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Effects of Light on Visual Function, Alertness, and Cognitive Performance: A Computerized Test Assessment

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Abstract: Background: Three computerized tests were designed to evaluate visual function, alertness, and visuocognitive integration under three different lighting conditions (white, red, and blue lighting). Methods: Three computerized tests were designed and programmed using the experimental design software PsychoPy version 2023.2.2. Test 1 evaluated visual acuity (VA), Test 2 assessed contrast sensitivity, and Test 3 measured alertness. This study was conducted on 53 young subjects who performed three computerized tests after adapting to each of the three different lighting conditions. A baseline aberrometric measurement was taken before and after the tests for each lighting condition. Measurements of accuracy and reaction time were taken for each test, along with total, high-, and low-order aberration values for each situation. Results: Statistically significant differences ($p \leq 0.05$) were found among the different lighting conditions across the three tests, with white lighting yielding better performance in Test 1 and Test 3. Additionally, the aberrometric analysis revealed significant differences ($p \leq 0.05$), with the baseline measurement being more myopic. Conclusions: White lighting produced the best VA results and faster reaction times, whereas red lighting had poorer VA effects. These findings suggest that different lighting conditions induce changes in vision and alertness, although further research is needed to understand the underlying causes.

Keywords: aberrometry; alertness; blue light; computer tests; contrast sensitivity; lighting conditions; reaction time; red light; visual acuity; white light

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1. Introduction

Visual function refers to the complex process by which the visual system perceives, processes, and interprets visual information from the environment. Light that reaches the corneal plane passes through all refractive media until it reaches the retina, which transforms the light into nerve impulses to convey information to the occipital lobe of the brain through the optic nerve and the posterior visual pathways. However, the fact that light reaches the retina does not guarantee good vision, as this information must be transmitted via posterior visual pathways to the occipital cortex, where it is processed and analyzed. Cognitive tasks such as pattern identification, depth perception, and recognition of shapes and colors, as well as other specific tasks related to vision, are performed there [1].

The retina is the innermost neurosensory layer of the eyeball and is nourished by the ophthalmic artery, which divides into several branches, including the central retinal artery that supplies the inner retina and the posterior ciliary arteries, which supply the outer retina, choroid, and sclera [2]. In the central region of the retina lies the macula lutea, the area with the highest density of photoreceptors and where the highest visual acuity (VA) is achieved. Specifically, vision is at its peak in the center of the macula, where many photoreceptors responsible for detailed color vision are found in the fovea [3,4].

Photoreceptors are responsible for converting light stimuli into nerve impulses through the process of phototransduction. There are two types of photoreceptors: rods and

cones [4,5]. Rods account for approximately 95% of all photoreceptors and are characterized by their high sensitivity to light but low spatial resolution. In contrast, cones make up the remaining 5% of photoreceptors and provide high spatial resolution at the expense of sensitivity. Importantly, between 15 and 30 rods converge onto a single bipolar cell, whereas each cone is associated with a single bipolar cell, resulting in these differences in spatial resolution. Rods are responsible for functioning under scotopic light conditions, where color vision and detail perception are greatly reduced due to the low activity of cones. Scotopic vision is considered to occur when luminance is below 0.01 cd/m² [6]. Under high levels of illumination, known as photopic conditions, above 0.3 cd/m², cones are the dominant photoreceptors, as rods become saturated by excessive light.

Traditionally, two of the most important tests for evaluating visual function are VA and contrast sensitivity (CS). VA is defined as the maximum spatial resolution capacity of the visual system for high-contrast stimuli, expressed mathematically as the inverse of the angle in minutes of arc subtended by the smallest detail of the optotype used [7]. The CS is defined as the inverse of the minimum contrast necessary to see an object, i.e., the inverse of the contrast threshold. If contrast thresholds are obtained for different spatial frequencies, the CS function is obtained, which reflects the detection capability of the visual system for any spatial frequency. For a standard subject, this function has an inverted U shape with a peak between three and six cycles per degree [7].

An objective way to describe the optical quality of visual function is through wavefront aberration. Wavefront aberration is the difference between the wavefront generated by the optical system and a reference spherical wavefront [8]. When an eye is free from aberrations, i.e., a perfect eye, a spherical wavefront forms ideal images on the retina. Thus, optical aberrations are defects in an optical system that prevent a clear and exact reproduction of the fixation object [8]. There are low-order aberrations (LOAs) (orders 0, 1, and 2) and high-order aberrations (HOAs) (order 3 and higher).

Alertness is defined as a state where high sensitivity to incoming stimuli is achieved and maintained [9]. An objective method to measure alertness is through reaction time (RT) to an unpredictable incoming stimulus. Higher alertness levels are expected to result in shorter RTs, and vice versa. One of the tests used for this measurement is the Go/No-go association task [10,11]. This test is designed to assess selective RT, where subjects must respond as quickly as possible to a specific stimulus and inhibit their response when a different stimulus appears. The literature suggests that RT may be influenced by various variables, such as age, sex, handedness, or education [12,13]. There is a consensus that RT tends to increase with age [14].

The effects of light, particularly light with a wavelength of approximately 480–500 nm, on alertness have gained importance with the discovery of a new type of photoreceptor [15] known as intrinsically photosensitive retinal ganglion cells (ipRGCs). ipRGCs are highly sensitive to blue light and play a crucial role in the suppression of melatonin, a hormone that regulates numerous processes related to circadian rhythm and sleep [9,16]. Exposure to blue light, especially in the evening and at night, can interfere with the natural circadian rhythm by inhibiting melatonin production through ipRGC activation [17]. On the other hand, red represents significant psychological connotations related to danger, caution, or alertness. Studies suggest that red light can also affect mood and visual well-being or modify alertness states [18–21].

Cognitive performance is defined as the brain's capacity to process information and carry out tasks such as perception, thinking, and reasoning [22]. This work focuses on attention and memory because of their relevance to the processing of visual stimuli. Attention is the mechanism involved in the selective processing of psychological activity [23], enabling a response to a single stimulus among various distractors and reducing the response time to expected events [23]. If an individual anticipates what will happen, they can prepare to act accordingly and achieve a shorter RT through preparatory action. Memory refers to the brain functions that allow us to organize, store, and retrieve information [23]. The Atkinson and Shiffrin model [24] divides memory into three types: sensory (a few seconds),

short-term (a few minutes), and long-term. Information is registered by sensory memory, transferred to short-term memory, and can either generate an associated response or be stored in long-term memory.

The main objective of this study was to design three computerized tests to assess visual function, alertness, and visuocognitive integration under three different lighting conditions (white, red, and blue) in healthy young subjects. Specifically, this study aimed to evaluate visual function under these lighting conditions, measure ocular changes via aberrometry after the tests compared with a baseline measurement, and analyze cognitive processing and alertness by quantifying accuracy and reaction time under different lighting conditions.

2. Materials and Methods

2.1. Sample Description and Selection

This study was conducted in accordance with the principles outlined in the Declaration of Helsinki and received approval from the Comité de Ética de la Investigación de la Comunidad de Aragón (CEICA), with registration number PI23/479. The participants provided informed consent prior to their inclusion in this study. The sample consisted of 53 healthy individuals aged between 19 and 30 years, comprising 22 (41.51%) men and 31 (58.49%) women. Participants who were excluded from the experiment met one or more of the following exclusion criteria: presence of ophthalmological or systemic pathologies affecting vision; color blindness; VA less than a 0.0 logarithm of the Minimum Angle of Resolution (logMAR), which is a standardized scale used to quantify the smallest angle that can be resolved by the eye with lower values indicating better VA [25], in each eye and binocularly; attending without their distance optical correction; use of electronic devices one hour before the measurements, stimulating accommodation; consumption of coffee; smoking; and/or engaging in high-intensity sports activities.

