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Long-term effects of blue-blocking spectacle lenses on color perception

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Abstract: The use of blue-blocking filters is increasing in spectacle lens users. Despite the low absorption in the blue range, some users complain about these filters because they affect their color perception. In a pilot study we have evaluated how the long-term use of 8 different blue-blocking filters impact the color perception during more than 2 weeks on a group of 18 normal color vision observers, compared with a control group of 10 observers. The evaluation was done using the FM100, the Color Assessment and Diagnosis (CAD) and an achromatic point measurement. Our results show that there is a trend to worsen with the filters on.

1. Introduction

The blue light emitted by different devices (LEDs, screens, etc.) has received a lot of media attention in recent years. This has created a controversial alarm among the population about its danger without sufficient scientific support to justify it. In 2018 two European Commission scientific committees issued a joint comprehensive report focusing on the assessment of potential risks to human health associated with the use of LEDs, [1] concluding that "*there is no evidence of direct adverse health effects from LEDs emission in normal use (lamps and displays) by the general healthy population*". They also recommended that further research is needed to ascertain the specific impact of LED lights on the circadian system because nowadays *"it is not clear if this evening disturbance of the circadian system leads to long-term adverse health effects*".

Despite the absence of strong scientific evidence highlighting the risk of blue light, some commercial companies decided, around ten years ago, to manufacture filters to block blue light, visualizing a commercial niche. Filters to absorb blue light are currently marketed as additional treatment in ophthalmic lenses, contact lenses or intraocular lenses, as well as in the form of specific filters as screen protectors for computers, mobile phones or tablets. Electronic devices also integrate functions that allow the user to change the intensity and color temperature of the display by dimming the blue LEDs in the RGB displays. An example of this function is the popular night mode present in most cell phones, tablets and computers.

We have noted the potentially confusing nature of terminology of "blue-blocking" filters. Here we do not deal with the study of filters that actually absorb almost all the blue content, which have been analyzed in other works [2–4], but with filters that, even named as blue-blocking for commercial purposes, their blue absorption is not remarkable. Today, virtually all manufacturers of ophthalmic lenses offer these options and a large majority of users opt to select them when buying their glasses because they have been warned about the potential risks of blue light in some marketing campaigns. However, optometrists sometimes encounter users that reject this type of filters because they affect their chromatic discrimination and color perception. Consequently, this may affect the performance in their professional activities particularly when these are related to color as, for example, graphic designers, photographers, lighting technicians, painters, tattooists, etc.

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In 2017 Leung et al. [5] evaluated, among other visual functions, the color discrimination of two blue-light filtering spectacle lenses using the Farnsworth Munsell 100 hue test (FM100) on 80 participants wearing the lenses for one month for a minimum of 2 hours per day. The color discrimination was evaluated after that month, but authors only considered the total error score from the FM100. Participants also assessed subjectively their performance through a questionnaire.

In the recent study in 2021 by Baldasso et al. [6] they evaluated how three commercial blue-blocking lenses filters change color discrimination on ten young subjects, just after putting on the glasses, with the following three computer-based color vision tests: Color Assessment and Diagnosis (CAD), Cambridge Color Test, and FM100. They concluded that no statistically significant effects on color perception were found.

In none of these Refs. [5,6] the authors tackled the analysis of long-term continuous changes in color perception due to the use of different commercial "blue-blocking" lenses. How does chromatic adaptation affect the chromatic perception through "blue-blocking" filters? How does the color perception change with long-term usage of these lenses?

Long-term chromatic adaptation has been experimentally induced by exposing observers for long periods to artificially colored lenses, showing that chromatic experience was altered [7,8]. In the work by Eisner and Enoch [7], three subjects wore a red filter over one eye for one week and their chromatic perception was evaluated using the unique-yellow experiment and an anomaloscope. Their results demonstrated that "long-term exposure to a long-wavelength world can induce relatively prolonged (at least hours) postreceptoral adaptation". The authors stated that the changes in sensitivity could not be attributed to preneural changes in the eye, as the anomaloscope settings appeared to remain unchanged.

Neitz et al. [8] subjected four observers to chromatically altered conditions (colored contact lenses, glasses with colored filters, or a room with colored lighting) over several days. The chromatic alteration period changed from 4 hours to 12 hours and the unique yellow was measured. Authors found that each subject's unique yellow shifted progressively, being the shift size not constant over time and varied between the subjects. The change in unique yellow induced by wearing colored lenses was largest during the first few days, and appears to change more slowly at the end of a 2-week chromatic alteration period. Neitz et al. claimed that their experiments of chromatic alteration demonstrate that "*long-term changes in chromatic experience induce a change in the weighting of the L and M cone inputs to the chromatically opponent red/green channel*".

