieron significativamente entre ellas.

Conclusiones: La polaridad de contraste no parece influir en la respuesta acomodativa al leer un texto en una micropantalla electrónica.

Introduction

In the last decade, there has been a significant increase in the use of electronic devices, such as smartphones, tablets and e-readers. E-readers were conceived to avoid the visual fatigue effect detected when using conventional electronic screens. Their advantages, as low power consumption and sunlight readability, expanded their use in the population. Initially, e-readers had no backlight. However, the readers demanded to be able to use it in environments with low illumination, and nowadays many e-readers include integrated light. Tablets and smartphones are other devices commonly used for reading tasks because of their portability, bigger screens, or the possibility to have coloured text and pictures. When the user is reading plain text in these devices, all of them allow to change letter size and text-background contrast polarity, i.e., whether text is presented as black letters on a white background (BoW) or white letters on a black background (WoB).

The contrast of an image or text is a well-known factor influencing the visual function of the eye.[1,2] In 1978, Ginsburg[3] measured contrast thresholds for two different tasks: detection and identification of letters of different sizes. He found that for smaller letters, the contrast required for identification was more than for detection. The effect of contrast polarity on reading performance has been studied using different methodologies. Some authors compared reading speeds for different text-background combinations, changing colour contrast or luminance contrast.[4–7] Others used forced choice task and compared the number of correct responses for each tested condition[8] or the number of grammatical errors detected in a text depending on the contrast polarity.[9–11] It has been reported that low vision subjects prefer WoB,[12] this could be the reason why most machine vision based aids for low vision subjects have the possibility to change the contrast of the image. Visual acuity (VA) has also been studied with contrast polarity, but experiments showed contradictory conclusions: VA improves with reverse contrast in older subjects,[13] or VA is better with normal contrast for all ages.[11] Even other authors have measured strain (breathing rate, heart rate, etc.) and self-reported fatigue, eyestrain or headache, finding no differences based on contrast polarity or room light, although proofreading performance was clearly superior with BoW than WoB contrast.[14]

From previous studies in the literature, there is no agreement on the effect of contrast polarity in the visual performance. Objective measurement of the refractive state of the eye when reading BoW text or vice versa may provide some insight about this regard. Since the response of the accommodative system to a near stimulus varies widely with the subject, the assessment of the accommodative response (AR) by means of the accommodative stimulus–response curve should be more appropriate to study the effect of contrast polarity. Recently, this curve has been studied with emoji symbols as stimulus that replaced a word or a sentence.[15] The analysis of the accommodative stimulus–response curve is important for the assessment of the relationship between accommodation and myopia or amblyopia development.[16–19]

Therefore, the purpose of the present study is to evaluate the accommodative stimulus–response curve using an adaptive optics system in order to assess the effect of text size and contrast polarity used in e-books applications frequently found in smartphones, tablets, and e-readers.