2.2. Arrangement of Elements and Ambient Lighting Conditions

The tests were programmed on a laptop computer and displayed on an LG model 60LA620S television (LG, Seoul, Republic of Korea) with a 60-inch screen using an HDMI cable placed approximately 2.50 m from the subject. To minimize distractions and ensure better control of ambient lighting, the test area was surrounded by a neutral gray Munsell N7 fabric, which evenly distributed the lighting throughout the room, creating a controlled lighting room (Figure 1D–F).

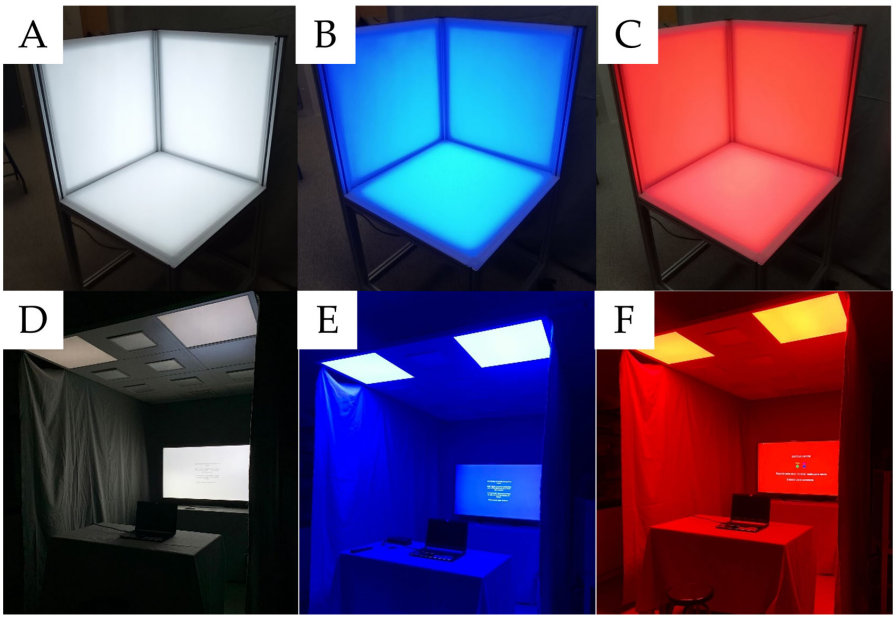

Figure 1. (**A**–**C**) Lighting table where participants were adapted to different lighting conditions. (**D**–**F**) Lighting rooms with different levels of ambient lighting.

Prior to conducting the tests, the participants had to adapt to the different lighting conditions. This adaptation was carried out via a light table (University of Zaragoza, Zaragoza, Spain) equipped with three LED luminaires (Figure 1A–C), the same model as those on the ceiling in the testing area. This table was linked to an iPad, 8th generation model A2270 (Apple Inc., Cupertino, CA, USA), configured with 3 lighting conditions of the same spectrum as the ceiling luminaires (white light, red light, and blue light).

The ambient lighting was achieved via two luminaires installed on the ceiling along with the light emitted by the television itself. Efforts were made to ensure that the emission spectra of the television and luminaires were as similar as possible for the different lighting conditions (Figure 2). Additionally, measurements of irradiance and illuminance on the corneal plane were taken, along with the luminance of the screens used in the experiment (Table 1).

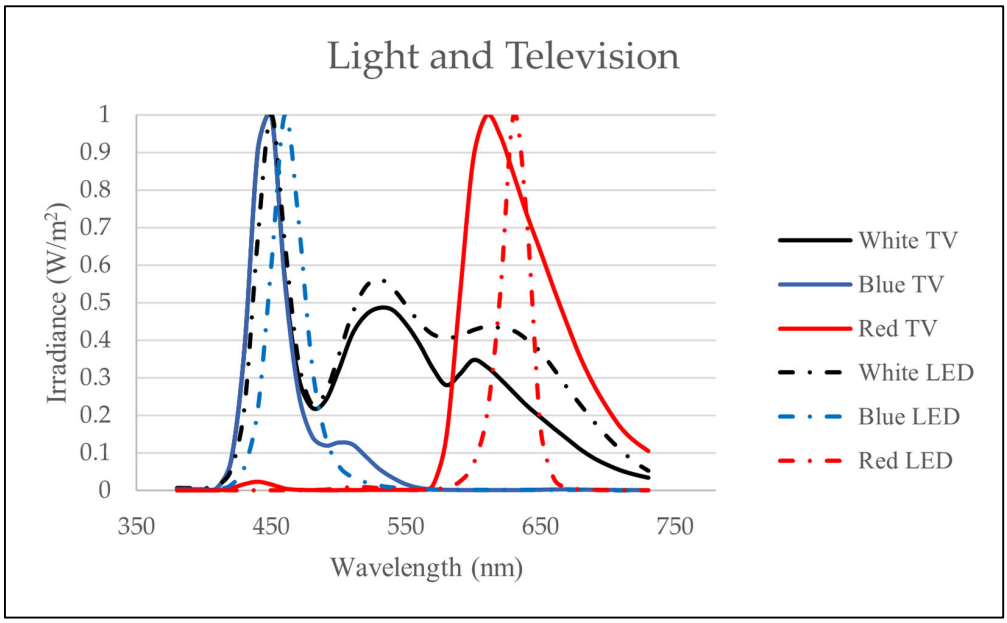

Figure 2. Normalized emission spectra of light sources for different lighting conditions.

Table 1. Results of irradiance, luminance, and illuminance in the corneal plane. The measurements of the luminaire were recorded at the corneal plane, whereas those of the television were taken on the screen.

	White TV	White LED	Blue TV	Blue LED	Red TV	Red LED
Irradiance (W/m^2)	1.20	1.00	0.33	0.39	0.28	0.80
Illuminance (lx)	62.00		76.00		83.00	
Luminance (cd/m^2)	350.37		33.47		71.00	

2.3. Test Designs

The program used for designing the three tests was PsychoPy version 2023.2.2 (Open Science Tools Ltd., Nottingham, UK). PsychoPy is open-source software designed primarily for creating experiments in psychology, neuroscience, and linguistics [26].

2.3.1. Test 1

The first of the three tests, "Test 1", was based on the recognition, memorization, and comparison of letters (Figure 3A). The test started with a 1.5 s fixation cross. Next, 9 letters of the same size appeared for 3.5 s in 9 different positions, allowing participants to freely move their eyes. After this time, all of the letters disappeared except for the central reference letter. The objective of the test was to determine how many peripheral letters

matched the central letter, with possible correct responses: press "1" if it was repeated once, "2" if it was repeated twice, and "0" if the central letter did not repeat among the peripherals. There was no time limit to respond, and participants had the option to respond from the moment the nine letters appeared.