Tregillus et al. [9] claimed that the mechanisms and timing that control the compensatory adjustments inherent to chromatic adaptation "are still poorly understood". In their paper they evaluated chromatic adaptation by having 12 young observers wearing glasses, 8 hour per day for 5 days during daylight hours, with yellow filters that approximated the lens transmittance of an older observer (around 70 years old). The observer's white point was measured on a calibrated monitor along the "blue–yellow" axis under different states of adaptation and with the lenses either on or off. After a 5 minutes dark-adaption, the white point was determined at the beginning and end of each 8 hours interval, both with and without the yellow lenses. Authors found large individual differences in the magnitude of the color settings. Results showed a large shift towards yellow for all observers, that occurred in the first 2 hours and that was reduced by up to 50% by the end of the day. Authors found that, after removing the glasses at the end of the day, the expected bluish aftereffect was not observed. They also concluded that "*significant compensation occurs within each day but did not transfer across days or lead to a prolonged aftereffect at the end of the day*".

In 2020 Werner et al. [10] evaluated the effects of long-term usage during two weeks of a model of EnChroma glasses (a broad-band spectrally selective filter) in eight anomalous trichromats and nine normal trichromats, on luminance and chromatic contrast response. Results showed that their chromatic perception changed as they wore the glasses over several days. Moreover, this color modification persisted days after the glasses were removed, demonstrating an adaptive visual response. Webster [11] states that vision is a plastic process and "*how the brain interprets the receptor signals to create our conscious impressions of color is still deeply mysterious*". Isherwood et al. [12] recently claimed that understanding compensatory adjustments can serve as an important insight into the general principles of adaptation and plasticity in the human visual system.

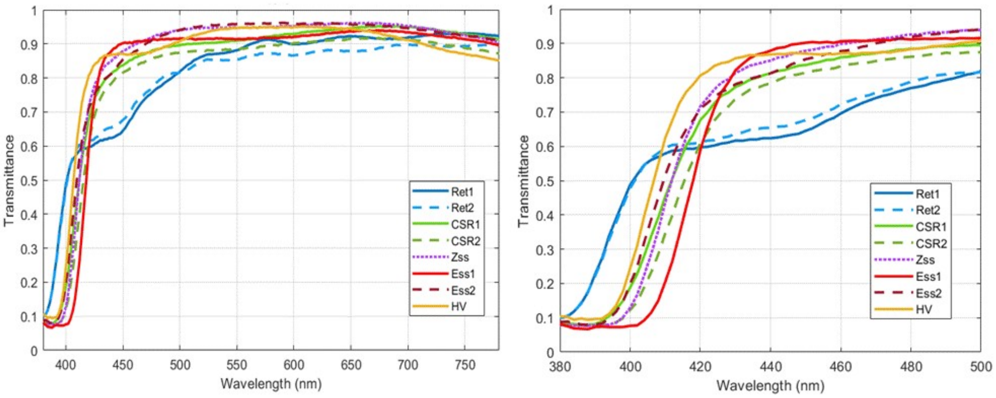
The main objective of this pilot study is to investigate how the long-term use of "blue-blocking" filters could modify the color perception of normal color vision observers, and to describe the temporal evolution of the changes. To do so we have investigated 8 blue-blocking filters from five different brands, whose transmittances have been measured, on a group of 18 normal color vision observers. A control group of 10 additional observers who did not use any filter was also included. To analyze the changes in color perception three different tests were used: the FM100 [13], the Color Assessment and Diagnosis (CAD) [14,15], and an achromatic point measurement similar to the one used by Tregillus et al. [9]. The comparison between these three tests was not an objective of our study, although the results obtained allowed us to compare which one was more sensitive to describe the potential changes in color perception.

This paper is organized as follows: Section 2 describes the filters used, the observers and the tests employed; Section 3 presents and analyses the results obtained; and in Section 4 we draw the conclusions.

2. Methods

2.1. Filter spectral transmittances

In this pilot work, trying to cover many of the different brands available in the market, we have used 16 blue-blocking lenses, all nominally plano afocal, from five different brands, incorporated to neutral lenses and mounted on eight conventional frames (see Table 1). The filter transmittances, shown in Fig. 1, were measured with a Spectroradiometer PR-745 (Spectrascan Ltd. USA) using a Sphere Optics calibrated white reference target. Half of the filters are made using matrix-based technology (the lenses are built with materials which present blue-blocking properties), and the other half using surface deposits on lenses with no blue-blocking properties.



a)   b)

Fig. 1. Spectral transmittances of the eight blue-blocking filters. (a) in the 380-780 nm range; (b) in the range 380-500 nm range. See Data File 1, Ref. [18] for underlying values.

