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Research article

Analyzing the effect of blue-blocking lenses on color vision tests using the chromaticity coordinate method

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ABSTRACT

Significance: Blue light with wavelengths of 380–445 nm can harm the retina, leading to the development of blue-blocking lenses (BBLs). Understanding whether BBLs affect color vision test outcomes and color discrimination ability is crucial for people in color-associated jobs.
Aim: This study aimed to evaluate the effect of BBLs on color vision tests and analyze color discrimination using mathematical models of color spaces.
Approach: Six pseudoisochromatic (PIC) tests and two Farnsworth-Munsell (FM) tests were conducted to assess participants' color vision. Friedman signed rank test was used to compare the outcomes of the Farnsworth-Munsell 100-Hue Tests (FM 100-Hue Tests) between the BBLs and ordinary lenses groups. The CIE color difference formula and a spectral illuminometer were employed to evaluate the color differences with and without BBLs.
Results: All subjects showed normal outcomes in all PIC tests and Farnsworth-Munsell Dichotomous D-15 Tests (FM D-15 Tests). There were no significant differences between ordinary lenses group and BBLs groups in FM 100-Hue Tests. In the color space, the effect of BBLs on each color light was equivalent to a translation on the CIE 1931 chromaticity diagram with minor distortion. Since BBLs do not disrupt the continuity of the chromaticity diagram, or cause different colors to appear the same, they do not lead to color confusion. However, colors with short wavelengths exhibited more changes in color difference when wearing BBLs.
Conclusions: BBLs do not impair the wearer's ability to discriminate colors or perform color vision tests accurately. However, BBLs can cause color differences especially in the recognition of blue hues.

1. Introduction

Visible light in the wavelength range of 380–500 nm is classified as blue light [1]. The human eye has very low tolerance for blue light radiation below 445 nm, as this high-energy blue light can damage multiple ocular tissues, including cornea, conjunctiva, lens, and especially to retina [2–6]. In the field of molecular and cell experiment, high exposure levels to blue light have been linked to retinal damage, including retinal degeneration and morphological changes [7–13]. Previous studies have shown retinal injury in

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albino rats exposed to blue light (403 nm) but not to green light (550 nm) [14]. To mitigate the harmful effects of blue light on human eyes, blue-blocking lenses (BBLs) were designed. BBLs reduce the amount of blue light transmission through two mechanisms: coating the lens surface to reflect harmful blue light and incorporating blue-light absorbing substances into the lens material to absorb harmful blue light [15]. Previous studies have demonstrated BBLs' ability to protect the retina from blue light [16,17]. However, by filtering out the short wavelength component of light, BBLs cause the centroid wavelength of transmitted light to shift toward longer wavelengths, resulting in a stronger yellow tint, commonly referred to as color difference.

Color vision is essential for human beings, playing a crucial role in maintaining normal perception, work and mental activity. Problems with color vision can affect an individual's ability to perform related occupations. For example, dentists require highly sensitive perception of color to ensure that dentures match the color of natural teeth precisely, maintaining the patient's aesthetics. Similarly, painters depend on acute color sensitivity. To accurately assess human color vision, several tests are utilized, including PIC tests [18] and arrangement tests (e.g. FM 100-Hue Tests [19] and FM D-15 Tests [20]). These tests effectively detect color vision deficits and can even assess the color discrimination ability of individuals with normal vision. Color vision tests have also been used to study the effects of BBLs on color vision. In 2017, Leung et al. evaluated color discrimination using Mars contrast sensitivity charts and FM 100-Hue Tests on 80 subjects wearing blue-light filtering spectacle lenses for at least 2 h daily over one month [1]. However, the study only considered the total error score. In 2021, Baldasso et al. examined how three different BBLs affected color discrimination on 10 young subjects immediately after putting on the lenses, with the methods of Color Assessment and Diagnosis (CAD), Cambridge Color Tests, and FM 100-Hue Tests. They found no statistically significant impacts on color perception [16]. In the same year, Alzahran et al. studied the color contract thresholds on 5 subjects wearing BBLs, using a visual search color detection task, finding that BBLs could unintentionally reduce color contrast sensitivity, particularly under low light levels [21]. Similar studies were also performed on blue-light filtering intraocular lenses by Hammond et al. [22,23]. Current studies mainly focus on the observational and statistical results concerning the effects of BBLs on color vision. However, there is a notable lack of explanations for these results, and a deficiency in mathematical methods for describing color vision and color differences.

Color is the human perception of different wavelengths of light. The retina contains three types of cone cells, each with photopigments sensitive to red, green, and blue light. When various colors of light are applied to the retina, these cone cells produce different levels of excitation. This excitatory information is processed and transformed into different combinations of optic nerve impulses, which are then transmitted to the cerebral cortex, resulting in the perception of different colors. Using the photoreceptor properties of these three cone cells as substrates, a three-dimensional space known as color space can be created. This space quantitatively describes the perceptual properties of color to the human eye [24,25]. Colors can be quantified by chromaticity coordinates, providing a precise and objective description of colors [26]. The International Commission on Illumination established color spaces including CIE 1931 XYZ and CIE 1976 Lab. The use of color spaces as mathematical models to study color differences and the human eye's ability to perceive colors is more objective and convincing. Each coordinate in the color space corresponds to a unique color, thus reducing errors caused by the subjectivity of color perception.