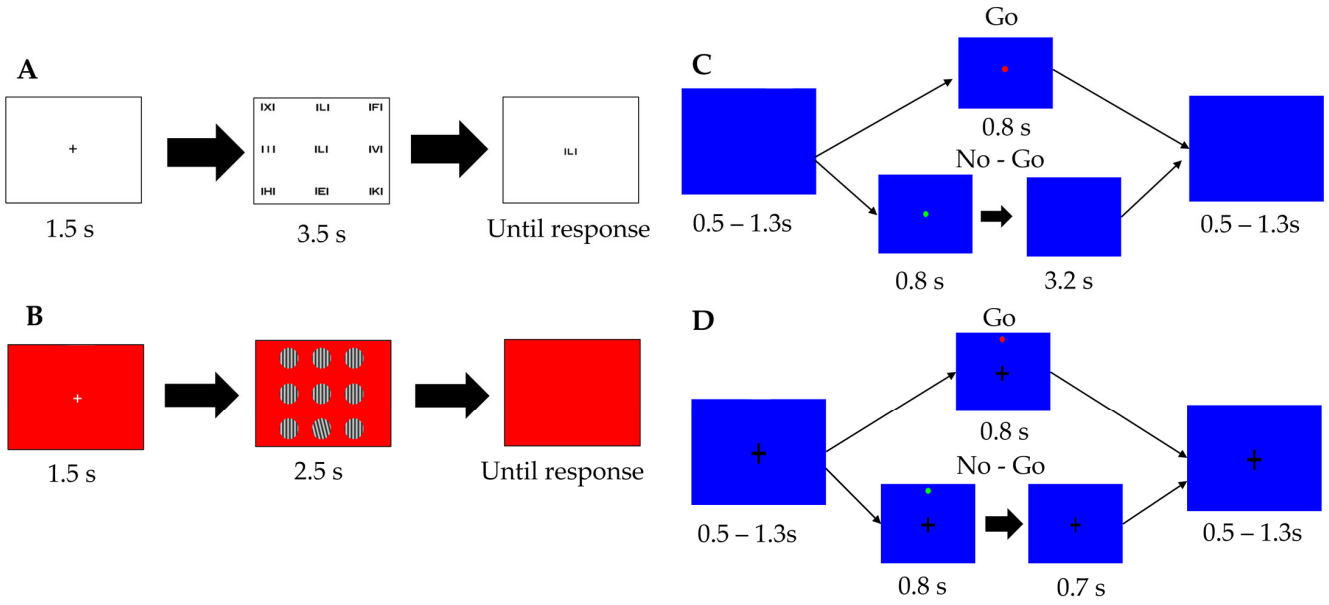

Figure 3. Diagrams of Test 1 (**A**), Test 2 (**B**), the first part of Test 3 with central stimulus (**C**), and the second part of Test 3 with peripheral stimulus (**D**). For the blue illumination of Test 3 (**C**,**D**), participants responded to a red stimulus and ignored a green stimulus.

The test began with four practice attempts, allowing participants to adapt to the test and become familiar with pressing the different keys. Throughout the test, four attempts were made for each letter size, starting from VA 0.22 logMAR and increasing in steps of 0.05 logMAR up to VA 0.0 logMAR. To ensure standardization and efficiency, we used a fixed step size protocol in Test 1, avoiding the need for additional programming and aligning with typical VA testing methods.

Owing to the screen resolution of the television where the tests were projected, easily recognizable letters were chosen starting from a VA of 0.10 logMAR to avoid distortion due to the small size or confusion caused by illuminated pixels. The selected letters were L, I, H, T, X, and F. This restriction did not apply to other VA levels. Additionally, a vertical bar was placed on both sides of each letter to make recognition more challenging due to the crowding phenomenon.

The background color varied depending on the type of ambient lighting. Thus, for white lighting conditions, the background of the screen used for Test 1 was white; for red lighting conditions, it was red; and for blue ambient conditions, it was blue. Moreover, the letters were white for red and blue lighting conditions, whereas they were black for white ambient lighting. Therefore, to maintain consistent conditions across different illuminations, for the case of white ambient lighting in Test 1, two variations were used: white letters on a black background and black letters on a white background. The participants performed either one format or the other pseudorandomly, never both.

2.3.2. Test 2

The second test, "Test 2", was based on the recognition and comparison of orientations among different stimuli (Figure 3B). The test began with a fixation cross lasting 1.5 s. Next, 9 stimuli appeared for 2.5 s in 9 different positions. After this time, all of the stimuli disappeared. The stimulus was a circle with a diameter of 11 cm made up of black and white stripes with variable spatial frequency and contrast. Some stripes were oriented vertically whereas others were oriented at 105° or 75° angles. Since the test was conducted

with the subject 2.5 m from the screen, the stimulus subtended 2.52° relative to the visual axis. Standardized CS tests are typically conducted in cycles per degree, but owing to the screen resolution, the stimulus could not be sized correctly (4.37 cm) to subtend 1° at the indicated distance. Instead, it was programmed to subtend the smallest angle that allowed recognition according to the screen's characteristics. PsychoPy's default grating for contrast sensitivity was used, modifying it to achieve desired levels of contrast and tilt, similar to other clinical tests. The final objective of the test was to recognize how many stimuli were not oriented with vertical stripes, offering possible correct options: press the "1" key if one stimulus was rotated; press the "2" key if two stimuli were rotated; and press the "0" key if all stimuli had vertical stripes. The participants were free to move their eyes and could respond as soon as the stimuli appeared.

The test began with eight practice attempts where stimuli were presented at different spatial frequencies and contrast levels to adapt the participant to the test. During the test, spatial frequencies of 1.5, 3, 6, 12, and 18 cycles/2.52° were examined across eight different contrast levels, ranging from a contrast level of 0.99 to 0.14 PsychoPy units in steps of approximately 0.11. These PsychoPy contrast units are based on Michelson's contrast definition [7].

As in the first test, the background color of the screen varied according to the ambient lighting, but in this case, the stimulus always consisted of white stripes on a black background regardless of the ambient conditions.

2.3.3. Test 3

The third test, "Test 3", was a variation of the Go/No-go association task (14) that focused on sustained attention and RT. In this test, participants were required to press the spacebar as quickly as possible in response to a stimulus of a specific color (Go stimulus) and withhold the response to a distractor of a different color (No-go stimulus). The stimulus consisted of a 5.0 cm diameter circle of varying colors depending on the ambient lighting.

The test was divided into two parts. During the first part of Test 3 (Figure 3C), the stimuli appeared in the central part of the screen for 0.8 s, with responses allowed up to 3.2 s after disappearance. The interstimulus interval after response or nonresponse varied from 0.5 s to 1.3 s, making their appearance unpredictable. The percentage of Go stimuli in this part was 70% of the total. In the second part of Test 3 (Figure 3D), the participants had to fixate on a central fixation cross while the stimuli appeared in the horizontal, vertical, and diagonal peripheral zones of the visual field. A total of 6 vertical and horizontal stimuli and 8 diagonal stimuli appeared, requiring responses to 4 and 6 stimuli, respectively. The vertical stimuli subtended 4.92° from the visual axis, the horizontal stimuli subtended 9.43°, and the diagonal stimuli subtended 10.58°. The stimuli were displayed for 0.8 s, with responses allowed up to 0.7 s after appearance. The time between stimuli remained consistent with the first part of the test.

The difference between the different illuminations, in addition to the background color, was the color of the stimuli. For blue illumination, the participants responded to a red-colored stimulus and ignored a green-colored stimulus. For red illumination, the response stimulus was blue, whereas the distractor was green. Finally, for white illumination, the response stimulus was blue, and the distractor was red. The colors of the stimuli were chosen to avoid color perception confusion, as during preliminary testing of the tests, it was observed that certain colors tended to be confused owing to their closely spaced wavelengths in the spectrum. Additionally, participants were pre-adapted to the ambient light color to minimize immediate color adaptation effects, ensuring consistent perceptual conditions during the test performance.

2.4. Assessment of Optical Changes: Aberrometry

An objective analysis of ocular optical changes under different lighting conditions was performed via an IRX3 Hartmann–Shack aberrometer (Imagine Eyes, Orsay, France). This

equipment uses a 780 nm light source projected onto the retina, generating an aberrometric map of the evaluated eye on the basis of the reflected rays.