We have calculated the chroma in CIELAB as the Euclidean distance between the filtered reference white and the center of the color space. These data were used to divide the filters into

Table 1. Filters technical specifications: acronym, brand, model, number of subjects, fabrication technology, average transmittance in the range 380-1080 nm, average transmittance in the range 380-500 nm, filter group(FG1 or FG2), and chroma in CIELAB color space space

Acronym	Brand	Model	Number of subjects that used this filter	Fabrication technology	Average total transmittance (380-1080 nm)	Average transmittance (380-500 nm)	FG1 or FG2	Chroma $\sqrt{a^2 + b^2}$
Zss	Zeiss	Duravision, BlueProtect UV + Duravision, Platinum UV	2	Surface deposits	83.66%	66.97%	FG2	6.28
Ess1	Essilor	Crizal Sapphire + UV35	3	Surface deposits	81.87%	63.67%	FG2	4.29
Ess2	Essilor	Crizal Prevencia 35	1	Surface deposits	84.87%	67.08%	FG1	8.30
HV	Hoya Vision	Hilux 1.6 Blue control	3	Surface deposits	83.20%	69.58%	FG2	5.62
CSR1	CSR1	CSR 1A	2	Matrix-based	83.56%	64.84%	FG2	6.47
CSR2	CSR	CSR 1A	2	Matrix-based	80.15%	61.24%	FG2	7.01
Ret1	Reticare	Reticare London	2	Matrix-based	85.55%	59.95%	FG1	16.08
Ret2	Reticare	Reticare London	3	Matrix-based	83.24%	61.39%	FG1	12.41

two groups for convenience of analysis: the first group (FG1, formed by Ret1, Ret2 and Ess2, comprising three filters) has a shift above 8 CIELAB units, while the second group (FG2, formed by HV, Ess1, Zss and CSR1 and CSR2, comprising five filters) have an achromatic point shift below 8 CIELAB units (see Table 1). As expected, the yellowish tint of the lenses in the first group is much more noticeable than in the second group. Although these filters are named as "blue-blocking" by manufacturers and practitioners, it is clear from Fig. 1 that the absorption of blue light is quite moderate.

2.2. Observers

A total of 28 observers have participated in the experiments. All subjects had normal color vision (as assessed by the Ishihara and FM-100 tests) and did not wear glasses, either because they were emmetropes or contact lens users. None of them had used blue-blocking lenses prior to this study.

Ten observers comprised the control group, and eighteen observers the group that performed the chromatic adaptation battery of tests (CA group). The age range for the control group was 21 to 37 years, with an average age of 23.5 years (standard deviation: 4.99 years). The subjects in the CA group had ages ranging from 19 to 49 years, with an average age of 27.16 years (standard deviation: 10.11 years). There were 16 females, 7 in the control group, and 9 in the CA group.

Each observer in the CA group wore one type of blue-blocking filters in their corresponding frames for 15 days with a maximum of 3 h allowance for taking off the glasses while the subject was awake, although they were encouraged not to take the glasses off except for showering or practicing sports. Three of the observers performed the adaptation experiments twice, with different blue-blocking filters. In these three particular cases the interval between both experiments was larger than a month. A total of 12 subjects were using filters with lower achromatic point shift (FG2 group), and 6 subjects were using filters with higher achromatic point shift (FG1 group).

All subjects signed their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the University of Granada (1804/CEIH/2020).

2.3. Experiments

2.3.1. Tests performed in each session

Each session included four tests: the achromatic point measurement, the FM100, and two rounds of CAD threshold measurements: one with the standard achromatic center (CIE 1931 chromaticity coordinates 0.305, 0.323), and one with a custom center (CIE 1931 chromaticity coordinates 0.2175, 0.2142) corresponding to the blue region in the CIE 1931 diagram.

The FM100 test was carried out in a cabin booth VeriVide CAC 60-5 with D65 illumination, and the standard setting for the test recommended by the manufacturer. The Total Error Score (TES) given by the manufacturer's software was used to analyze performance. Superior discrimination corresponds to a TES value ranging between 0 and 20 [16].

We have designed an achromatic point measurement test similar to the one used by [9]. The stimuli were presented in a calibrated color display LG Flatron E1940. The method of 2AFC four-interleaved staircase was used for threshold determination in four different directions: red, green, yellow and blue. The subject's task was to identify which of the two square areas presented side by side on the screen contained a non-achromatic color, presented during 500 ms. In case the subject perceived the two colors as equal, he/she should provide a random answer. The chromaticity coordinates of the achromatic center were $L^* = 46.53$, a^*=-0.031, b^*=-0.55 with a luminance of 15.03 cd/m^2. There were 11 steps of approximately equal size in the CIELAB space between the center and the furthest ends of the staircase in each direction, which were located at coordinates ($L^* = 46.49$, $a^* = 10.78$, b^*= -0.12) for the red, ($L^* = 49.60$, a^*=-13.97, b^*=-0.023) for the green, ($L^* = 46.47$, $a^* = 0.24$, b^*=-9.71) for the blue, and ($L^* = 49.28$, $a^* = 0.14$, $b^* = 13.00$) for the yellow. The background color was set to black (chromaticity coordinates $L^* = 1.52$, $a^* = 0.32$, b^*=-3.63) and luminance 0.17 cd/m^2. The threshold was determined as the mean of three reversals of the staircase in each color direction. Between the offset of the stimulus and the subjects' response, an adaptation screen with the black background color was presented. Besides, at the beginning of the session, the subject was adapted to the dark room conditions and the black background of the monitor for two minutes. The achromatic center was not used for adaptation because it would break the subject's adaptation state, and so condition his/her answer to the achromatic setting. The achromatic point was obtained as the average of the four threshold settings, and the threshold was computed as the CIELAB color difference with the center achromatic color. The duration of this test was typically around 3 minutes. In Fig. 2 we present a trial example and the temporal distribution of presentation and adaptation screens.