In this study, we initially assessed color discrimination ability in 40 subjects wearing BBLs or control lenses using PIC tests, alongside FM D-15 Tests and FM 100-Hue Tests commonly utilized in similar researches. The outcomes uniformly indicated that BBLs exert no discernible impact on human eye color discrimination ability. Furthermore, we measured the CIE 1931 chromaticity coordinates of different color lights before and after passing through BBLs using a spectral illuminometer. Subsequent analysis illuminated the effects and patterns of BBLs on color vision within the context of color spaces, as illustrated in Fig. 1. After passing through BBLs, the chromaticity coordinates of the color lights displayed a tendency to disperse outward from the blue pole on the chromaticity diagram. This transformation did not disrupt the continuity of the chromaticity diagram, nor did it map two different colors to the same color. Therefore, although BBLs cause color differences, they do not affect the color discrimination ability of the human eye, nor do they affect the outcomes of the related color vision tests. Notably, this study pioneered the utilization of color space analysis to scrutinize BBLs-induced color differences, offering theoretical underpinnings for observed effects on color vision tests and presenting a

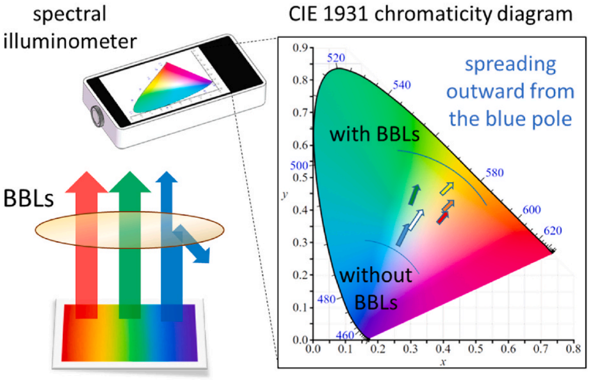


Fig. 1. Measuring the chromaticity coordinates of different color lights before and after they passed through BBLs. The results showed that after passing through BBLs, the chromaticity coordinates of the color lights showed a tendency to disperse outward from the blue pole on the chromaticity diagram.

novel approach to investigating tinted lenses effects on color vision.

2. Methods

2.1. Subjects

The study was conducted at Hospital of Stomatology and the Second Hospital of Jilin University. 40 students, including 22 females and 18 males, aged 18 to 25, were involved. Each subject had a best-corrected visual acuity of no worse than 0 logMAR in each eye. All subjects gave their informed written consents before taking part. The research protocol observed the tenets of the Declaration of Helsinki and was approved by the ethics committee of Hospital of Stomatology, Jilin University (No. 202046).

2.2. Test tools

Three pairs of BBLs, including Chemi Ultra 6 series (refractive index 1.597, Chemi lens Co., Ltd, Jiaxing, China), Zeiss single vision Superb Asiana series (refractive index 1.600, Carl Zeiss Vision Technical Services Co., Ltd, Guangzhou, China), Essilor Crizal A4 series (refractive index 1.591, Shanghai Essilor Optical Co., Ltd, Shanghai, China) were adopted. The blue light filtering characteristics of the lenses meet the criteria of national light industry standard of China (Uncut finished spectacles lenses - Optical hard resin lenses, QB/T2506-2017). Essilor Crizal A plus series (refractive index 1.591, Shanghai Essilor Optical Co., LTD, Shanghai, China) without blue light filtering function were used as control lenses.

Six sets of PIC plates [27–32] were used under standard test circumstance described in each user manual. FM D-15 Tests were adopted. FM 100-Hue Tests were conducted as quantitative methods. Four indexes calculated by the FM-100 software, including total error score (TES), confusion angle (CA), selectivity index (SI) and confusion index (CI), were utilized to analyze the data. TES is the sum of all error scores. The error score for a cap amount to the absolute differences between the number of the cap and those adjacent to it, which represents the magnitude of the perceived chromatic difference between the adjacent caps. CA is an indicator of type of color defect. SI identifies the selectivity or scatter in the cap arrangement. CI quantifies the degree of color loss relative to a perfect arrangement of caps [32].

2.3. Test procedure

The refraction of each subject was determined with an auto-refractor (Topcon KR-800, Topcon Corp, Tokyo, Japan) and a phoropter (Topcon VT-10, Topcon Corp, Tokyo, Japan). The corrected trial lenses combination was inserted into the cells of trail frame for best-corrected visual acuity. Four pairs of blue-blocking and ordinary lenses were selected in a randomized order. Each pair of the lenses was inserted into the outermost cells of the trial frame in right and left side simultaneously. Each combination of lenses was worn for 5 min for binocular viewing adaptation. Before starting, each subject was assured of familiarity with every color vision test. The sequence of color vision tests was random. All the tests were carried out in a clinic room under the illumination of a 6500 K lamp tube which attached to the phoropter [33,34], as shown in Fig. 2.