A baseline measurement was taken from each eye upon the subject's arrival before the tests were conducted, always under scotopic ambient conditions. Immediately after the three tests for each type of lighting were completed, the aberrometric measurements of each eye were repeated. The aberrometer uses a Snellen E optotype as a fixation stimulus on a white background surrounded by two concentric circles. To prevent the color of the white background from influencing the measurement, a red filter was inserted into the device for red lighting, and a blue filter was inserted for blue lighting, maintaining the white background for measurements following white ambient lighting conditions. This approach ensured that the aberrometric measurements were conducted with light stimuli equivalent to the environments in which the tests were conducted.

2.5. Experimental Protocol

Following the protocol, baseline aberrometric measurements of each eye and monocular VA measurements with the Optonet Vision Unit application (Optonet LTD, Warrington, UK) were performed [27]. The participants were subsequently asked to sit in front of the light table and adapt to one of the types of ambient lighting. The adaptation period lasted 15 min, and the choice of lighting was pseudorandomized to prevent biases in the results. Following adaptation, the participants were instructed to move to the controlled lighting environment area to perform the three tests designed with PsychoPy in a pseudorandom order. Once the tests were completed under specific lighting conditions, another aberrometric measurement of each eye was taken separately. Specifically, if adaptation began under blue lighting conditions at the light table, the ambient lighting conditions for performing the computerized tests were blue, and aberrometry was conducted with a blue filter for each eye. This process was repeated with pseudorandom adaptation under red or white lighting at the light table, maintaining these conditions for both the computerized tests and the aberrometry. This procedure was then repeated for the remaining two types of lighting. The complete measurement session lasted approximately 1 h per participant.

Finally, each participant was asked to complete a questionnaire designed in Google Forms regarding symptoms and performance before and during the tests under different ambient conditions.

2.6. Data Processing and Statistical Analysis

The data collected with the IRX3 aberrometer were exported to an Excel database (Microsoft® Office Excel 2021, Washington, DC, USA). The aberrometric data were obtained on the corneal plane and at the maximum pupil diameter. Since the number of aberrations depends on the pupil diameter, a rescaling process [28,29] up to the 6th order of aberration for a 4.00 mm diameter pupil was performed via a programming code written in MATLAB version R2022b (MathWorks Inc., Natick, MA, USA). Once the Zernike coefficients were rescaled for a 4.00 mm pupil, the corresponding objective refraction was calculated using the spherical equivalent (M), J0, and J45 of each subject under each lighting condition [30]. Finally, all aberrometric measurements were treated as left eyes (OS), transforming the measurements from right eyes (OD) to OS using the ISO 24157:2008 standard [31].

The variables under study were analyzed via the Statistical Package for the Social Sciences (SPSS 26.0, SPSS Inc., New York, NY, USA). First, a descriptive statistical analysis of the sample was conducted for each of the three computerized tests and the aberrometric measurements under each ambient lighting condition. This included calculating the mean, standard deviation, and minimum and maximum values for each variable. The sample variables did not follow a normal distribution on the basis of the Kolmogorov-Smirnov test, likely due to the small sample size and data skewness. Therefore, the different variables from the designed tests and the IRX3 aberrometer across different lighting conditions were compared pairwise via the nonparametric Wilcoxon signed-rank test for related samples. A p value ≤ 0.05 was considered statistically significant in all of the cases.

3. Results

The sample consisted of 53 young participants, among whom 22 (41.51%) were men and 31 (58.49%) were women, with a mean age of 22.36 ± 2.18 years, ranging from 19 to 30 years, all of whom met the inclusion criteria.

3.1. Computerized Tests

To analyze the results of the three designed tests, the number of correct responses and the RT for each test were considered and compared across the three lighting conditions: white, red, and blue.

3.1.1. Results of Test 1

The number of correct responses and RT were classified into five different variables, one for each VA level described previously.

Compared with the results obtained under white ambient lighting conditions using tests with black letters on a white background and white letters on a black background, no statistically significant differences were detected between the two groups in terms of either the number of correct responses or RT for any VA level. Therefore, when comparing different lighting conditions, these two groups were considered together within the white lighting condition.

Thus, the best results in terms of correct responses (Figure 4A) were obtained with white ambient lighting, where statistically significant differences ($p \leq 0.05$) were found compared with the results obtained under red ambient lighting across all VA levels. Conversely, when comparing results between white and blue lighting conditions, statistically significant differences were found only at a VA of 0.05 logMAR ($p = 0.002$).

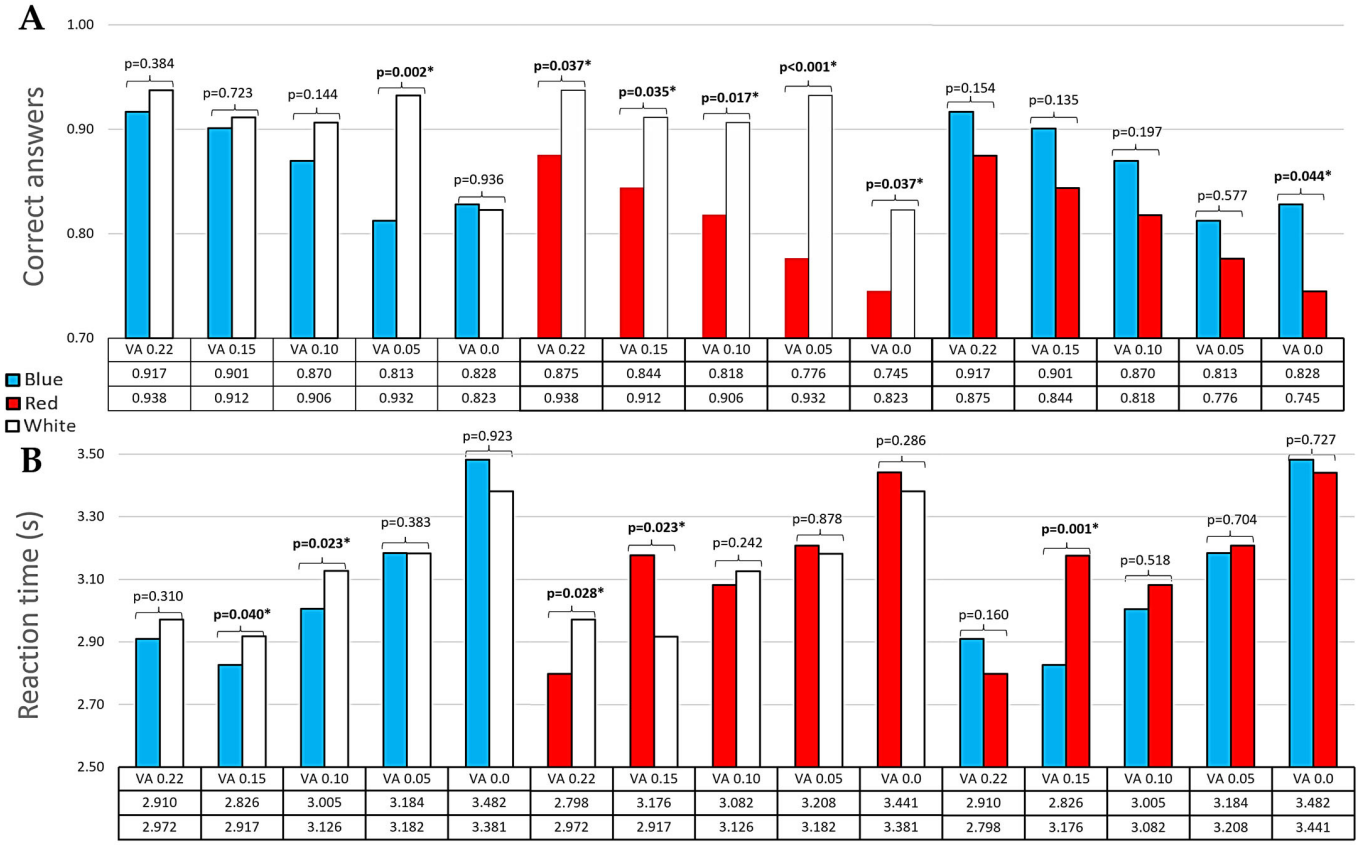

Figure 4. The comparison of the correct answers (**A**) and reaction times (**B**) for each VA in logMAR of Test 1 between each type of lighting. Each *p* value is represented on the bars, where * and bold letters indicate statistically significant differences ($p \leq 0.05$).