The CAD was carried out using the standard instructions for the achromatic center ($x = 0.3050$, $y = 0.3230$) and the blue center ($x = 0.2175$, $y = 0.2142$). The duration of each test was around 9 minutes. Eight different directions in the CIE 1931 chromaticity diagram along red-green or blue-yellow axes were tested, with two color stimuli in each direction, and opposite places from the reference color center. The luminance of each stimulus was changed each 50-80 ms, and the subject's task was to determine the direction of movement of the color stimuli against an achromatic background. Apart from the thresholds computed by the CAD test software in the r-g and b-y axes, an ellipse was fitted and the chromaticity coordinates of the 16 threshold colors found during each CAD measurement. The set of (x,y) chromaticity coordinates was fitted to the equation of an ellipse, obtaining the parameters a,b (semi-minor and semi-major axis of the ellipse) and φ (orientation). After, the ellipse was plotted using the fitted parameters.

Fig. 2. Left: typical screen of the achromatic setting test. Right: temporal scheme of the achromatic setting trials.

2.3.2. Experimental paradigm description

For the control group, there were four experimental sessions spanning 15 days, including the tests described in section 2.3.1. Each session lasted 30-40 minutes, and there were 4-5 days between sessions.

For the CA group, the tests in each session were the same as for the control group. The CA group subjects completed a total of 10 sessions. Data were gathered before each subject started wearing the filtered lenses, and following each 2-3 days within the span of 15 days of using the lenses. The 15th day of use, the subjects participated in two sessions: one just before taking off the lenses, and one just after taking them off. Finally, one more session was completed, 24 h after stopping the use of the filters. Since the de-adaptation was not complete after 24h for all the observers, we decided to perform an extra session 7 days after stopping the use of the filters only for some subjects. For those who did, results showed that the de-adaptation was complete after one week of the end of using the filters, and hence the color vision tests results were similar to those at the beginning of the study (before starting using the filters).

3. Results

3.1. *Control group*

The results obtained by the control group observers were used to determine approximate ranges of tolerance for intra-observer variability of each of the parameters measured in the experiments (FM100 TES, the achromatic setting thresholds, and the CAD thresholds). The tolerances were determined in normalized units for the FM100 and CAD, dividing each of the scores or thresholds by the result obtained in the first session. For the achromatic point settings, the tolerance was determined in CIELAB units. For each parameter (threshold or score), the tolerance was computed as the average of the standard deviation in the parameter across the four sessions for each of the ten observers in this group. Inter-observer variability was also studied by calculating the standard deviation of normalized thresholds across observers in each session, and averaging the values corresponding to the four sessions. In Table 2, we show the average normalized scores, the intra-observer variability (tolerance) and the inter-observer variability. These values will be used for comparison with CA group results.

In Fig. 3(a) the FM100 average TES and standard deviation are shown. The average TES value obtained is below 20 in all sessions, which according to the manufacturer corresponds to superior performance in color discrimination. The variation in average score between sessions is less than 5 units, and the tolerance is 1.1 units (see Table 2).

Table 2. Normalized average scores, inter-observer variability and tolerance (intra-observer variability) for the control group. The data for the achromatic point threshold settings are in CIELAB units

		Average scores	Tolerance	Inter-observer variability
FM100	Normalized TES	1.8	1.1	3.0
Achromatic point threshold		2.8	0.9	1.7
CAD achromatic center	*a*	0.97	0.08	0.1
	b	1.01	0.23	0.3
	r - g threshold	0.97	0.09	0.10
	y - b threshold	0.96	0.11	0.12
CAD blue center	*a*	0.97	0.09	0.12
	b	1.03	0.18	0.23
	r - g threshold	0.97	0.08	0.11
	y - b threshold	0.98	0.11	0.15