Methods

Subjects

Eighteen young adult subjects with a mean age of 29 ± 8 years (range from 21 to 41 years) were enrolled in the study. The mean spherical equivalent refractive error was -0.16 ± 1.30 diopters (D). Astigmatism was limited to ≤ 1.00 D. All subjects had a best-corrected VA of 20/20 or better, showed no ocular pathology, no previous conducted ocular surgery, and normal clinical amplitudes of accommodation for their ages. The study followed the Declaration of Helsinki, the subjects were informed about the details and possible consequences of the study, and a signed formal consent was obtained from each subject.
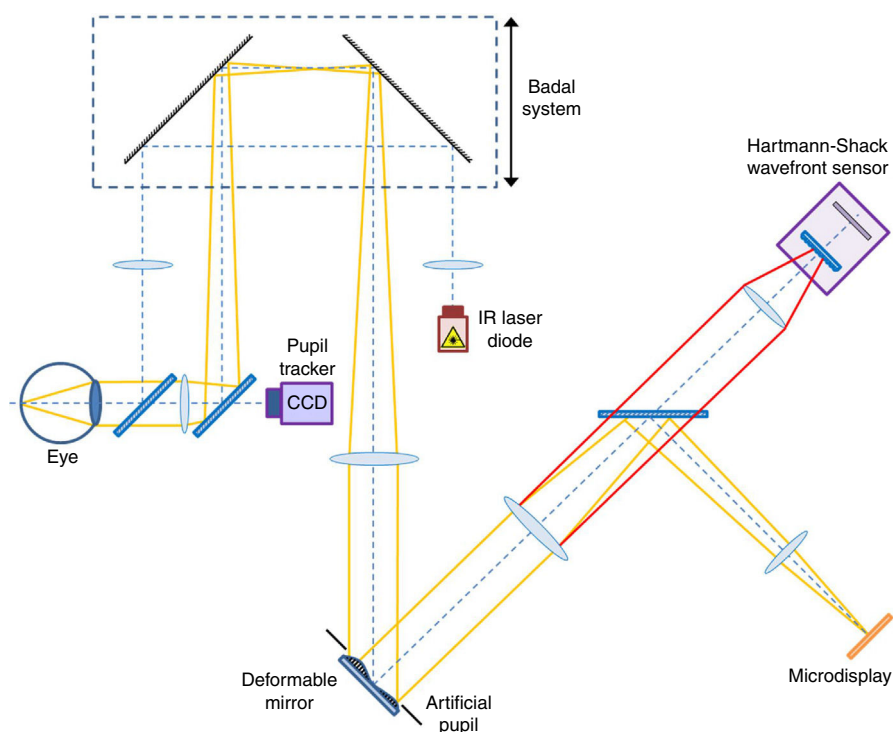
Experimental system

An adaptive optics system was used to carry out the measurements. Fig. 1 shows a detailed description of the experimental setup used. The system is composed of a Hartmann–Shack wavefront sensor (Haso32, Imagine Optic, France) and a 52-actuators deformable mirror (Mirao 52e, Imagine Eyes, France). The wavefront sensor employs a square array of 1024 microlenses and a near-infrared light source with a wavelength of 850 nm. An internal microdisplay is used to display the target, while the Badal system is employed to change the accommodative demand (AD). A precise alignment of the subject's pupil is required, that was controlled with an additional camera. Head movements were reduced employing a chin and forehead rest.
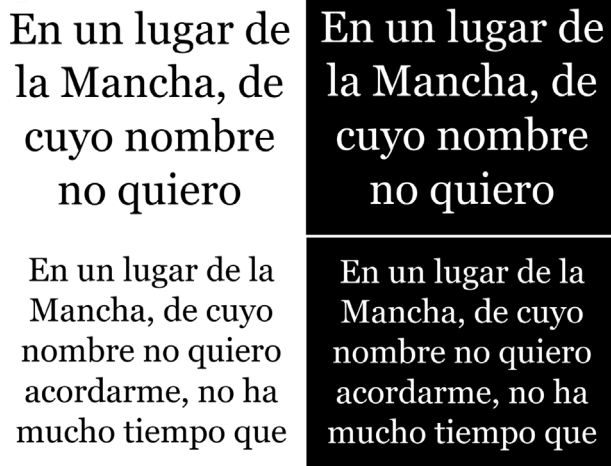
All measurements were taken using custom-made software developed in Matlab (Mathworks, Inc., Natic, MA), based on the analysis and simulation software library and software development kits provided by the manufacturer (Imagine Eyes, France).

Experimental procedure

The accommodative stimulus–response curve was measured under two different contrast conditions. In the first condition, we measured the refractive state of the eye when the subject was reading a text with BoW (named BoW condition). In the second condition, the text was shown in reverse contrast, i.e., WoB (named WoB condition). In both conditions, the measurements were performed monocularly, obtained from the dominant eye of each subject, and the other eye was patched. The text target was comprehensible prose from the book *Don Quijote de la Mancha* by Miguel de Cervantes. Fig. 2 shows an example of the text targets that were used. Before each trial, the motored Badal system corrected the spherical refraction of the subject, and the deformable mirror corrected all aberrations in the optical system, ensuring that differences found in the measured aberrations came from the accommodative response of the eye. In each condition, the AR was acquired with the AD varying from 0 to 3 D, with a step of 0.5 D, and with two letter sizes corresponding to 0.6 and 0.8 VA. The range of ADs used was chosen to include normal reading vergences and limited to the first lineal part of the stimulus–response curve. AR was obtained from measured aberrations, calculated as Zernike refraction. The wavefront data measured with the Hartmann–Shack wavefront sensor were exported

