CLINICAL AND EXPERIMENTAL
OPTOMETRY

RESEARCH

Modelling the effect of commercially available blue-blocking lenses on visual and non-visual functions

Clin Exp Optom 2019 DOI:10.1111/cxo.12959

Hind S Alzahrani MSc BSc
Sieu K Khuu PhD BSc (Hons)
Maitreyee Roy PhD MPhil MSc
School of Optometry and Vision Science, The University of New South Wales, Sydney, Australia
E-mail: maitreyee.roy@unsw.edu.au

Background: Blue-blocking lenses (BBLs) are marketed as providing retinal protection from acute and cumulative exposure to blue light over time. The selective reduction in visible wavelengths transmitted through BBLs is known to influence the photosensitivity of retinal photoreceptors, which affects both visual and non-visual functions. This study measured the spectral transmittance of BBLs and evaluated their effect on blue perception, scotopic vision, circadian rhythm, and protection from photochemical retinal damage.
Methods: Seven different types of BBLs from six manufacturers and untinted control lenses with three different powers (+2.00 D, −2.00 D and Plano) were evaluated. The whiteness index of BBLs used in this study was calculated using Commission International de l'Eclairage (CIE) Standard Illuminates D65, and CIE 1964 Standard with a 2° Observer. The protective qualities of BBLs and their effect on blue perception, scotopic vision, and circadian rhythm were evaluated based on their spectral transmittance, which was measured with a Cary 5,000 UV–Vis–NIR spectrophotometer.
Results: BBLs were found to reduce blue light (400–500 nm) by 6–43 per cent, providing significant protection from photochemical retinal damage compared to control lenses ($p \leq 0.05$). All BBLs were capable of reducing the perception of blue colours, scotopic sensitivities and circadian sensitivities by 5–36 per cent, 5–24 per cent, and 4–27 per cent, respectively depending on the brand and power of the lens.
Conclusion: BBLs can provide some protection to the human eye from photochemical retinal damage by reducing a portion of blue light that may affect visual and non-visual performances, such as those critical to scotopic vision, blue perception, and circadian rhythm.

Submitted: 12 October 2018
Revised: 18 July 2019
Accepted for publication: 25 July 2019

Key words: blue-blocking lenses, non-visual functions, transmittance, visual functions

High-energy visible blue light that consists of wavelengths ranging from 400 nm to 500 nm in the visible spectrum is essential for visual perception,[1] and internal body regulation (particularly the circadian rhythm[2]), yet exposure to blue light has been linked to retinal damage,[3] which suggests a need to limit their use as a light source. However, human exposure to blue light has become common with the increasing use of new light-emitting diode (LED) light sources to provide bright illumination to the environment. Blue LED light sources are widely used in many prevalently used electronic devices such as TVs, smartphones, tablets, computers and laptops, screens and iPads.[4] With the increased exposure to blue light in the environment, concern has been raised as to whether and how this might impact biological functions that are dependent on light.

The wavelength of light plays an important role in scotopic vision,[5] colour perception,[1] and regulation of non-visual responses.[5] For example, previous studies have demonstrated that vision is more dependent on blue light under scotopic conditions than photopic vision.[6] The wavelength of approximately 507 nm in the blue-green range is sufficient to activate the photopigment rhodopsin in human rod-photoreceptors, which is the basis for scotopic vision.[5] Additionally, the absorption of blue light by S-cones enhances visual acuity, and the S-cone function is maximally activated at a wavelength of approximately 430 nm.[1] Intrinsically photosensitive retinal ganglion cells (ipRGCs) contain the photopigment melanopsin, which is most sensitive to blue light at a wavelength of approximately 480 nm[5] and is vital in controlling non-visual physiologic responses in the human body including circadian entrainment, melatonin secretion, cognitive performance, mood, and mental activity.[2]

Based on animal models and cell culture experiments, overexposure to blue light may damage cells in the retina.[3,7] These studies demonstrate that short exposures (seconds to hours), to high irradiance of white light above 10 mW/cm^2, resulted in photochemical damage to the retinal cells that increases at shorter wavelengths of light, with damage sharply peaking at approximately 440 nm.[3,7] However, the action spectrum of this photochemical damage is broad, ranging in wavelengths of light of between 400 and 500 nm.[3] Indeed, retinal damage that occurs in animals after 48 hours of exposure to blue light,[3,8] resembles that from direct viewing of a solar eclipse (38–48 hours). Data on sunlight exposure and antioxidant level proposed that chronic exposure (for example, over periods of months or years) to intense sunlight is associated with early stages of age-related macular degeneration (AMD) in elderly humans with low levels of antioxidants.[9]