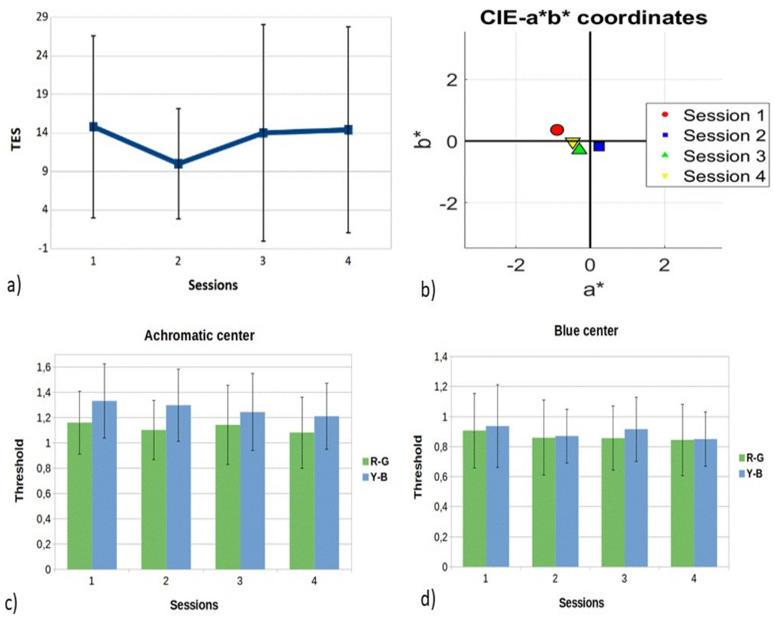


Fig. 3. Control group results. (a) Mean TES and standard deviation across observers for each session. (b) Average achromatic point settings in the CIELAB space for each session. (c) Average CAD r-g and b-y thresholds and standard deviations for each session with the achromatic center (d) Average CAD r-g and b-y thresholds and standard deviations for each session with the blue center.

In Fig. 3(b) we show the average achromatic setting points for the control group in each session. As shown in Table 2, the average threshold value across observers and across sessions was 2.8 CIELAB units, with an inter-observer variability of 1.7 units and a tolerance (intra-observer mean standard deviation across sessions) of 0.9 units. These results suggest that normal observers are not able to obtain very precise measurements of the achromatic point, since both the average threshold and the tolerance are above what is usually considered visually perceptible for color differences in the CIELAB space.

In Fig. 3(c) and (d) we can see the CAD r-g and b-y averaged thresholds for each session, with their corresponding standard deviation values for the achromatic and blue centers. These plotted data are not normalized for visualization purposes.

Note that the reference normal thresholds are provided by the manufacturer of the CAD for the achromatic center, but not for the blue color center. The control group values are within the range considered normal by the CAD manufacturer for achromatic center. For the bule center, the tolerances found are very similar to achromatic one. There is a slight trend towards lower thresholds in the r-g axis in both color centers, and for slightly higher thresholds for the achromatic than for the blue color center.

For all the test scores and results presented in Table 2, the inter-observer variability is above the tolerance (intra-observer variability). The tolerance and inter-observer variability are closer for the CAD results than for the FM100 and achromatic point results, which suggests that there is less intrinsic variability in the CAD results across observers when compared with the variability of each individual measurement.

3.2. CA group wearing filters from FG1

The FG1group is formed by the two Reticare filters (Ret1 and Ret2) and the Ess2 filter, all of them producing achromatic point shifts higher than 8 CIELAB units. Then, we should expect more noticeable effects on the color vision of the observers wearing these filters than for the FG2 group. A total of 6 subjects used these filters and completed the 10 experimental sessions.

For each test, we have compared the results obtained during the period when the observers were wearing the filters to the results of the first and the last sessions, in which the observers were not wearing the filters. After the analysis of sessions-wise results (with the filters), no clear trend was found. Hence, the averages across all sessions with the filters are considered in the following discussion.

In Fig. 4, we show the normalized FM100 TES score in the two conditions (with and without the filters), for FG1 and FG2. In the bar graph, the results of the first and last sessions are pooled together, while in Fig. 4 right we can see the difference between the initial and the final sessions. The TES scores tend to be higher when wearing the filters, and the variability between observers' results is also higher. Moreover, it can be observed how the subjects tend to revert to the original TES score in the final session. The difference between the two conditions is higher than the tolerance established for the control group (1.1 for the TES scores, see Table 2). In the figure, the data are normalized to facilitate comparison between observers. If we analyze the original (not normalized) data, the average TES score without the filter is 13.6 for this group, and it rises to 17.02 when the filters are on. Both data are below 20, which could be considered as superior discrimination, but there is a trend towards worsening results when the filters are used.

In Fig. 5, we show the results of the average achromatic point settings in CIELAB color space for FG1 and FG2, in the initial and last sessions, and on average for the period when the observers were wearing the filters. There is very little variation in the achromatic settings, and not a clear trend towards reverting to the initial setting in the final session. The average threshold in CIELAB units for the six observers without filters (initial and final sessions) is 0.692, and the average threshold with the filters on is 0.987 units. Given that the intra-observer variability for this group