Fig. 2. Photograph of the test setup. BBLs or control lenses were inserted into the forwardmost cells, while correct lenses were inserted into the rearmost cells of the trial frame.

2.4. Statistical analysis

PASW Statistics software (version 26, IBM SPSS Inc., Chicago, United States) was adopted. Shapiro-Wilk test was used to explore the distribution of data. If the data was normally distributed, parametric test was used to test the difference between groups. If the data were not normally distributed, non-parametric test was adopted.

2.5. Experimental and theoretical analysis based on CIE color spaces

The optical spectrum of a fluorescent lamp was measured with a spectral illuminometer (HP320, Duotone Cloud Co., Hangzhou, China). The spectrum was measured again when the fluorescent lamp was screened by a pair of BBLs.

Next, the CIE 1931 chromaticity coordinates of objects with different colors (red, orange, yellow, green, blue and purple) were measured with the spectral illuminometer, both without and with the BBLs. Then, arrows were drawn on the CIE 1931 chromaticity diagram, starting from the chromaticity coordinates without BBLs and ending with the chromaticity coordinates with BBLs. The directions and lengths of the arrows represent the directions and degrees of the chromaticity changes when wearing BBLs, respectively.

The chromaticity coordinates measured by the spectral illuminometer were based on the CIE 1931 XYZ color space. The more commonly used color space currently is the CIE 1976 Lab, as the latter is closer to the color perception of the human eye. The CIE 1931 XYZ system can be converted to the CIE 1976 Lab system through equations:

$$\begin{cases} L^* = 116f(Y/Y_n) - 16 \\ a^* = 500[f(X/X_n) - f(Y/Y_n)] \\ b^* = 500[f(Y/Y_n) - f(Z/Z_n)] \end{cases} \tag{1}$$

wherein

$$f(t)\begin{cases} t^{\frac{1}{3}}, t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{16}{166}, \text{otherwise} \end{cases} \tag{2}$$

X_n, Y_n, and Z_n are the tristimulus values of CIE standard illuminants.

Next, we calculated the color difference with and without BBLs based on the values of L*, a*, and b*. The CIE 1976 Lab color difference formula was used in this study:

$$\Delta E = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2} \tag{3}$$

3. Result and discussion

3.1. BBLs do not impact the outcomes of PIC tests

All subjects in this study had normal outcomes for all sets of PIC plates, regardless of whether they wore BBLs or regular lenses. The subjects were able to correctly read the figures and graphs in the PIC plates within 3 s, suggesting normal color vision among all subjects. Notably, the use of BBLs did not influence the subjects' ability to recognize PIC plates.

The PIC test consists of confusing figures and graphs with different hues and saturations, stands as one of the most commonly

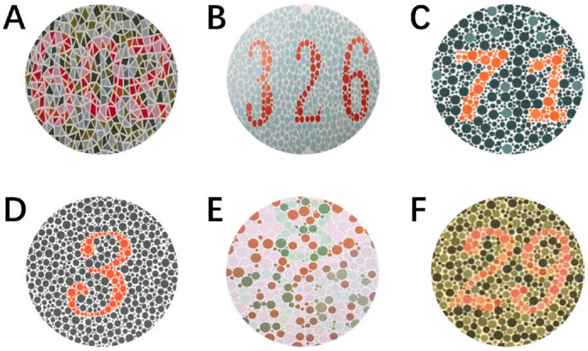


Fig. 3. Examples of six sets of PIC plates designed by (A) Ziping Yu [27], (B) Chunhui Li [28], (C) Fangrun Wang [29], (D) Lezheng Wu [30], (E) Kechang Wang [31] and (F) Ishihara [32].