Finally, among the results from the blue and red ambient lighting conditions, better results were achieved with blue lighting. However, statistically significant differences were found only at a VA of 0.0 ($p = 0.044$).

There was no clear lighting condition that globally reduced the RT (Figure 4B). Thus, red lighting resulted in a lower RT for a VA of 0.22 logMAR; blue lighting resulted in VAs of 0.15 logMAR and 0.10 logMAR; and white lighting resulted in VAs of 0.05 logMAR and 0.0 logMAR. However, statistically significant differences ($p \leq 0.05$) were found only when comparing TRs under white lighting with blue lighting at VAs of 0.15 logMAR and 0.10 logMAR and white lighting with red lighting at VAs of 0.22 logMAR and 0.15 logMAR. Additionally, when comparing blue lighting with red lighting, statistically significant differences in RT were found only at a VA of 0.15 logMAR, indicating faster reaction times with blue light.

In all cases, as the level of VA required increased, the RT increased, and the number of correct answers decreased.

3.1.2. Results of Test 2

The number of correct responses and the RT were statistically analyzed in two distinct ways: by spatial frequency and by the contrast level of the stimulus.

For spatial frequency, the results were divided into six variables: 1.5, 3, 6, 12, and 18 cycles/2.52°. For contrast, the results were divided into eight levels in descending order of contrast (C1, C2. . .C8), ranging from 0.99 PsychoPy contrast units at the first level to 0.14 units at the last level, with steps of approximately 0.11.

For the number of correct responses by spatial frequency (Figure 5A), no statistically significant differences ($p \leq 0.05$) were found when comparing blue ambient lighting with white or red lighting. However, when red ambient lighting was compared with white ambient lighting, better results were observed with the former, with statistically significant results only for frequencies of 3 and 6 cycles/2.52° ($p = 0.037$ and $p = 0.030$, respectively).

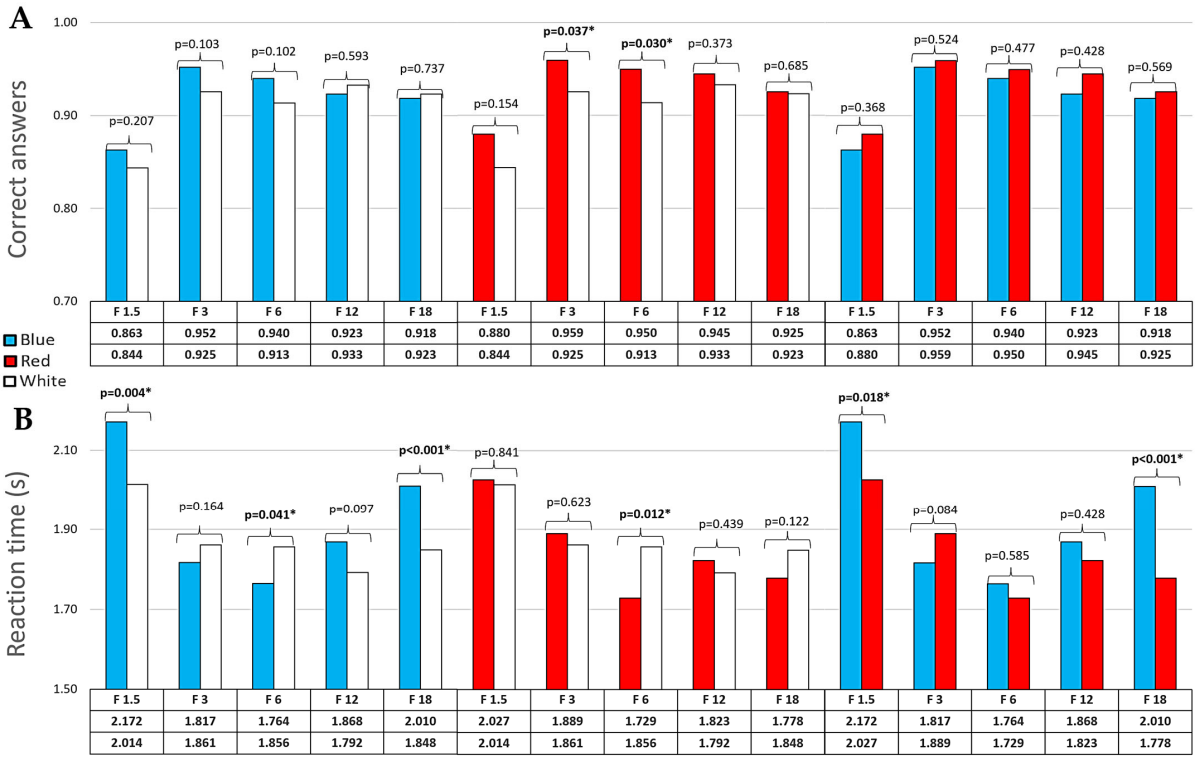

Figure 5. The comparison of the correct answers (**A**) and reaction times (**B**) in each spatial frequency (in cycles/2.52°) of Test 2 for each type of lighting. Each p value is represented on the bars, where * and bold letters indicate statistically significant differences ($p \leq 0.05$).

Analyzing the RT by spatial frequency (Figure 5B), blue lighting resulted in slower RTs at frequencies of 1.5 and 18 cycles/2.52°, with statistically significant differences compared with the other two ambient conditions. However, at a frequency of 6 cycles/2.52°, a significantly faster RT (p = 0.041) was observed with blue light than with white light. Between white and red lighting, statistically significant differences were found only at a frequency of 6 cycles/2.52° (p = 0.012), with a shorter RT observed under red lighting.

An analysis of the results based on the stimulus contrast revealed that although there were multiple significant differences ($p \leq 0.05$) among the three ambient conditions, no overall condition consistently produced better or worse results in terms of the number of correct responses (Figure 6A), or RT (Figure 6B).