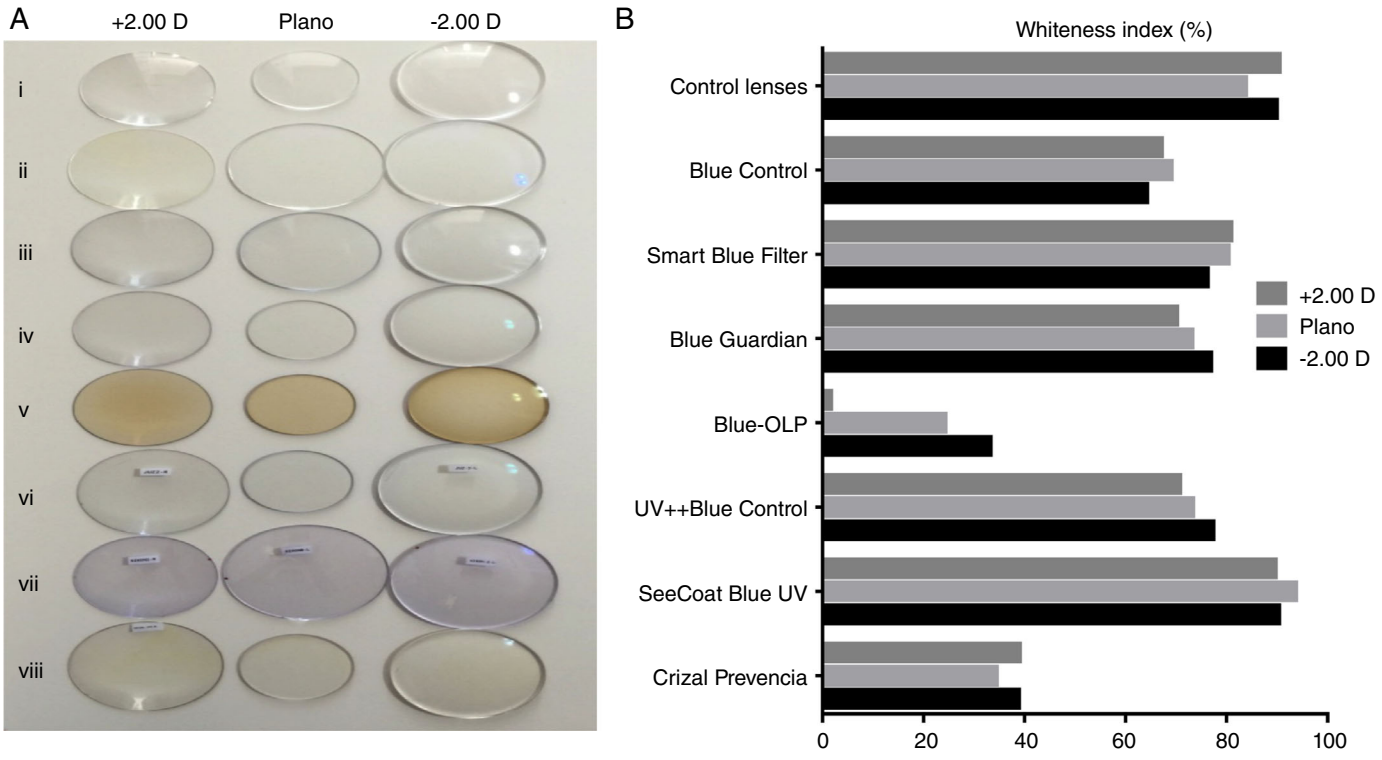

Figure 1. A: Blue-blocking lenses (BBLs) evaluated in this study: i. Control lenses (untinted); ii. Blue Control; iii. Smart Blue Filter; iv. Blue Guardian; v. Blu-OLP; vi. UV++Blue Control; vii. SeeCoat Blue UV; viii. Crizal Prevencia. B: The whiteness index (%) of BBLs respectively.