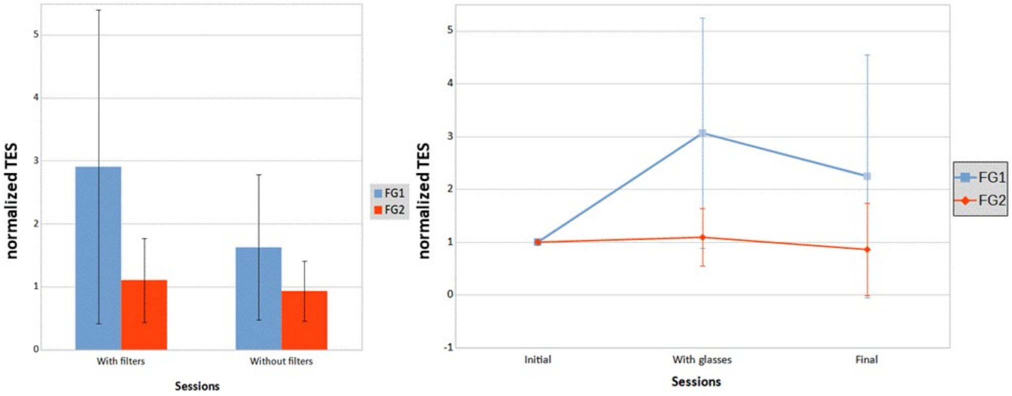


Fig. 4. CA group results with FG1 and FG2 filters for the FM100 test. Left: average normalized TES and standard deviation with filters and without filters (first and last sessions). Right: average normalized TES and standard deviation for the initial session, period with glasses and last session.

in the achromatic settings threshold is 0.91 units, the trend towards a slightly higher threshold with the filters on cannot be considered as consistent enough.

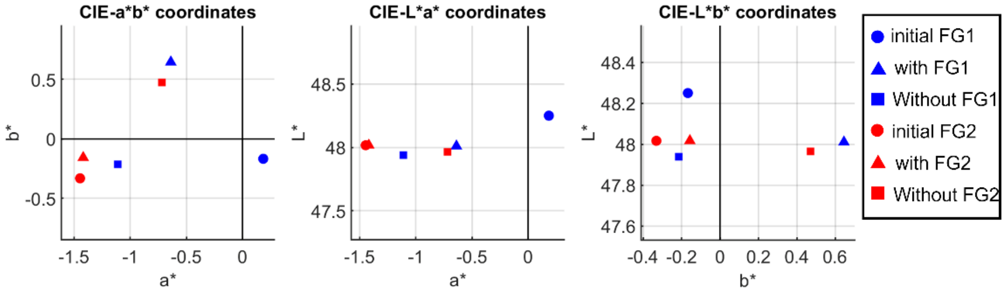


Fig. 5. Average achromatic point settings for the CA group results with FG1 and FG2 filters, in CIELAB color space. *Circle*: initial session. *Triangle*: average of the sessions with the filters on. *Square*: last session.

In Fig. 6 we show two examples of the fitted ellipses obtained for the blue and achromatic center in the CAD test results. For the observer in Fig. 6 left, there is a trend towards increasing the angle value after wearing the glasses, and a considerable change in the ellipse size between the days 7 and 9 of wearing the glasses. The ellipse obtained in the final session is similar to the one obtained in the initial session, showing a trend towards reverting to the initial results. The subject shown in Fig. 6 right has a trend towards an area increase of the ellipses during the period with the filter on, that tends to revert after taking off the filter. These two examples show that there is no clear trend in the CAD ellipses for observers wearing FG1 filters, although there are certain variations in the parameters of the ellipses from the initial and final sessions to the intermediate sessions in which the observers were wearing the filters.

In Table 3, we show the global average normalized scores for the CAD parameters (ellipse semiaxis length in the CIE 1931 space, and r-g and y-b thresholds), as well as the original average data (not normalized), and the tolerance values determined from the control group results. There is a trend to increase both the ellipse semiaxis length and threshold values in both r-g and y-b directions, when the observers are wearing the filters. The trend is the same for both color centers, and for the minor axis (a) threshold values it is slightly above the tolerance for the

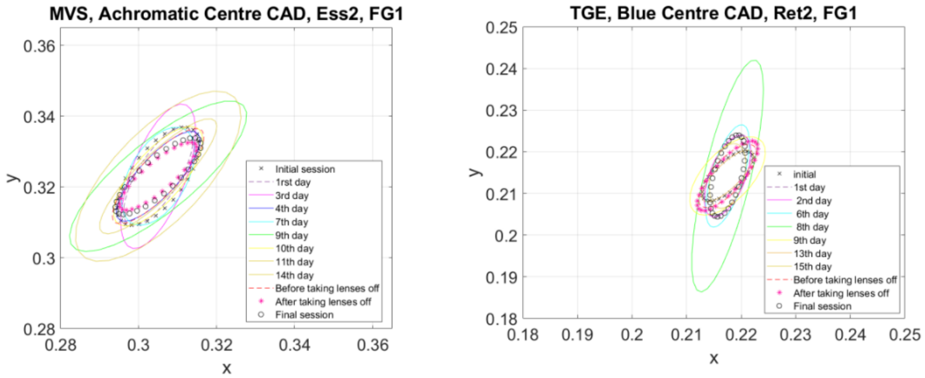


Fig. 6. Examples of CAD ellipses for two of the observers wearing FG1 filters. Left: blue center for TGE observer. Right: achromatic center for MVS observer.

control group (shown in the last column of Table 3). These results show that globally, the color discrimination tends to worsen (ellipses of bigger size) with the filters on, although the effect is not very substantial. For the blue color center, the increase in the *b* axis is more marked than for the achromatic color center.