Figure 1 Detailed scheme of the experimental system used. Yellow lines represent the path followed by visible light. Red lines represent the last section of the path followed by infrared light.

En un lugar de la Mancha, de cuyo nombre no quiero

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Figure 2 Targets used as stimulus. Up: 0.6 VA. Down: 0.8 VA. Left: normal contrast. Right: reverse contrast.

as Zernike coefficients up to 6th order. The AR was objectively assessed from the wavefront of the subjects by the Zernike defocus term. The AR was estimated in diopters employing the following equation:

$$AR = AD + \frac{4\sqrt{3}}{r^2} \times C_2^0 \qquad (1)$$

where C_2^0 is the second-order Zernike coefficient for defocus in μm and r is the pupil radius in mm. During the measurements, the room light was dark. Subjects were allowed to rest between trials, and all targets were shown in random order.

Data analysis

Data corresponding to each one of the different conditions were fitted to linear models using Matlab 2015b. For each regression analysis, the intercept, the slope, the determination coefficient, and the p-value were obtained. An additional ANCOVA analysis was performed to elucidate whether the slopes of the four conditions (changing the contrast and the letter sizes) were different. A p-value of less than 0.05 was considered to be statistically significant (<5%).

Results

The mean ARs obtained for all subjects for each measured AD and for the four different conditions of this experiment are shown in Fig. 3. The dotted lines in these figures show the regression lines obtained, while the dashed line represents the ideal response of the accommodation system (in which the AR equals the AD). The slopes for the averaged stimulus–response curves fitted to linear models were 0.628 for 0.6 AV with normal contrast, 0.595 for 0.6 AV with reverse contrast, 0.659 for 0.8 AV with normal contrast and 0.614 for 0.8 AV with reverse contrast. The p-values for these slopes were statistically significant ($p < 0.01$ for all conditions). The determination coefficients were $R^2 \geq 0.99$ in all experimental conditions.

As can be seen, there was a difference for all conditions towards the same direction between the ARs and the ideal
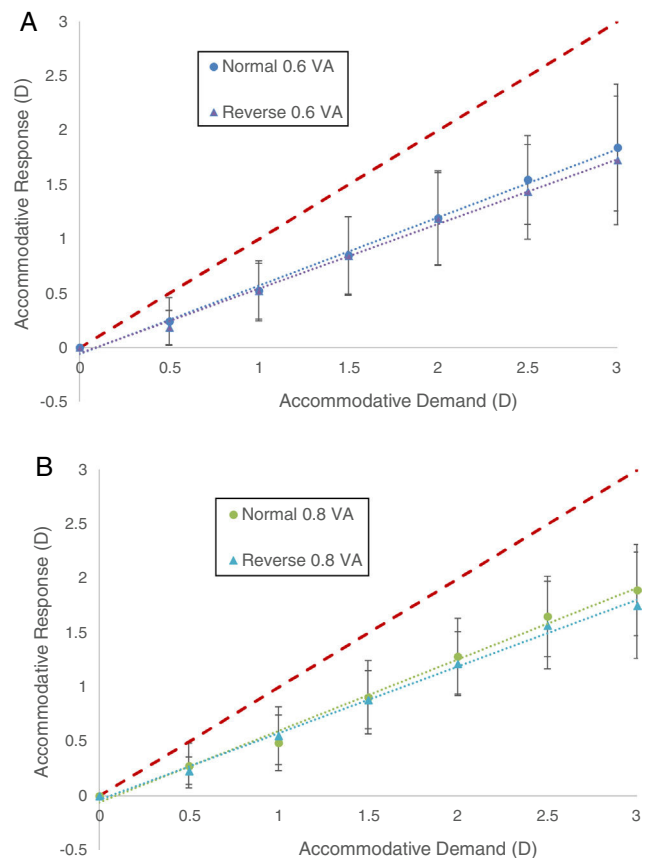
Figure 3 (A) Mean accommodative–response curve among subjects obtained with the 0.6 VA stimulus. Blue circle is for normal contrast. Purple triangle is for reverse contrast. (B) Mean accommodative–response curve among subjects obtained with the 0.8 VA stimulus. Green circle is for normal contrast. Light blue triangle is for reverse contrast.