The International Commission on Non-Ionizing Radiation Protection Guidelines[10] define the safety limits of ocular exposure in humans to visible radiation (400–780 nm) based on the type of damage which can be thermal or photochemical. However, the present study was focused only on the photochemical retinal damage induced by extreme, chronic exposure to blue light (400–500 nm), which currently blue-blocking lenses (BBLs) intend to reduce. For an exposure duration t greater than 0.25 s but less than 10,000 s, the blue-light radiance exposure limit is $10^6/t$ ($W/m^2/sr$). For an exposure duration greater than 10,000 s, the exposure limit to a blue-light radiance is 100 ($W/m^2/sr$).[10,11]

Exposure to blue light at night time can lead to suppression of melatonin secretion which disrupts the circadian clock and may cause adverse consequences on mental, physical health,[12–16] and sleep.[17] The disruption of circadian rhythm is associated with mood disorders,[12] breast cancer,[13] obesity and chronic diseases,[14] heart disease, high blood pressure, and other cardiovascular problems.[15] Conversely, the reduction in blue-enriched light during daytime hours can increase daytime melatonin levels, which may lead to sleepiness, mood and cognitive deficits.[16]

A viable solution to protect ocular tissues and control exposure is to filter blue light through the use of BBLs. For many years, a large number of BBLs have been designed in different colours (red, green, blue, orange, pink, brown, and yellow).[18] However, yellow lenses have been shown to provide the most protective effect because they absorbed almost all blue wavelengths of light and can

BBLs type	Refractive index	Lens material/filtering technique
Essilor (Crizal Prevencia lens)	1.50	Clear plastic/anti-reflection coating
Nikon lens (SeeCoat Blue UV)	1.60	Clear plastic/anti-reflection coating
JuzVision lens (UV++Blue Control)	1.60	Clear plastic/absorbing material 'UV++'
GenOp lens (Blu-OLP)	1.56	Plastic/absorbing material 'pigment'
Opticare (Blue Guardian)	1.56	Clear plastic/anti-reflection coating 'multi-coating'
Essilor (Smart Blue Filter)	1.50	Clear plastic/absorbing coating
Hoya (Blue Control)	1.60	Clear plastic/anti-reflection coating
Opticare (untinted control lens)	1.499	Plastic/without blue-filtering coating