Table 3. Mean and standard deviation (in brackets) of the CAD results for the ellipse semiaxis length and r-g and y-b thresholds in the CA group with FG1 filters. The tolerance obtained for the control group in each parameter is shown in the last column

Achromatic center	Average without filters, initial +24 h	Average with filters	Initial +24	Average with filters	Tolerance control group
	Not normalized		**Normalized**		
a	0.0055 (0.0011)	0.0061 (0.0047)	1.07 (0.15)	1.24 (0.96)	0.08
b	0.013 (0.005)	0.015 (003)	1.03 (0.36)	1.15 (0.26)	0.23
r-g	1.13 (0.11)	1.14 (0.20)	0.96 (0.08)	0.94 (0.20)	0.09
y-b	1.04 (0.22)	1.18 (0.15)	0.96 (0.19)	1.06 (0.15)	0.11
Blue center	**Average without filters, initial +24 h**	**Average with filters**	**Initial +24**	**Average with filters**	**Tolerance control group**
	Not normalized		**Normalized**		
a	0.0034 (0.0002)	0.0038 (0.0012)	0.97 (0.05)	1.09 (0.34)	0.09
b	0.012 (0.003)	0.016 (0.009)	1.02 (0.26)	1.50 (1.11)	0.18
r-g	0.81 (0.05)	0.84 (0.10)	0.98 (0.05)	1.03 (0.10)	0.08
y-b	0.81 (0.09)	0.85 (0.11)	0.98 (0.10)	1.03 (0.11)	0.11

3.3. CA group wearing filters from FG2

This group is formed by the HV, Zss, Ess1, CSR1 and CSR2 filters. These filters produce achromatic shifts lower than those in the FG1, and so the expected effect on color vision is to be less noticeable. A total of 12 subjects wore these filters and participated in the experiments as observers.

Regarding the TES score results for the FM100 test, the two conditions (with and without the filters) produce very close results (Fig. 4), although the standard deviation (related to intra-observer variability) is higher when the subjects are wearing the filters. In Fig. 4 right, we see that the TES score tends to be lower in the final session than in the initial one, although the three values represented are quite close to each other. For the FG2 observers, the difference between the two conditions is considerably lower than for the FG1 observers, and much lower than the tolerance established by the control group observers (1.1 for the normalized TES score, see Table 2).

For the achromatic setting experiment (see Fig. 5), comparing with the FG1 observers, we see an even less noticeable effect in the achromatic settings, which are very close together especially in the initial and with glasses conditions, as expected. The average threshold values for the achromatic settings are 1.034 CIELAB units with filters on, and 0.743 CIELAB units without filters (initial and final sessions). Given that the tolerance is 0.910 CIELAB units for the control group (intra-observer variability), we can conclude that there is no effect in the achromatic settings.

In Fig. 7, we show two examples of CAD ellipses sets for the different sessions in which the most noticeable changes happen. Comparing with the FG1 results (see Fig. 6), there are less noticeable changes in the ellipses size and orientation, that varies only in the session immediately after taking the filters off. In the case corresponding to the blue center (Fig. 7 left), the changes are even less noticeable and tend to happen again in the sessions just before and just after taking off the filters. In the achromatic center (Fig. 7 right), we see how there is a trend to revert to the initial session ellipse in the last session.

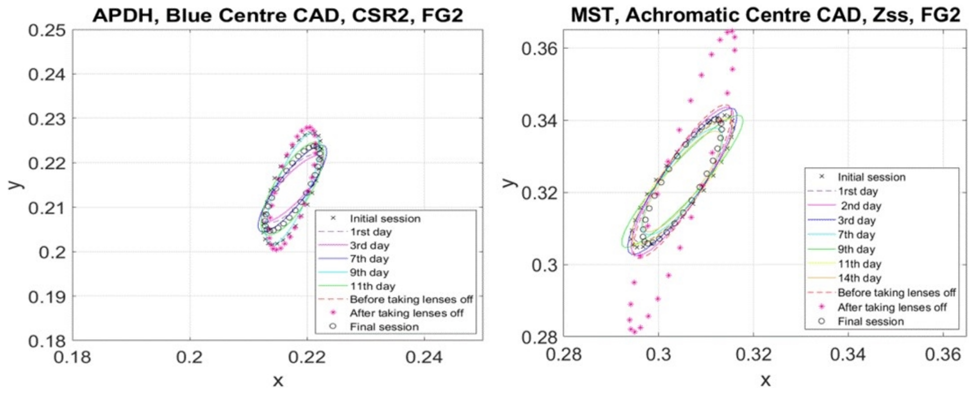


Fig. 7. Examples of CAD ellipses for two of the observers wearing FG2 filters. Left: blue center. Right: achromatic center.

Table 4 shows the semiaxes length and r-g/y-b thresholds along with the tolerance for these parameters obtained by the control group. Comparing with Table 2, we see that there are no changes in the semiaxes length values when comparing the two conditions (with and without filters), although the a values tend to be slightly lower in the filters on condition. In any case, the difference between the two conditions lower than the tolerance value in the majority of cases. The changes in r-g and y-b thresholds were slightly higher in Table 2 (FG1 group), and the opposite trend was found (towards decreasing the thresholds in the filters on condition).