response, showing accommodative lags for all subjects, conditions, and ADs.

To assess any possible statistically significant differences between the measurements obtained for the four different conditions, an additional ANCOVA analysis was performed. The results of this analysis revealed that the slopes for the ARs of the four conditions were not significantly different from each other ($p = 0.16$).

As it is expected, pupil diameter was decreasing during accommodation due to the accommodative triad. Fig. 4 shows the difference in size of the pupil throughout the stimulus–response curve for each subject and condition. Paired t-tests were performed between conditions and no significant difference was found ($p > 0.09$). The mean maximum pupil diameter for our subjects was 5.72 ± 0.45 mm for 0.6 AV with normal contrast, 5.91 ± 0.31 mm for 0.6 AV with reverse contrast, 5.72 ± 0.52 mm for 0.8 AV with normal contrast and 5.91 ± 0.40 mm for 0.8 AV with reverse contrast. Maximum pupil was bigger for reverse than for normal contrast with statistical significance ($p < 0.03$).
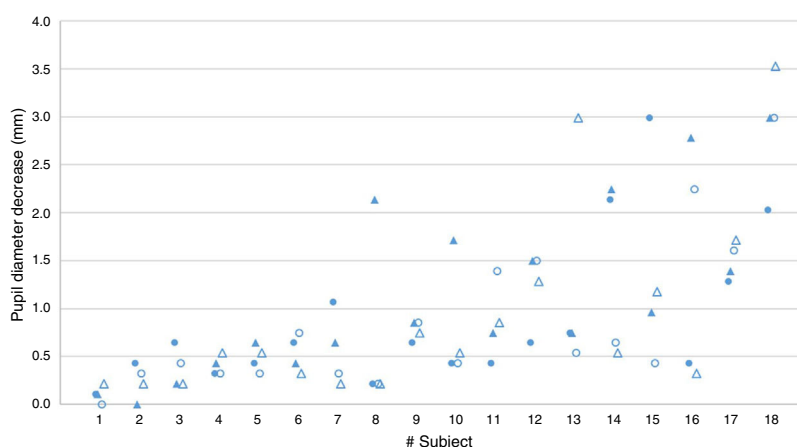
Figure 4 Pupil diameter decrease for each subject and condition in the measured stimulus–response curve. Circles are for 0.6 VA and triangles for 0.8 VA. Solid symbols represent normal contrast and empty symbols represent reverse contrast.

Discussion

In order to find out whether contrast polarity is a factor influencing the behaviour of the accommodation system, the stimulus–response curve has been measured and studied through its slope. The slope of the averaged stimulus–response curve for our subjects was bigger for normal than for reverse contrast for the two letter sizes, although there were no statistical differences. The slope was also bigger for 0.8 VA than for 0.6 VA text, as expected.[20]

The criteria applied to choose the stimulus to be tested was to emulate real reading conditions; this is high text-background contrast, two typical letter sizes in e-books, and normal or reverse contrast polarity. Although the stimulus was shown on a screen that emits light, its angular subtense of $2° \times 1.5°$ and the fact that it was seen monocularly through a close optical system, differ from real use of electronic devices and so, the application of our results is limited.

The comprehensive prose set as stimulus was occupying as much surface of the display as possible regarding the letter size. Notwithstanding this, luminance was not equal for normal and reverse contrast polarity, as occurs in real reading situations. Because of that, the maximum pupil found was bigger for reverse than for normal contrast, being statistically different.