Table 1. Characteristics of the blue-blocking lenses (BBLs) used in the study

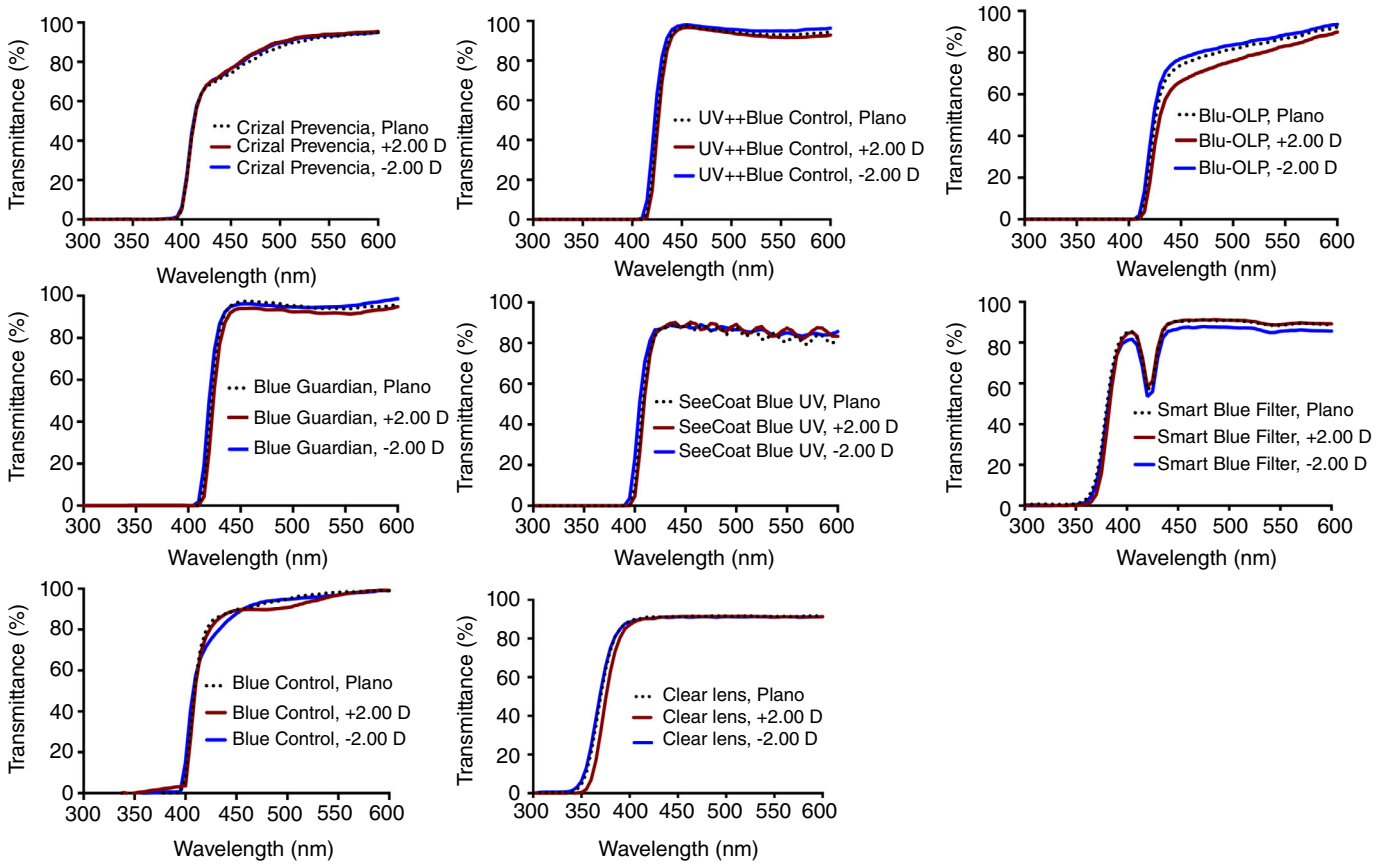

Figure 2. Spectral transmission characteristics of 21 blue-blocking lenses (BBLs) from seven brands and clear control lenses with and without powers

provide efficient protection to retinal cells from damage.[19]

For non-visual function, a number of studies have shown that yellow BBLs can be helpful for the treatment of insomnia, mood disorders, mania and delayed sleep phase disorder.[20–22] For visual function, yellow BBLs have been recommended for ophthalmic purposes to correct the quality of vision for low-vision patients,[23,24] and in AMD patients, to enhance contrast sensitivity.[25] Additionally, such BBLs are commonly used for outdoor visual tasks such as shooting, night driving, flying and skiing to enhance visual performance, especially under low visibility conditions of dusk, haze, and high luminance environments.[26,27]

Although yellow BBLs have been reported to improve non-visual and some visual performances as well as provide protection against blue light, they might be undesirable for everyday use. Wearing BBLs in daytime hours is known to increase sleepiness and might be dangerous for night time driving.[28] This is because BBLs block wavelengths that are required for scotopic vision,[29] alertness and cognitive performance,[2] and interfere with colour perception.[18]

In recent years, a new generation of BBLs has been developed and manufactured by various ophthalmic industries with acceptable cosmetic appearances that are close to a preferred transparent[30,31] such as BBLs provided by Essilor, GenOp, Hoya, JuzVision, Nikon, and Opticare. These BBLs are produced to offer high visible light transmission that is required for visual and non-visual functions and attenuate the most harmful wavelengths of blue light. These BBLs are available in the market and advertised as safety glasses with high visual properties for computer users and other digital devices users as well as regulating the circadian clock when wearing them in evening hours, which increases their popularity. However, the protective effect and the potential benefits and risks of these new BBLs for essential visual and non-visual functions remain to be determined.

This study investigated the spectral transmittance of different wavelengths of visible light through various types of commercially available BBLs with and without refractive power that is currently available in the market. The goal of this investigation was to provide a theoretical estimation and statistical analysis on the protective effect of commercially available BBLs for visual perception, scotopic vision, and non-visual performances.

Methods

Samples

In this study, seven different types of BBLs by six manufacturers with three different powers (+2.00 D, −2.00 D and Plano) were evaluated. These lenses were the Crizal Prevencia and Smart Blue Filter (Essilor), Blu-OLP (GenOp), Blue Control (Hoya), UV++Blue Control (JuzVision), SeeCoat Blue UV (Nikon) and Blue Guardian (Opticare) as shown in Figure 1A. All lenses function as a blue blocker based on either absorption or reflection of the specific blue wavelengths (Table 1).