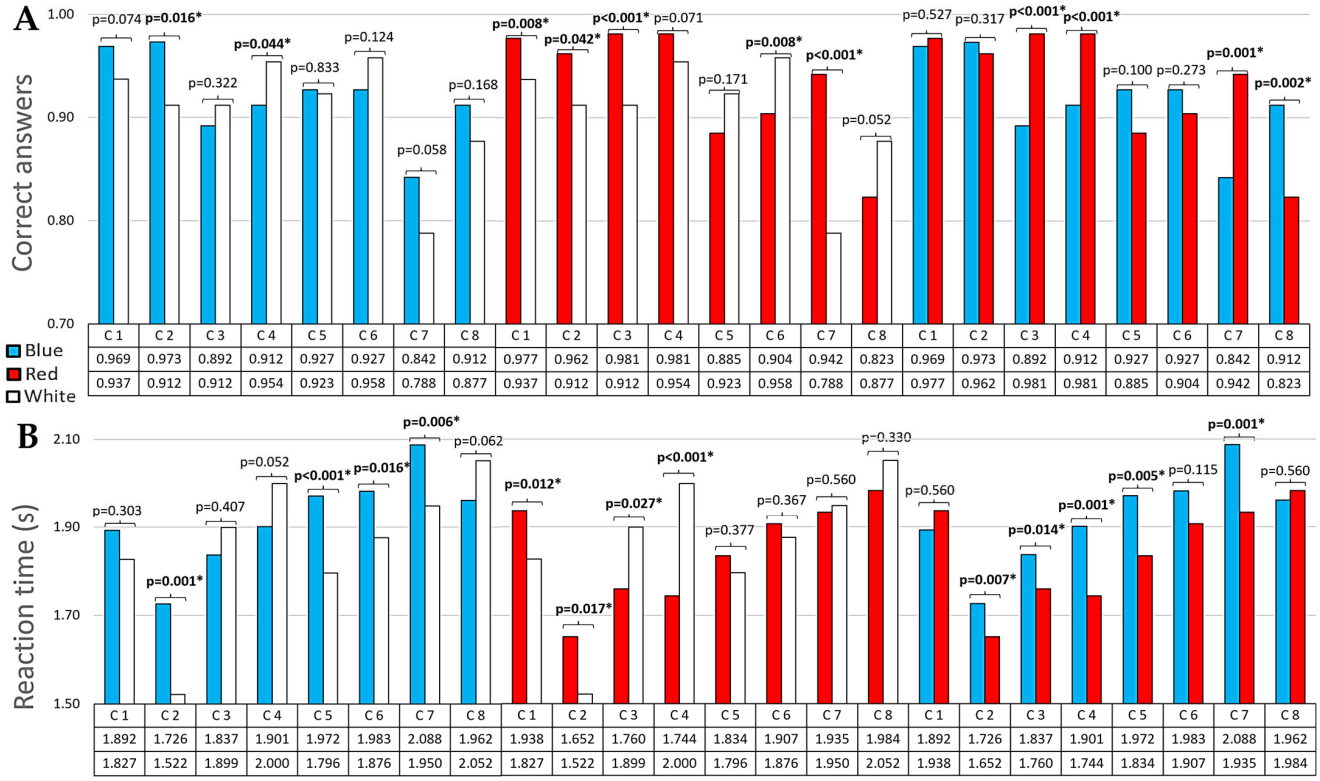

Figure 6. The comparison of the correct answers (**A**) and reaction times (**B**) for each contrast level (C1–C8) of Test 2 between each type of lighting. Each p value is represented on the bars, where * and bold letters indicate statistically significant differences ($p \leq 0.05$).

However, a general trend of increasing RT was observed as the contrast between the stripes of the stimulus decreased, except for contrast level C1.

3.1.3. Results of Test 3

The number of correct responses and RT were divided into five variables on the basis of the stimulus location. Thus, the results of the first part of the test were represented by the parameter 'Center'.

The second part of the test was divided into three parameters on the basis of the stimulus appearance location: 'vertical' if it appeared above or below; 'horizontal' if it appeared to the left or right; and 'diagonal' if it appeared in one of the four diagonals. Therefore, the entirety of the second part of the test was represented by the parameter 'Peripherical'.

With respect to correct responses (Figure 7A), it was under the red lighting condition where worse results were obtained compared with the other two types of lighting, with statistically significant differences ($p \leq 0.05$) observed when the stimulus appeared in peripheral and vertical locations. There were no significant differences in the number of correct responses between the results obtained under white and blue light. Furthermore,

no significant differences between lighting conditions were found in any case when the stimulus appeared in the center.

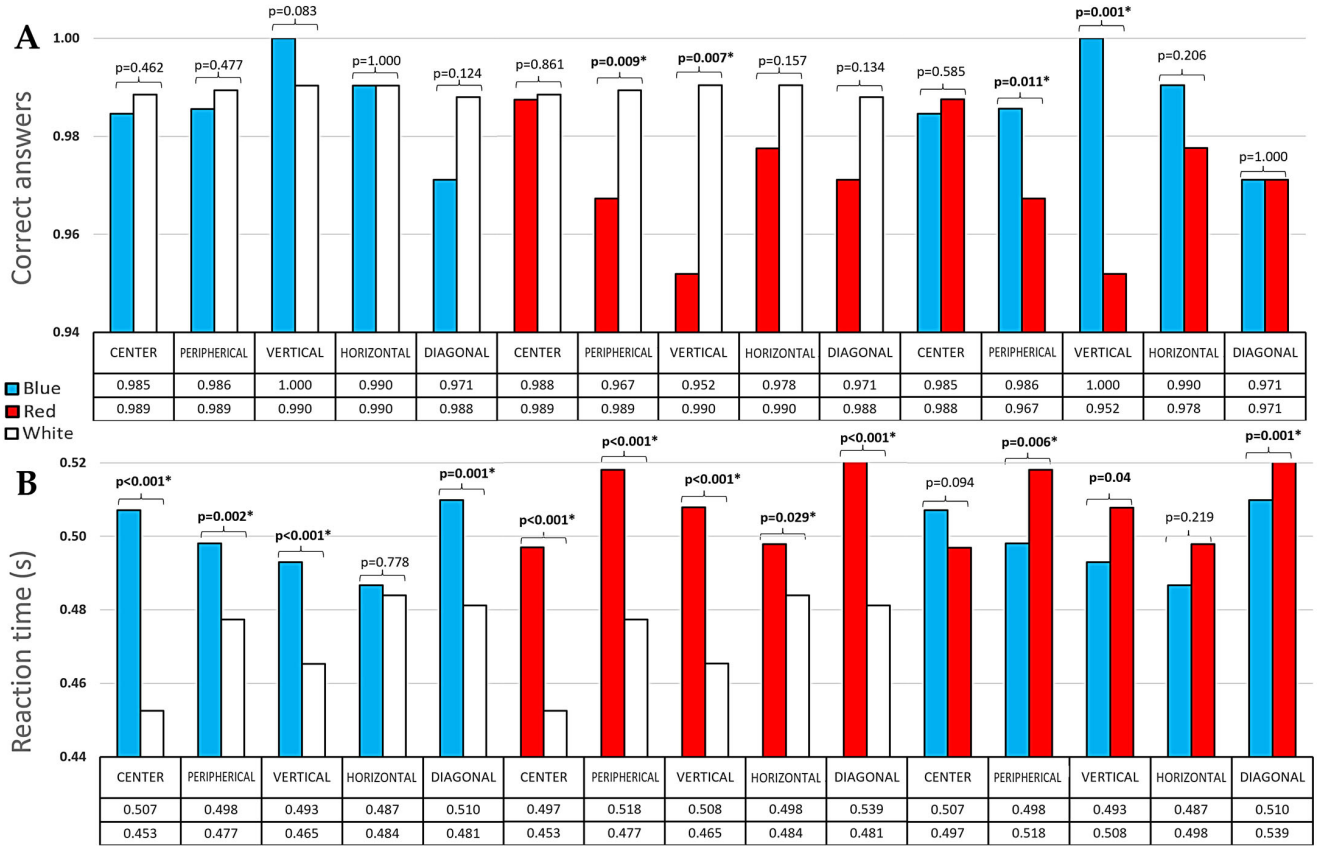

Figure 7. The comparison of the correct answers (**A**) and reaction times (**B**) for each stimulus appearance position in Test 3 between each type of lighting. Each *p* value is represented on the bars, where * and bold letters indicate statistically significant differences ($p \leq 0.05$).