Table 4. Mean and standard deviation (in brackets) of the CAD results for the ellipse semiaxis length and r-g and y-b thresholds. CA group with FG2 filters. The tolerance obtained for the control group in each parameter is shown in the last column

Achromatic center	Average without filters, initial +24 h	Average with filters	Initial +24	Average with filters	Tolerance control group
	Not normalized		**Normalized**		
a	0.0058 (0.0026)	0.0043 (0.0012)	1.22 (0.48)	0.97 (0.27)	0.08
b	0.016 (0.003)	0.016 (0.003)	0.94 (0.19)	0.95 (0.21)	0.23
r-g	1.02 (0.11)	0.98 (0.08)	0.93 (0.10)	0.90 (0.08)	0.09
y-b	1.22 (0.16)	1.16 (0.13)	0.94 (0.13)	0.89 (0.13)	0.11
Blue Center	**Average without filters, initial +24 h**	**Average with filters**	**Initial +24**	**Average with filters**	**Tolerance control group**
	Not normalized		**Normalized**		
a	0.0033 (0.005)	0.0031 (0.0003)	0.94 (0.12)	0.88 (0.10)	0.09
b	0.014(0.005)	0.013 (0.004)	0.94 (0.24)	1.02 (0.33)	0.18
r-g	0.79 (0.10)	0.74 (0.07)	0.94 (0.11)	0.90 (0.07)	0.08
y-b	0.81 (0.07)	0.82 (0.08)	0.96 (0.09)	0.99 (0.08)	0.11

4. Conclusions

This pilot study evaluates how the long-term use of several blue-blocking filters (which is equivalent to a change of illuminant and state of chromatic adaptation) impact the color perception during more than two weeks on a group of normal color vision observers, and compared with a control group. The evaluation was done using the FM100, the Color Assessment and Diagnosis (CAD), and an achromatic point measurement. Our results have been divided in two sections depending on high (FG1) and low (FG2) chroma of the filters.

FM100 results suggest that there is an increase in the number of errors when the observers wear the filters but when the filters are taken off, after two weeks of continuous use, the TES tends to the initial value. This effect seems lower for FG2 than for FG1 filters.

The achromatic point settings results show that the observers are not able to obtain very precise measurements of the achromatic point, since both the average threshold and the tolerance are above what is usually considered visually perceptible for color differences in the CIELAB color space. In this pilot experiment we did not find any substantial variation in the test's results due to the filters usage for any of the two filter groups. The intra-observer variability is generally above the measured changes.

CAD results reveal the worsening of blue/yellow color vision and the systematic change in the major axis of the chromatic discrimination ellipse (which appears to be greater for the FG1 filters), which has been reported previously in relation to macular pigment optical density [17], that latter absorbs preferentially short wavelength light and produces an effective change in the spectral responsivity of S-cones with a subsequent change of orientation of the blue/yellow axis. In addition, CAD results show ellipses variation for observers wearing the filters, although there are certain changes in their parameters from the initial and final sessions to the intermediate sessions, especially for the FG1 filters. These results show that the color discrimination tends to worsen (bigger ellipses) with the filters on.

The longer-term use of these filters does appear to cause some form of adaptation to the altered illuminant, but the effects are small and variability is high. Chromatic discrimination sensitivity and the orientation of the blue/yellow axis return to pre-adaptation levels immediately after the filters are taken off.

To sum up, this pilot study shows that there is slight worsening of blue/yellow color discrimination (although the effects are small even when using the FG1 filters). The high inter-observer variability supports that the acceptance of the filters varies among individuals. The longer-term use of these filters does appear to cause some form of adaptation to the altered illuminant, but the effects are small and variability is high.

We have to highlight some limitations of our pilot study. The first is the experimental design itself, in which 8 different filters were used with a low number of observers per filter. This choice can be explained by the long duration of the experiment, in which users had to commit to wear the filters for two weeks, and to come to the laboratory for more than three weeks every 48 hours. This made it difficult to repeat the analysis with many subjects for each filter, or for the same subject to repeat the experiment with different filters, which would have made our results more robust. In addition, the experiments were conducted during COVID pandemic, which made it even more difficult to find observers willing to participate in the study. The second limitation is the mean age of the subjects, which corresponds to a young and healthy population. The third limitation is the unbalanced sample size between FG1 and FG2. After the trends found in this pilot study, in follow-up experiments it would be interesting to consider using a reduced number of filters and increasing the number of observers per filter. Also, to consider a broader age range and design the experiment to have a good balance between the number of users.

The same experimental design developed in our pilot study could be used to analyze contact lenses with blue-blocking filters. However, in the case of intraocular lenses, there is the intrinsic difficulty of comparing with the subject just "before" the intraocular lens replaces the crystalline lens and that, in addition, their color vision has been progressively degraded by the cataract.

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Data availability. The filter transmittances shown in Fig. 1(a) are available in Data File 1, Ref. [18].

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