BBL type	Lens power (D)	Transmittance of direct incident blue light (mean ± SD) %	Blue light hazard prevention (%)[†]
Essilor (Crizal Prevencia lens)	–2.00 D	69.81 ± 0.25	22.75
	Plano	74.98 ± 0.02	17.80
	+2.00 D	72.49 ± 2.80	22.78
Nikon lens (SeeCoat Blue UV)	–2.00 D	81.73 ± 0.06	9.98
	Plano	79.51 ± 0.29	13.14
	+2.00 D	78.90 ± 0.04	13.08
JuzVision lens (UV++Blue Control)	–2.00 D	73.47 ± 0.14	19.17
	Plano	79.51 ± 0.29	22.58
	+2.00 D	78.90 ± 0.04	23.97
GenOp lens (Blu-OLP)	–2.00 D	60.87 ± 0.02	32.93
	Plano	58.01 ± 0.07	36.44
	+2.00 D	51.53 ± 0.15	43.42
Opticare (Blue Guardian)	–2.00 D	74.07 ± 0.49	17.88
	Plano	73.02 ± 0.72	20.60
	+2.00 D	69.80 ± 0.003	23.15
Essilor (Smart Blue Filter)	–2.00 D	81.31 ± 0.05	10.38
	Plano	84.77 ± 0.08	7.07
	+2.00 D	85.10 ± 0.09	6.24
Hoya (Blue Control)	–2.00 D	79.87 ± 0.13	12.15
	Plano	80.39 ± 0.45	11.46
	+2.00 D	79.34 ± 1.03	13.68
Opticare (untinted control lens)	–2.00 D	90.74 ± 0.06	0.00
	Plano	89.58 ± 1.07	0.00
	+2.00 D	90.96 ± 0.14	0.00

[†]Percentage of blocked blue light (400–500 nm) = 100 – ([T_{BBL} /$T_{control}$] × 100), where T_{BBL}: the transmittance mean for individual BBL, and $T_{control}$: the transmittance mean of control lens.

Table 2. The calculated percentage values of transmittance mean of direct incident blue light, and blue light hazard prevention of each blue-blocking lens (BBL) with and without power in the wavelength range of 400–500 nm

Measurements

The whiteness indexes of BBLs used in this study were calculated using Commission International de l'Eclairage (CIE) Standard Illuminates D65 and CIE 1964 Standard with a 2° Observer (Figure 1). The whiteness of each lens was measured relative to a preferred white.

The spectral transmittance characteristics of the seven above-mentioned BBLs and a clear, untinted lens (control lens) (Table 1) were measured at the centre of the front surface of each lens using a Cary 5,000 UV–Vis–NIR spectrophotometer (Model: EL04043683) with an integrating sphere. The measurement of the transmission spectrum was performed at 5 nm intervals at a speed of 120 nm/second from 280 to 780 nm at a bandwidth of 2 nm. The spectral transmittance of each BBL was plotted as a function of the wavelength, as shown in Figure 2.

The spectral transmittance data analysis was conducted using IBM SPSS Statistics for Windows software (version 22.0; IBM, Armonk, NY, USA). To estimate the potential protective effect provided by BBLs, the spectral transmittance of each type of BBL at each power was measured and recorded four times in the wavelengths range between 280 nm and 780 nm. Three statistical tests were performed on the BBLs transmission means for the direct incident blue light (400–500 nm) as provided in Table 2.

First, the Welch analysis of variance (ANOVA) and Brown-Forsythe tests were used to indicate if there was a significant difference in the transmittance means of 21 BBLs. Second, post-hoc multiple comparisons (Games-Howell test) were used to determine which BBLs differ significantly from each other. Finally, the difference in the average transmittance between each type of BBL and a clear lens was assessed using an independent samples t-test.

A difference in the mean transmittance was considered statistically significant if the p-value was < 0.05. The protective effect of each BBL type was evaluated at the peak of photochemical retinal damage (440 nm) and correlated with their whiteness index, as shown in Figure 3.

The wavelength of light has different effects on the visual and non-visual systems due to the wavelength-dependent sensitivity of photoreceptors. The spectral sensitivity of a photoreceptor describes the efficiency of photopigment in the photoreceptor in converting light into a physiological signal inducing a biological visual or non-visual response.[32,33] The action spectrum of the spectral sensitivity of each photoreceptor is defined by function $S(\lambda)$, as shown in Figure 4. This action spectrum $S(\lambda)$ can be applied as a weighting function to the spectral power distribution of a light source to infer the degree to which the light source might affect the visual or non-visual response.[32,33]

When viewing a light source, the amount of irradiance acting on each photopigment is