In their study about adaptive optics correction benefits, Marcos et al.[21] found that visual performance with natural aberrations, based on VA, was higher with WoB targets than with BoW for luminance lower than $25\,cd/m^2$. Contrary, Buchner et al.[9] observed no advantage when display luminance was equivalent for both contrast polarities, neither with $77\,cd/m^2$ nor $10\,cd/m^2$ display luminance, when the task was to find various types of errors in a text. In 1990, Taptagaporn and Saito[22] recommended WoB polarity for dark environments, although later studies revealed that reading performance is better with BoW than with WoB display polarity, and that ambient illumination does not play a role in the reading performance.[14] A recent study found worse visual performance for WoB polarity under dark ambient illumination.[23] With reverse contrast, the tails of the light distribution can be more visible and thus, the image

of the text deteriorated. Some authors who found better performance with normal contrast polarity (BoW condition) justified their results in the smaller pupil diameter due to the higher luminance of the stimulus. The smaller the pupil, the smaller the higher-order aberrations (mainly spherical aberration) and the greater the depth of field, thus the quality of the retinal image is expected to be better. Although in our study pupil diameter was significantly smaller for normal contrast, the AR of the subjects was not statistically different from that for the reverse contrast polarity condition.

As a second experiment of their study, Ciuffreda et al. measured the accommodation subjectively using a Hartinger coincidence optometer in twelve subjects, using as stimulus a text at 3 D of AD with both contrast polarities.[24] Contrast was quite similar for the two text-background conditions and they did not find statistically significant differences in the AR. In 1994, Collins et al.[25] measured the AR of seven subjects with an infrared optometer when they were looking at a letter displayed on a screen at 2 D of AD with normal and reverse contrast polarity. They found that the AR was similar, independently of the contrast polarity, reporting then the same results as the ones obtained in our study. The age range of the subjects included in these studies was similar to our subjects' age and the range of AD also coincides. This study included a larger number of subjects and used an objective and precise technique. Our results are comparable with previous experiments and indicate the same conclusion. In 2007, Bakaraju et al.[20] found, with statistical significance, that the mean accommodative lag with normal contrast was lower than for reverse contrast, using the MEM retinoscopy technique. The tendency of our results agrees with their findings (see Fig. 3), although we did not find significant differences. This higher lag (lower AR) when reading white letters on black background was consistent with a bigger pupil diameter found on average.

In our experiment, a deformable mirror was used to correct all aberrations of the optical system except subject's own aberrations, avoiding any aberration effect not due to the tested eye. The stimulus was shown on a high contrast microdisplay that, after the light goes through the optical system, showed a luminance of around $90\,cd/m^2$ with the normal contrast target. We performed the AR measurements

for the natural pupil size of our subject in each condition, emulating real situation of reading. Although pupil diameter of our subjects was bigger with reverse contrast polarity, its decrease with accommodation was not statistically different between contrast polarities (see Fig. 4) and so, it does not seem to vary significantly the AR of the eye in terms of its slope. Given that the order in which the different stimulus were shown was randomized, any possible learning effect that could influence the AR was avoided.

In conclusion, the latest studies previously mentioned are generally based on ergonomic proofs, and agree that BoW text produce better visual performance. However, the results from the present experiment agree with those studies that found no difference in the behaviour of the accommodation of the eye with contrast polarity. Thus, the contrast polarity of the text when reading from an electronic device could be individually selected depending on the reader's preference without compromising the accommodative system.

The study presented here is an attempt to objectively evaluate the response of the accommodative system when reading on an electronic microdisplay with normal or reverse contrast. If one condition caused a slope in the stimulus–response curve less than the other, the former could be a better option to decrease the effort of accommodation and therefore fatigue. A more extensive study, including more subjects and an experimental system with larger visual field more similar to typical electronic devices' screens, would be necessary to confirm the conclusion drawn.

Conflicts of interest

The authors have no conflicts of interest to declare.

Acknowledgement

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