Under red ambient lighting (Figure 7B), significantly lower values than under white light were obtained for the RT at all stimulus appearance locations. When red light was compared with blue light, statistically significant differences were found only in the second part of the test, except for the 'horizontal' parameter ($p = 0.219$).

In contrast, under white light, significantly faster RT values were achieved at all stimulus positions, except for the 'horizontal' location ($p = 0.778$), than under blue light.

3.2. Aberrometric Measurements

The values of the Zernike coefficients and M, J0, and J45 were collected and compared among each other for the four measurements: baseline and after performing tests under different types of lighting (white, red, and blue). Each order of aberration from order 2 to order 6 was analyzed separately. Order 2 includes LOAs (defocus, C0 (2, 0); and astigmatism, C0 (2, 2) and C0 (2, −2)), whereas HOAs consist of orders from 3 to 6.

For the M values (Figure 8), statistically significant differences ($p \leq 0.05$) were observed when the lighting conditions were compared with the baseline measurement, with the baseline being more myopic in all cases. Among the lighting conditions, significant differences were found only between white and red light ($p = 0.012$). With respect to the J0 and J45 values (Figure 8), no significant differences were found except when blue light was compared with red light for J45 ($p = 0.030$).

Within LOAs, significant differences were found in order 2 for the coefficient C0 (2, 0) among all lighting conditions except when comparing blue and red light (Table 2). In HOAs, significant differences were obtained in the central terms of even orders and in

coefficients C0 (3, −1) and C0 (6, 2). No statistically significant differences were found in the rest of the coefficients.

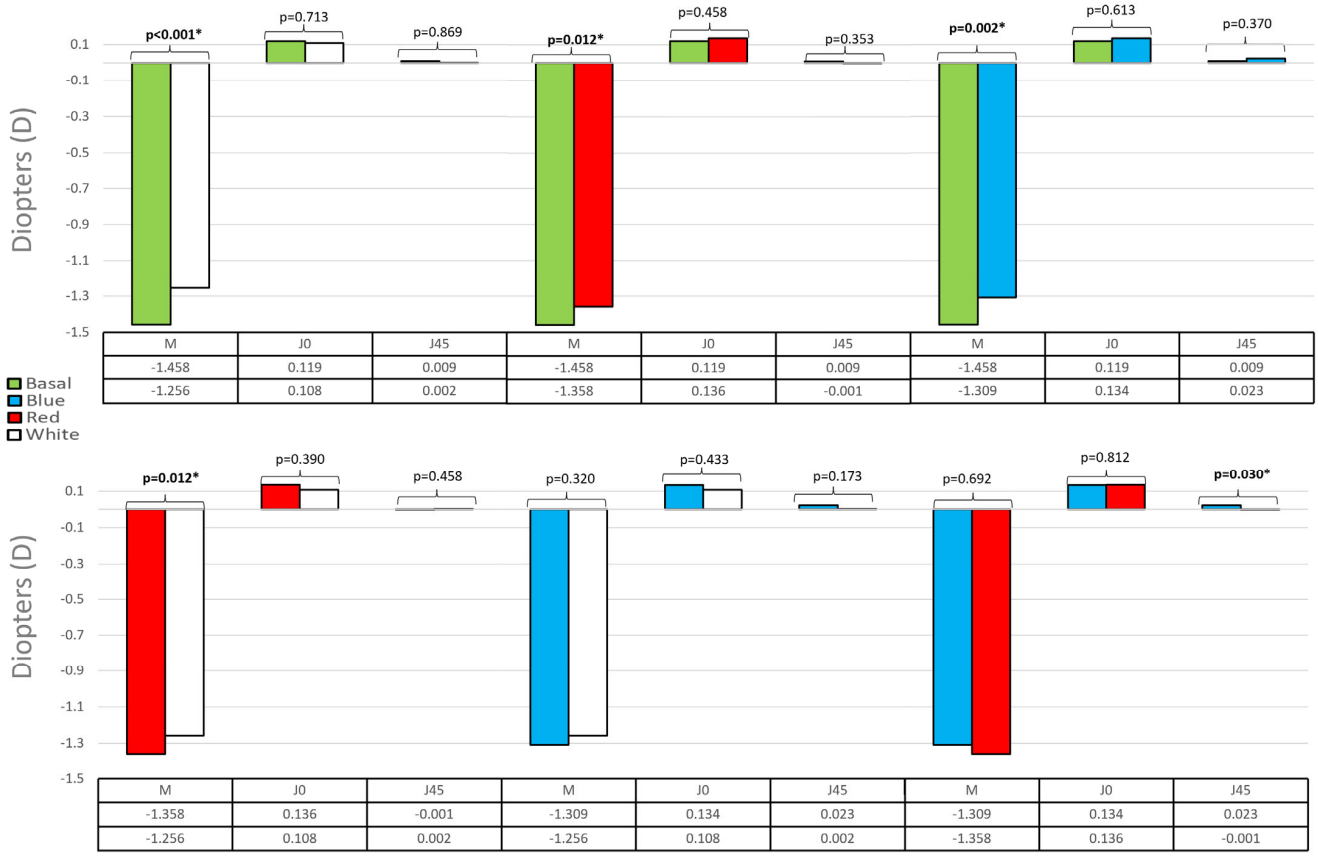

Figure 8. Comparison between the basal measurement and the three types of lighting in terms of M, J0, and J45. Each *p* value is represented on the bars, where * and bold letters indicate statistically significant differences ($p \leq 0.05$).

Table 2. Statistical significance (*p* value) for order 2 of LOA (A) and for the coefficients C0 (3, −1), C0 (4.0), C0 (6.0), and C0 (6.2) belonging to HOA orders (B). An asterisk (*) indicate statistical significance ($p \leq 0.50$).

p Values	C0 (2, −2)	C0 (2, 0)	C0 (2, 2)	C0 (3, −1)	C0 (4, 0)	C0 (6, 0)	C0 (6, 2)
Basal–White	$p = 0.631$	$p < 0.001$ *	$p = 0.267$	$p = 0.224$	$p = 0.079$	$p = 0.280$	$p = 0.009$ *
Basal–Red	$p = 0.417$	$p = 0.042$ *	$p = 0.267$	$p = 0.302$	$p = 0.023$ *	$p = 0.015$ *	$p = 0.961$
Basal–Blue	$p = 0.660$	$p = 0.006$ *	$p = 0.396$	$p = 0.037$ *	$p = 0.050$ *	$p = 0.003$ *	$p = 0.954$
White–Red	$p = 0.183$	$p = 0.002$ *	$p = 0.827$	$p = 0.439$	$p = 0.849$	$p = 0.584$	$p = 0.084$
White–Blue	$p = 0.836$	$p = 0.008$ *	$p = 0.721$	$p = 0.392$	$p = 0.471$	$p = 0.045$ *	$p = 0.051$
Blue–Red	$p = 0.151$	$p = 0.653$	$p = 0.702$	$p = 0.033$ *	$p = 0.841$	$p = 0.421$	$p = 0.809$

It should be noted that since defocus, C0 (2, 0), was the predominant aberration in all cases, whenever significant differences were found in this coefficient, it was expected that they would also be found when comparing M values.

3.3. Subjective Survey Results

In the subjective survey of symptoms and performance under each lighting condition, most subjects believed that they had performed better (43.4%, 23 responses) and

experienced a greater sense of visual well-being (41.5%, 22 responses) overall during tests conducted under white lighting conditions, followed by blue lighting, where performance (34%, 18 responses) and visual well-being (35.8%, 19 responses) were also perceived positively. Consequently, the subjects perceived themselves to have performed worse (22.6%, 12 responses) and experienced a lower sense of visual well-being (22.6%, 12 responses) under red lighting.