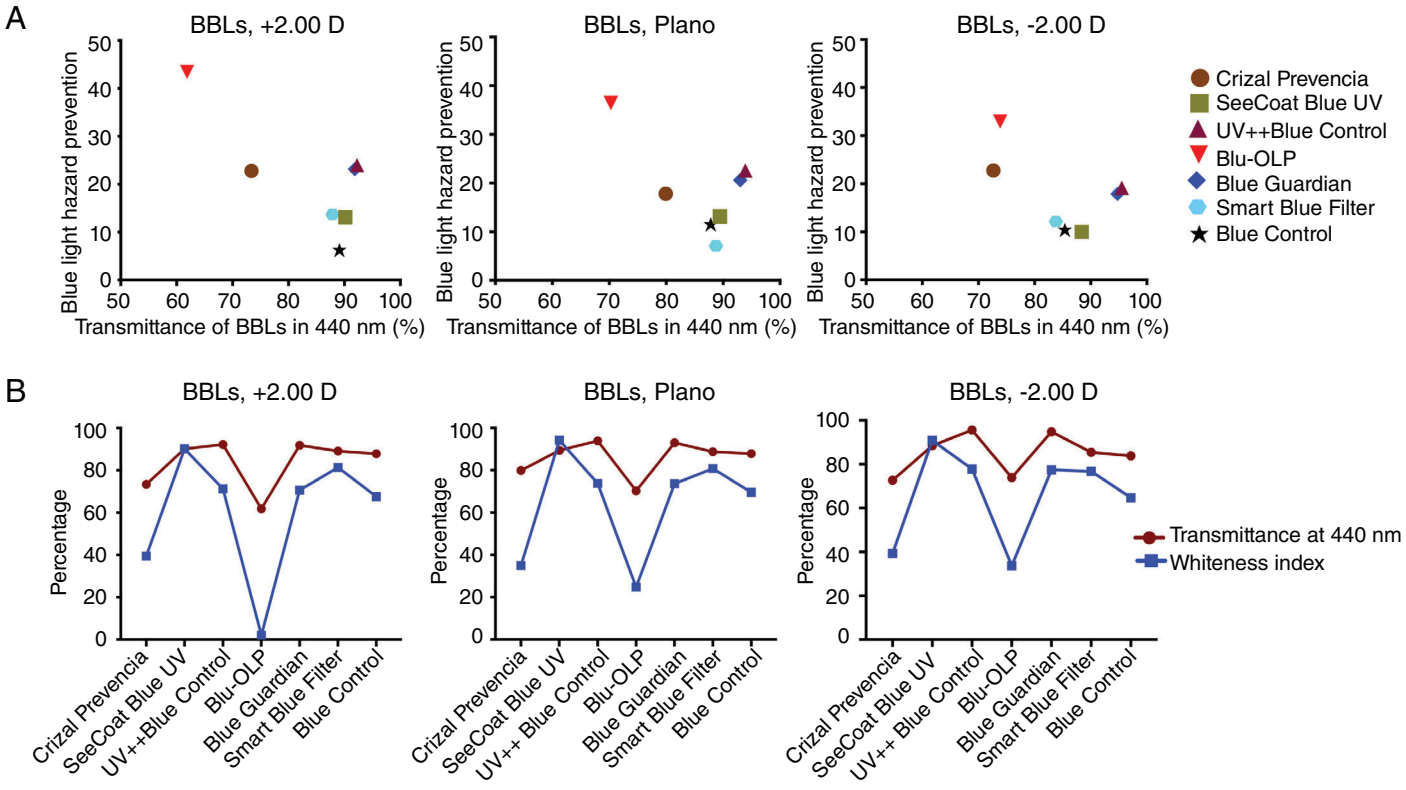

Figure 3. A: Relationship between how much blue light hazard is blocked in the range of 400–500 nm and the percentage of transmittance at 440 nm for tested blue-blocking lenses (BBLs) with and without powers. B: Correlation between the whiteness index and transmittance at 440 nm (the peak of photochemical retinal damage) for tested BBLs with and without powers.

determined by the effective irradiance (E_α). To calculate the effective irradiance for each of the photoreceptors (E_α), the spectral power distribution of the light source (E) is weighted with the appropriate spectral sensitivity function $S_\alpha(\lambda)$ given by the following formula:[32,33]

$$E_\alpha = \int_{\lambda_1}^{\lambda_2} E(\lambda)\, S_\alpha(\lambda)\, d\lambda \,\mathrm{W.m^{-2}} \quad [1]$$

where α relates to a human photopigment (photopsin, rhodopsin, or melanopsin).