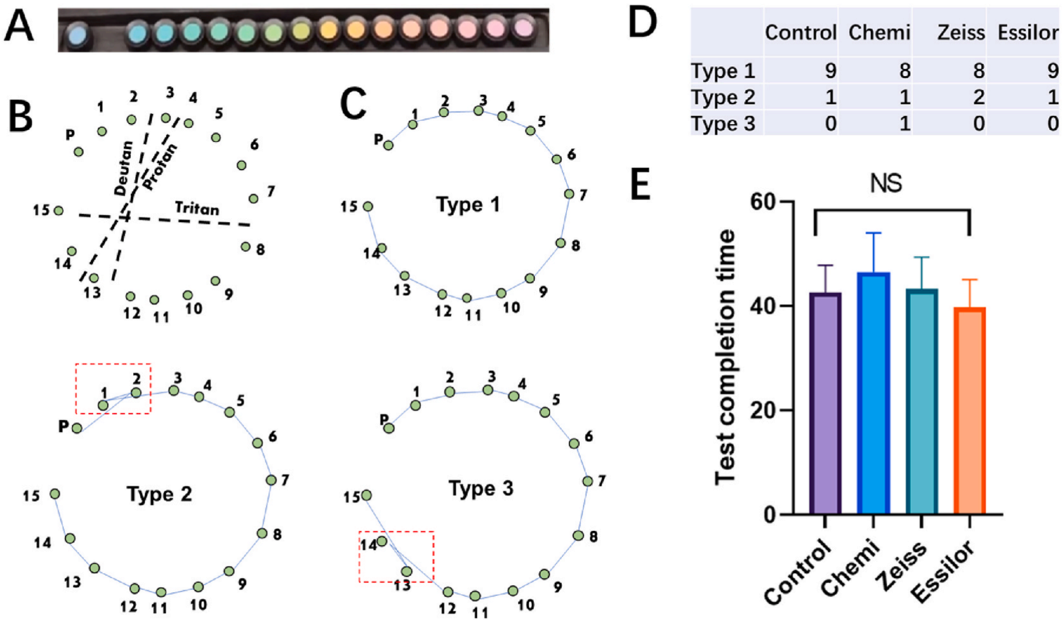
employed clinical color vision screening method [35]. Its underlying principle lies in the observation that individuals with normal color vision typically differentiate colors based on hue, whereas those with color vision deficiencies rely on brightness and saturation. Generally, in PIC tests, patterns such as numbers, curves, or other shapes are crafted using dots of one hue against a backdrop of dots in several other hues. Individuals with abnormal color vision cannot accurately identify patterns by hue, so PIC tests are generally used to identify color vision abnormality. Due to their affordability, rapidity, and simplicity, PIC tests are widely used in clinical color vision examinations, driving license exams and professional qualification exams. The PIC plates used in this study are shown in Fig. 3(A-F). Test subjects are instructed to maintain a distance of 30–40 cm from the PIC plates and attempt to identify the patterns within 3 s, with a specified maximum time of 10 s, to minimize potential interference from external factors.

The principle of BBLs involves either reflecting harmful blue light through surface coating or absorbing it with added blue-light absorbing substances [36]. Therefore, as light traverses through the lenses, harmful blue light can be filtered out, shifting the spectrum received by the eye towards yellow light. Despite this shift, the graphs retain their color differences. Since all the subjects in this experiment had normal color vision, they were able to distinguish the graphs in the PIC tests even while wearing BBLs.

3.2. BBLs have no discernible impact on the outcomes of FM tests

Both the FM D-15 Test and the FM 100-Hue Test are color alignment experiments in which subjects are required to arrange color caps in the correct order according to color transitions. The FM 100-Hue Test consists of four sets of color caps, including 85 consecutively numbered movable color caps and 8 fixed color caps. Following the cap arrangement, subjects' color discrimination ability could be judged by scoring. In addition, this test can be used to determine the types and degrees of color vision deficits. The FM D-15 Test is a simplified version of the FM 100-Hue Test, serving primarily as a screening tool for color vision deficits, such as red-green and blue-yellow deficits, rather than color acuity [37]. The test consists of a fixed reference color cap and 15 movable color caps numbered consecutively [Fig. 4(A)]. At the end of the test, subjects connect corresponding numbers sequentially on recording papers based on cap arrangements. In individuals with normal color vision, the shapes of the connections appear semicircular. Abnormal color vision can be indicated by lines crossing the semicircle, with classifications including deutan, protan, and tritan [Fig. 4(B)]. In this experiment, most of the subjects could arrange the color caps in order accurately regardless of wearing BBLs [Fig. 4(C), Type 1]. Only a few subjects reversed the order of color caps 1 and 2 in the blue zone [Fig. 4(C), Type 2], while just one subject reversed the order of color caps 13 and 14 in the pink zone [Fig. 4(C), Type 3]. Although some subjects reversed a small number of color caps, the connections on the recording papers remained semicircular with no line crossing the semicircle, indicating normal vision for all subjects [Fig. 4(D)]. We also recorded the time taken to arrange the color caps and found that all subjects completed the task within 1 min [Fig. 4(E)]. There was no statistical difference between various BBLs and control groups. All these findings suggest that BBLs have no discernible impact on the outcomes of FM D-15 Tests.

The data of FM 100-Hue Tests are shown in Fig. 5(A-D). TES, CA, SI and CI did not accord with a normal distribution (Shapiro-Wilk test, all $P < 0.05$). No significant difference was found in TES, CA, SI and CI between various BBLs and control groups processed with



	Control	Chemi	Zeiss	Essilor
Type 1	9	8	8	9
Type 2	1	1	2	1
Type 3	0	1	0	0

Fig. 4. FM D-15 Tests. (A) Color caps used for FM D-15 Tests. (B) Result recording paper. Subjects connected the corresponding numbers on the recording paper in the order in which they arranged the color caps. (C) Three types of connection corresponding to the color cap arrangements. (D) Statistical table of the connection types of the experimental and control groups. (E) There was no significant difference in the test finishing time among different groups.