4. Discussion

This study examined changes in visual function, alertness, and cognitive performance in a sample of healthy young adults without pathologies following their adaptation to various lighting conditions. The participants were instructed to perform three computerized tests designed for this purpose.

Additionally, optical changes in the visual system were investigated through aberrometric measurements conducted before (baseline) and after the completion of the tests under each of the different lighting conditions.

In Test 1, under red ambient lighting conditions, poorer results were obtained across all VAs. This could be attributed not only to the direct effect of the lighting itself but also to the lower contrast between the white letters and the red background (0.66) compared to the contrast between white letters on a blue background (0.83) or black letters on a white background (0.98). These lower differences in contrast likely increased the difficulty in letter recognition. This observation also explains why the best results were achieved under white lighting, despite contradicting findings by Lin et al. [32], who argued that background color did not significantly affect VA. However, Shieh and Lin [33] suggested that the combination of background color relative to the stimulus had a profound effect on visual performance, which is consistent with our findings. These discrepancies could stem primarily from differences in ambient conditions and in the optotypes used in the experiments.

Previous studies have also examined the relationships between VA in logMAR and white, blue, and red lighting conditions, as well as luminance levels [32,34–36]. The experimental conditions described by these authors differ significantly from ours and among themselves, posing challenges for a comprehensive analysis. Clavé et al. [34,35] reported higher VAs under white and red lighting conditions (VA −0.100 and VA −0.107, respectively), whereas worse results were obtained under blue lighting (VA 0.260), contrary to our findings. In Fernández-Alonso et al.'s work [36], the difference between red and white lighting (VA −0.041 and VA −0.049) and blue lighting (VA 0.041) was much smaller. The discussion in these studies revolves around Longitudinal Chromatic Aberration (LCA), where subjects become myopic when measured on blue (resulting in poorer VA) and hyperopic when measured on red in the absence of accommodation. This phenomenon is based on the refractive index's dependence on wavelength—shorter wavelengths correspond to higher refractive indices and vice versa and could explain these findings.

However, upon examining the aberrometric measurement data (Figure 8), our results did not reveal significant differences in the coefficients of order 2 (Table 2) or in M and J0 between blue and red lighting conditions, suggesting that the effect of the LCA would be minimal. Consequently, LCA may not be the primary cause of the decreased VA or test accuracy in our study. These findings are consistent with studies that have measured VA with and without LCA correction [37–40], where improvements were not achieved under high-contrast conditions or with adaptation time for correction. A slight decrease in VA values was observed when the LCA was doubled [39]. In contrast, Roorda et al. [40] reported a difference in VA, but only when both the LCA and transverse chromatic aberration (TCA) were corrected simultaneously.

Other factors that could contribute to the differences among these studies include the use of different VA measurement methods and varying room lighting conditions. Additionally, in the mentioned studies [34,35], the subjects were not adapted to ambient lighting, and the illuminance reaching the corneal plane under different lighting conditions

was not specified. Moreover, the luminance levels and contrasts evaluated in those studies differ from ours, which directly affects VA outcomes [7].

Finally, no studies have evaluated how cognitive processing varies with lighting conditions during VA measurement. Furthermore, our study did not observe a trend indicating that better test results correlate with faster response times.

In Test 2, no illumination condition resulted in significantly better overall performance, neither when analyzed according to spatial frequency nor contrast. Generally, poorer performance was observed in terms of accuracy at lower spatial frequencies and faster response times at medium frequencies.

According to the CS curve for normal healthy subjects, it would be expected that as the spatial frequency increases, the accuracy decreases, reaching a peak at medium spatial frequencies. However, this pattern was not observed in our results, possibly because the stimulus subtending angle requires a much higher spatial frequency than that measured, which is limited by the screen resolution. Moreover, as contrast decreased, there was a progressive increase in RT across all lighting conditions, except at the maximum contrast (C1), where slower response times were recorded compared to lower contrast levels (C2). This could be influenced by the learning effect for each spatial frequency. Additionally, Roorda et al. [40] reported an improvement in CS when both LCA and TCA were corrected simultaneously. However, no studies have measured CS under lighting conditions such as those in our study, indicating that this is a novel finding that could serve as a starting point for future research. Additionally, our test measures both contrast sensitivity and tilt angle sensitivity, offering a comprehensive assessment of CS-related visual performance similar to traditional clinical tests.

For Test 3, when the stimulus appeared centrally, the average RT was faster for white illumination and slower for blue illumination, with a mean difference of approximately 44 ms. Moreover, when the stimulus appeared peripherally, the average RT was minimal for white illumination and maximal for red illumination, with a mean difference of approximately 41 ms.

Furthermore, during the test where the stimulus appeared peripherally, the subjects exhibited poorer response inhibition control with red light, resulting in an average 2% higher error rate than those of the other two types of illumination. This difference was not observed when the stimulus appeared in the center of the screen (Figure 8).

Previous studies have utilized the Go/No-go test to examine whether RT varies on the basis of the color of the stimulus to which participants must respond, typically under achromatic background lighting conditions [41–44]. Some studies [41,42] have reported faster RTs when the stimulus color was blue, which contrasts with the findings of this study. In contrast, Amini et al. [43] reported faster RT with a red stimulus, whereas Hourinouchi et al. [44] did not find significant RT differences between blue and red stimuli.

In our study, despite white illumination (blue stimulus to respond to) resulting in a faster RT, no significant differences were found between blue illumination (red stimulus to respond to) and red illumination (blue stimulus to respond to). This finding suggests that this effect may have been partially masked by the background illumination to which the subjects were exposed. Moreover, other studies comparing RT under different lighting conditions [45,46] did not find significant differences between red and white illuminations, contrary to our findings in this study. The emission spectra of the television and ceiling light differ, with the red television spectrum overlapping the red LED minima and affecting M-cones. However, these differences are not expected to significantly impact our study's focus on cognitive performance and alertness.

With respect to the aberrometric measurements, significantly more myopic values of M were obtained in the baseline measurement than in all types of illumination. Similar results were reported in a study by Orduna-Hospital et al. [47], although in their study, the subjects remained adapted to different lighting conditions without engaging in any additional vision-stimulating activities. This discrepancy could be attributed to the accommodation of subjects during the baseline measurement, which did not occur during subsequent

illuminations. Additionally, more myopic values of M were obtained with red illumination than with blue light, but this difference was not statistically significant, which aligns with findings from this study [47].

Finally, the results of the subjective survey carried out by the subjects, where they believed that they had performed better in the tests with white light and worse with red light, were correlated with the results obtained in Test 1 and Test 3.

5. Conclusions

Several conclusions can be drawn from this research study. PsychoPy facilitated the development of computerized tests aimed at evaluating visual function, cognitive performance, and alertness under three different lighting settings, allowing for the quantification of accuracy rates and reaction times. The findings revealed that white illumination produced the best results, whereas red illumination yielded the poorest outcomes in the VA assessment. In the CS, similar results were observed across all lighting environments; furthermore, white light was found to significantly increase alertness levels, leading to faster RT. Additionally, the evaluation of ocular aberrations conducted before and after the tests under different lighting conditions revealed significantly greater myopic values in the baseline measurements than in the red illumination measurements under the other lighting conditions. These results suggest that visual function and alertness are influenced by the ambient lighting environment to which subjects are exposed. However, the current literature lacks sufficient information regarding the potential cellular pathways in the brain that could explain these effects, indicating a need for further research to understand the underlying causes of light-induced changes.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ethical reasons.

Conflicts of Interest: The authors declare no conflicts of interest.

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