However, because the retina is exposed to light attenuated by the BBL, it is assumed that:

$$E_{\alpha,BBL} = \int_{\lambda_1}^{\lambda_2} E(\lambda)\, T(\lambda)\, S_\alpha(\lambda)\, d\lambda \,\mathrm{W.m^{-2}} \quad [2]$$

where $E_{\alpha,\ BBL}$, denotes the effective irradiance for each of the photoreceptors when light is viewed through BBLs. $T(\lambda)$ is the spectral transmittance of the BBL. $E(\lambda)$ is the spectral power distribution of a D65 light source (a standard daylight illuminant, 6,500 K) in W/m^2.

For each BBL, the effective irradiance values were calculated using the irradiance toolbox,[33] which represent blue perception value (E_{sc}), scotopic sensitivity (E_r), and circadian sensitivity (E_z). Then, in order to evaluate the visual and non-visual effects of BBLs, the percent change in the effective irradiance E_α and $E_{\alpha,\ BBL}$ for each photoreceptor while wearing BBLs was determined by the following formula:

$$\text{Percent change in effective irradiance} = 100 \times \frac{E_\alpha - E_{\alpha,BBL}}{E_{\alpha.}}$$

The relative change in the blue perception ΔE_{sc}, scotopic sensitivity ΔE_r, and circadian sensitivity ΔE_z were calculated using the following equations:

$$\Delta E_{sc}(\%) = 1 - \frac{\int_{380}^{780} E(\lambda)\, T(\lambda)\, S_{sc}(\lambda)\, d\lambda}{\int_{380}^{780} E(\lambda)\, S_{sc}(\lambda)\, d\lambda} \quad [3]$$

$$\Delta E_r(\%) = 1 - \frac{\int_{380}^{780} E(\lambda)\, T(\lambda)\, S_r(\lambda)\, d\lambda}{\int_{380}^{780} E(\lambda)\, S_r(\lambda)\, d\lambda} \quad [4]$$

$$\Delta E_z(\%) = 1 - \frac{\int_{380}^{780} E(\lambda)\, T(\lambda)\, S_z(\lambda)\, d\lambda}{\int_{380}^{780} E(\lambda)\, S_z(\lambda)\, d\lambda} \quad [5]$$

where $S_{sc}(\lambda)$ is the spectral sensitivity function of S-cones (containing photopsin), $S_r(\lambda)$ is the spectral sensitivity function of rods (containing rhodopsin), $S_z(\lambda)$ is the spectral sensitivity function of the ipRGCs (containing melanopsin). These functions describe the response of photoreceptors to light in a 32-year-old standard human observer with an undilated pupil. More detail about these functions and calculations can be found in the guideline published by the CIE (SI CIE TN 003:2015).[32,33]

Results

Spectral transmission characteristics of BBLs

Figure 1 shows a variation in the whiteness index values of different BBLs with and without powers of the same brand name. A greater increase in variation of the whiteness index was observed for Blu-OLP lenses with and without powers.

Figure 2 shows the spectral transmittance characteristics of the seven types of BBLs and the control lens at three different powers. The BBLs were found to reduce the blue light (400–500 nm) by 6–43 per cent (Table 2), depending on the brand and