Friedman signed rank test (all P > 0.05, Table 1). All of the above results indicate that FM 100-Hue Tests were also not affected by the BBLs.

Given the rising prevalence of myopia, many brands of myopic glasses apply the BBLs technique. Previous studies were not clear on whether myopic patients should remove their BBLs when performing color vision tests. If tests were performed by forcibly removing myopic glasses, the outcomes are often affected by the subjects' difficulty in clearly perceiving patterns or color caps. The outcomes of both PIC tests and FM Tests showed that BBLs have no discernible impact on the outcomes of color vision tests, nor on the ability of individuals with normal color vision to discriminate most colors, so myopic patients can keep BBLs on during the tests.

3.3. BBLs do not influence color vision tests primarily because the human eye responds to color in a linear manner

First, we examined the blue-blocking capability of a pair of BBLs using a handheld spectral illuminometer. Fig. 6(A) showed an effective reduction of the blue component in the spectrum below 440 nm by the BBLs. Fig. 6(B) depicted the BBLs' transmittance curve obtained by dividing the normal spectrum by the spectrum filtered by the BBLs. As we can see, blue light in the range of 380–410 nm had the lowest transmittance, blue light in the range of 410–500 nm had partial transmittance, and visible light with wavelength greater than 500 nm had the highest transmittance.

In addition, we used a spectral illuminometer to measure the CIE 1931 chromaticity coordinates of objects in various colors with and without BBLs, respectively, as shown in Fig. 7(C) we found that when using BBLs, the arrows on the chromaticity diagram representing chromaticity changes, consistently pointed towards yellow, i.e., the complementary color of blue. Moreover, the directions of the arrows showed a slight divergence. This phenomenon can be explained by the principle of color-light mixing. As blue light composition decreased, white light shifted towards yellow, while the saturation of red, orange, yellow, and green light increased, and that of blue light decreased. Overall, the effect of BBLs on each color light was equivalent to a translation on the chromaticity diagram, accompanied by minor distortion, as shown in Fig. 7(A). Since the one-to-one correspondence remains, BBLs do not lead to confusion of different colors. However, Fig. 7(B) also reveals varying arrow lengths, indicating differences in the degree of chromaticity change for different colors when using BBLs. This will be discussed in the next section.

Color is not an objective physical property. The light that reaches the human eye all conforms to some continuous spectral distribution functions. Mathematically, this is an infinite-dimensional function space (Banach space). Most people have three types of retinal cells in the retina that are sensitive to red, green and blue. Their light-sensitive characteristic curves are equivalent to three bases built in this infinite-dimensional function space. According to Grassmann's Law [38], human eye perception of color is linear at

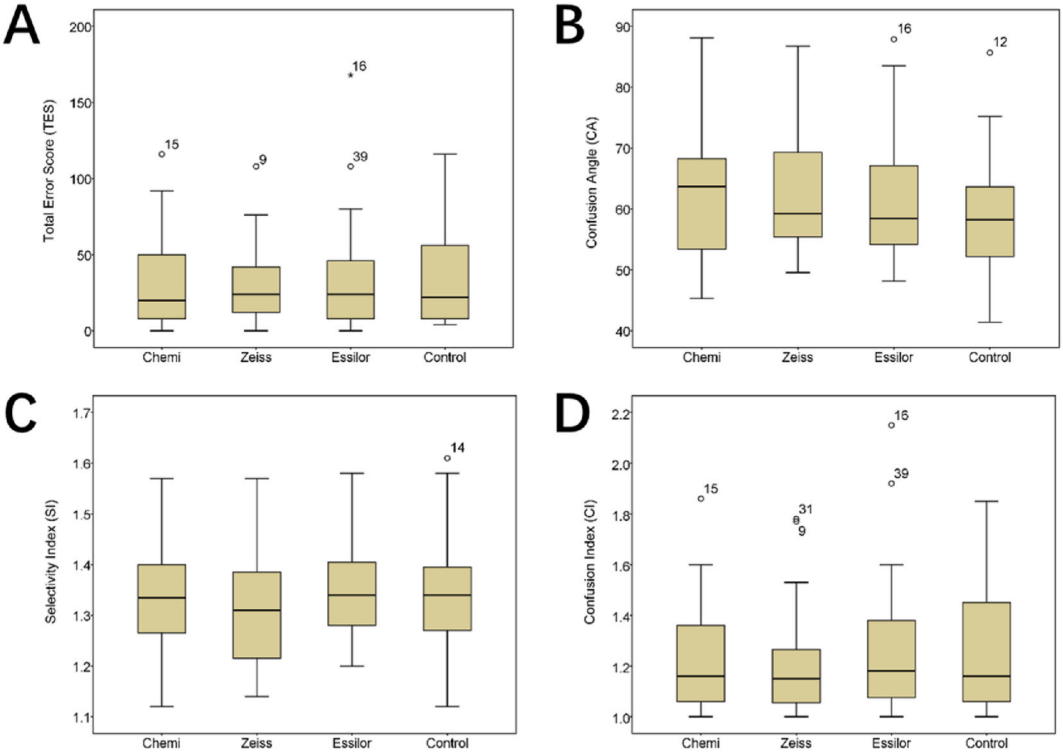


Fig. 5. Boxplots of the four indexes of FM 100-Hue Tests for four lenses groups: (A) total error score (TES), (B) confusion angle (CA), (C) selectivity index (SI) and (D) confusion index (CI). The line perpendicular to the whisker below the box represents the minimum value; the lines of the box represent interquartile range (the lower edge represents the first quartile; the upper edge represents the third quartile); the line in the box represents median value; the line perpendicular to the whisker above the box represents the maximum value; the circles and asterisks represent outliers.

Table 1

Median (interquartile range) and Friedman signed rank test result of the FM 100-Hue tests.

Index	Lenses				Chi-square	P value
	Chemi	Zeiss	Essilor	Control		
TES	20 (43)	24(31)	24(39)	22(50)	6.714	0.082
CA	63.74(15.13)	59.25(14.31)	58.48(13.10)	58.23(11.90)	5.744	0.125
SI	1.34(0.14)	1.31(0.18)	1.34(0.13)	1.34(0.13)	5.739	0.125
CI	1.16(0.32)	1.15(0.23)	1.18(0.31)	1.16(0.40)	2.596	0.458

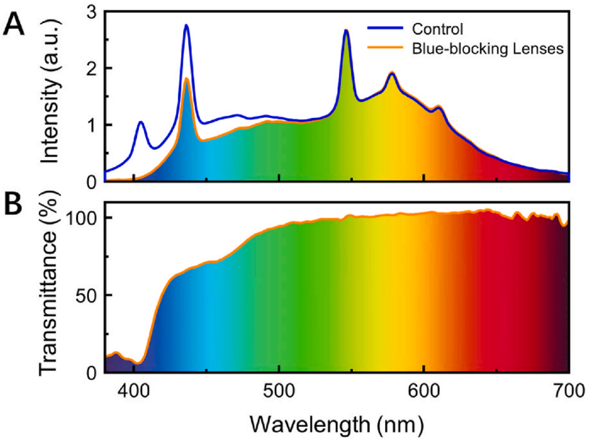


Fig. 6. The effect of a pair of BBLs on color lights. (A) The spectrum of a fluorescent lamp without/with the BBLs. The blue component was effectively reduced. (B) The transmittance curve of the BBLs, obtained by dividing the two spectra above. Blue light in the range of 380–410 nm had the lowest transmittance, blue light in the range of 410–500 nm had limited transmittance, and visible light with a wavelength greater than 500 nm had the highest transmittance.

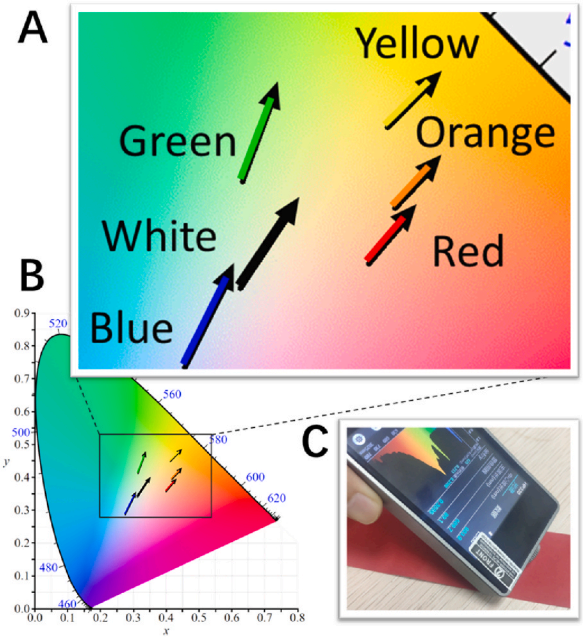


Fig. 7. Quantitative analysis of color differences induced by BBLs. (A) The chromaticity coordinate measurement results of various colored objects. Arrows represent the direction and degree of chromaticity change induced by BBLs. (B) The complete CIE chromaticity diagram. (C) The spectral illuminometer used for chromaticity coordinate measurement.

the experimental level. Therefore, CIE color spaces are actually linear spaces, similar to the vector space in linear algebra, where the addition and subtraction operations on a base are linear transformations. On the CIE 1931 chromaticity diagram, wearing BBLs effectively involves subtracting a portion of blue from some color vector (x_0, y_0), resulting in (x_0+x', y_0+y'). All chromaticity coordinates follow the linear transformation, i.e., translation through the vector (x', y'). As each chromaticity coordinate corresponds to a unique color, this translation transformation ensures that different coordinates remain distinct, thereby avoiding the mapping of different colors to the same color. Thus, individuals who can distinguish various colors without BBLs can still do so while wearing BBLs. Moreover, the continuity of chromaticity remains after linear transformation, allowing individuals with normal color vision to accurately arrange color caps even when wearing BBLs. On the other hand, the reason why individuals with color vision abnormalities are unable to distinguish different colors properly is because they lack the ability to perceive one or more basic colors. BBLs cannot restore the ability of individuals to perceive the colors. Therefore, if a subject fails a color vision test without BBLs, he or she will likely fail the test while wearing BBLs as well.

3.4 Under the influence of BBLs, different colors exhibit varying degrees of color differentiation.

In this experiment, the spectral illuminometer measured the chromaticity coordinates in the CIE 1931 XYZ color space, where X, Y, and Z represent the stimulus values of three basic colors, roughly corresponding to red, green and blue, respectively. To further fit the color response of the human eye and to facilitate the application of the CIE 1976 color difference formula, we used Eq. (1) and Eq. (2) to convert the chromaticity coordinates into the CIE 1976 Lab color space, where L* represents the luminance, a* represents the range from magenta to green, and b* represents the range from yellow to blue [24,25]. The converting results were shown in Table 2.

Color difference △E refers to the difference in color perception between two specimens, and it is this difference that enables the human eye to distinguish between two colors (see Table 3). In color spaces, the degree of color difference between two stimulus color samples can be quantitatively expressed. The CIE 1976 Lab color difference formula (Eq. 3) allows for a more objective and accurate assessment of color difference. When the color difference $\triangle E < 1$, it is difficult for the human eye to identify the two colors, and this color difference can only be measured with a colorimeter. When the color difference value exceeds $\triangle E > 3$, the human eye can noticeably distinguish the difference in color. From the color differences shown in Table 3 and it can be concluded that when using BBLs, colors with shorter wavelengths like blue exhibit the largest △E, colors with longer wavelengths like yellow demonstrate the smallest, while the ΔEs of all colors exceeded 3. This observation aligns with the lengths of the arrows depicted in Fig. 7(B). This indicates that when utilizing BBLs, there indeed exists a color difference perceived by the human eye, with varying degrees across different colors. Therefore, although wearing BBLs may not impact the outcomes of color vision tests, people engaged in color-associated jobs should exercise caution when using them.

3.5 BBLs could potentially influence the capacity to discriminate between blue hues of varying saturations to a certain degree.

Based on the preceding analysis, it can be concluded that the color differences of long-wavelength colors are relatively minor with the use of BBLs, while the color differences of short-wavelength colors are more pronounced. As can be seen from the spectra in Fig. 6 (A)–as blue saturation increases, the centroid wavelength of the spectrum decreases. Therefore, it can be speculated that BBLs have little impact on the discrimination of warm colors such as yellow and red, but may affect the discrimination of blue with varying saturations. When BBLs are worn, the color difference between blue hues of different saturations tends to diminish, i.e., the saturation of highly saturated blues is substantially reduced, while the saturation of less saturated blues remains relatively unchanged. Consequently, this discrepancy in saturation alteration affects the recognition of blue hues with different saturations. This conclusion is supported by prior research [21,39].

This phenomenon can also be explained by the change of coordinates on the chromaticity diagram. In Fig. 8, points A and B represent blue hues with different saturations, with point A being more saturated and having a shorter centroid wavelength, and point B being less saturated with a longer centroid wavelength. With the BBLs on, point A shifts to A' with a longer displacement, indicating a more significant change in chromaticity, whereas point B shifts to B' with a shorter displacement, indicating a lesser change in chromaticity. The distance between A and B represents the color difference △E between the original two blue hues, and the distance between A' and B' represents the color difference $\triangle E'$ between the two blue hues in the presence of the BBLs. From the diagram, we can see that △E is larger than △E’, implying that the color differences between different saturated blue hues diminish when BBLs are worn. In the experiment involving the arrangement of color caps, BBLs did not affect the arrangement of the blue area, probably

Table 2

Chromaticity coordinate converting results of CIE 1931 and CIE 1976 systems.

	X	Y	Z	L*	a*	b*
Red	55.95728	50.14796	33.38923	3.390546	13.14375	6.456928
Red + BBLs	44.12443	40.29218	19.04618	−0.42036	9.116636	11.47411
Orange	91.91829	87.15672	40.38744	17.7006	13.62206	25.4756
Orange + BBLs	69.63902	66.41576	20.77989	9.680759	9.680019	27.48917
Yellow	78.94115	86.22547	25.62021	17.34052	−7.25719	36.78516
Yellow + BBLs	70.31469	76.29881	11.80646	13.50221	−5.62383	41.32748
Green	48.85485	64.22623	41.64611	8.834144	−22.5968	9.171733
Green + BBLs	28.55302	39.93958	16.41066	−0.55669	−17.2113	13.36827
Blue	30.23546	31.59871	47.43507	−3.78183	−0.40172	−17.2568
Blue + BBLs	19.5614	22.27589	22.07481	−7.38666	−3.31406	−2.98357
Purple	23.52587	23.79693	25.15015	−6.79852	1.003548	−4.4541
Purple + BBLs	15.14534	16.16467	10.83994	−9.74966	−0.76199	2.018893

Table 3
Color differences of various colors induced by BBLs.

	Red	Orange	Yellow	Green	Blue	Purple
ΔE	27.95634	41.95599	19.01654	67.40108	112.6012	26.86299

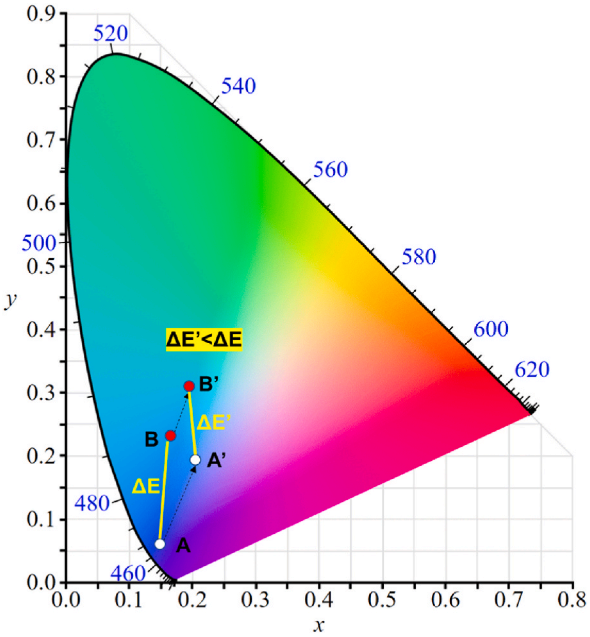


Fig. 8. Change in color difference between blue hues with different saturations induced by BBLs. Points A and B represent blue hues of different saturations. When using BBLs, A switches to A′, B switches to B'. The line segments of AB and A'B' represent the color differences ΔE and ΔE'. It can be seen that ΔE is greater than ΔE', indicating that the color differences between different saturated blue hues diminish when BBLs are worn.

because the color differences between the blue caps was already substantial enough. Even with the BBLs, the resulting color differences remained greater than the minimum color difference discernible by the human eye.

Whether or not dentists need to remove BBLs when performing the denture colorimetry is also a matter of great concern. Dentists usually need to color match the denture to the surrounding teeth for aesthetic purposes. Based on our study, it can be concluded that the color difference when wearing BBLs is not significant, since teeth are in yellowish-white hue with a long centroid wavelength. Therefore, dentists can keep BBLs on during colorimetric comparison. However, for some professions that require very fine color recognition, such as painters, it is necessary to consider the color differences induced by BBLs. As we can see, color vision tests such as PIC tests and FM tests serve only to identify normal color discrimination, but they do not allow for a more precise assessment of the subjects' color discrimination. In future studies, more precise color vision testing methods will be developed to explore the practical implications of BBLs in these specific professional contexts.

The chromaticity coordinate analysis proposed in this study holds promise for investigating the effect not only of BBLs but also of any tinted lenses on color vision. This methodology is particularly relevant for jobs such as laser operators, where protective eyewear is essential for isolating specific colors of lasers. Protective eyewear typically filters out a broad spectrum of color light with ultralow transmittance. There is a critical need to examine and develop sign color standards in workplaces with lasers. These standards would ensure that warning labels and signs remain effectively visible to individuals wearing protective eyewear. This effort is essential for enhancing workplace safety and efficiency for laser operators and other professionals working with tinted lenses.

4. Conclusion

The human eye perceives colors within a linear color space comprising three basic colors. After passing through BBLs, the chromaticity coordinates of the color lights showed a tendency to disperse outward from the blue pole on the chromaticity diagram. This transformation did not disrupt the continuity of the chromaticity diagram, nor did it map two different colors to the same color. Therefore, BBLs do not affect the color discrimination ability of the human eye, nor do they affect the outcomes of the related color vision tests. However, BBLs do introduce color difference, especially for hues near the blue pole on the chromaticity diagram. Therefore, it is recommended that people in color-associated jobs wear regular lenses. This study pioneered the utilization of color space analysis to scrutinize BBLs-induced color differences, offering theoretical underpinnings for observed effects on color vision tests and presenting a novel approach to investigating tinted lenses effects on color vision.

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Ethics statement

- This study was reviewed and approved by the ethics committee of Hospital of Stomatology, Jilin University, with the approval number: 202,046.
- All participants/patients (or their proxies/legal guardians) provided informed consent to participate in the study.
- All participants/patients (or their proxies/legal guardians) provided informed consent for the publication of their anonymised case details and images.

Data availability statement

Data included in article/supp. material/referenced in article.

CRediT authorship contribution statement

Huiyao Yu: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Data curation. **Xinwei Guo:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Jian Wu:** Resources, Formal analysis. **Huang Wu:** Investigation, Conceptualization. **Hongyan Zhao:** Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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