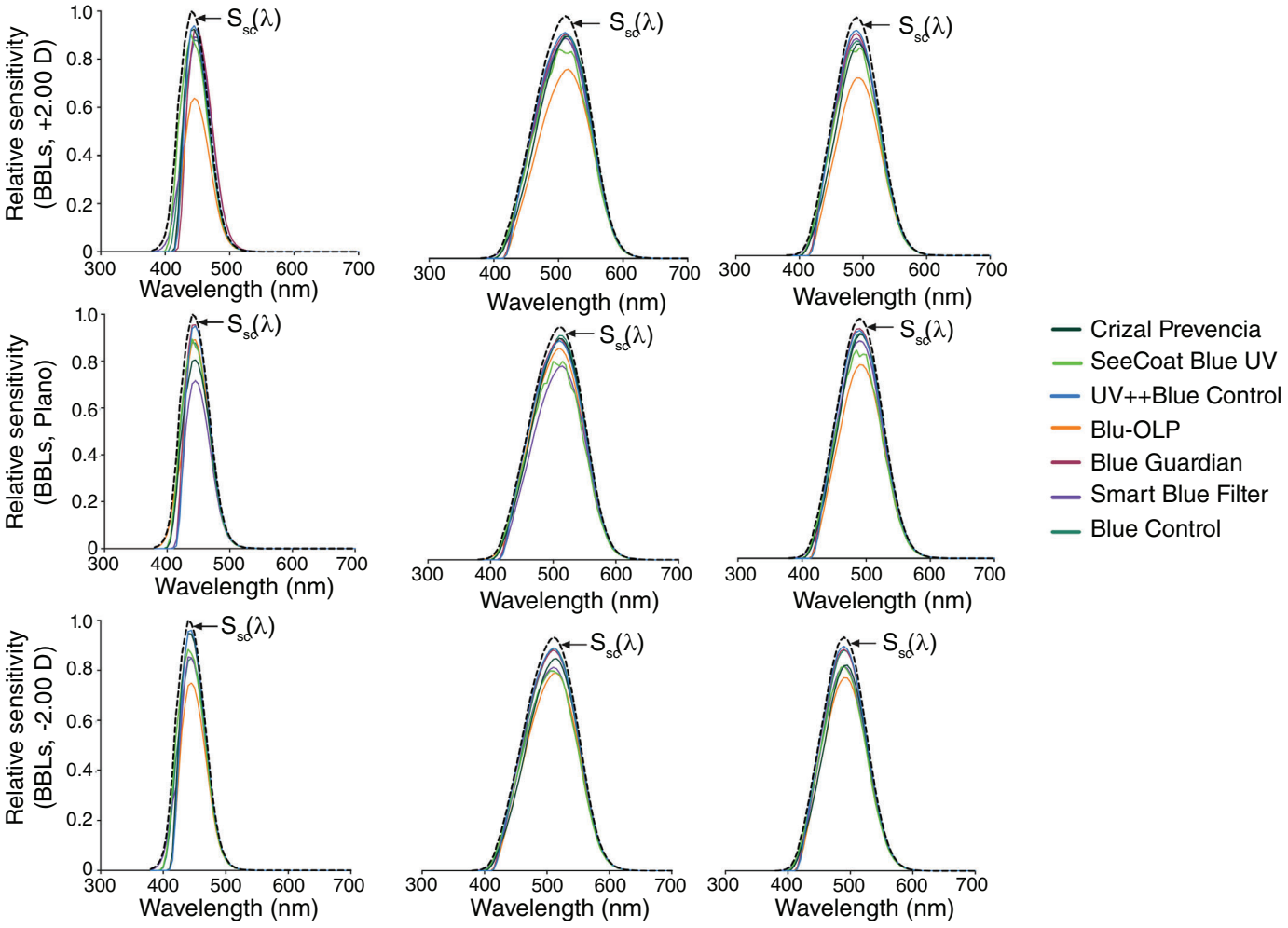

Figure 4. Relative sensitivities of the blue perception, scotopic vision, and circadian rhythm for various commercially available blue-blocking lenses (BBLs) with +2.00 D, −2.00 D and Plano in comparison to the spectral sensitivity curves of S-cones $S_{sc}(\lambda)$, rods $S_r(\lambda)$, and intrinsically photosensitive retinal ganglion cells (ipRGCs) $S_z(\lambda)$ respectively. Dashed lines indicate the spectral sensitivity curves ($S_{sc}(\lambda)$, $S_r(\lambda)$ and $S_z(\lambda)$) of a 32-year-old standard observer as recommended by Commission International de l'Eclairage (CIE) TN 003:2015.

power of the lens. For clear lenses, the curves showed high transmission with an average of 88 per cent of visible light beyond ultraviolet radiation and blue wavelengths (> 360 nm). Although all the BBLs were manufactured differently, they followed approximately the similar spectral transmission characteristics by reducing short wavelengths, while allowing longer wavelengths to pass through.

Evaluation of the protective effect of BBLs

Welch ANOVA and Brown-Forsythe tests indicated there was a significant difference in the transmittance means (400–500 nm) of the 21 BBLs from seven brands at three different powers ($p < 0.05$).

Post-hoc multiple comparisons between BBLs of the same brand, but with different powers, showed there was no significant difference in the transmittance means of some BBLs: Crizal Prevencia ($p = 0.283$, +2.00 D versus −2.00 D); SeeCoat Blue UV ($p = 0.963$, +2.00 D versus Plano); Blue Control ($p > 0.05$, +2.00 D versus −2.00 D, +2.00 D versus Plano); and Blue Guardian ($p = 0.124$, −2.00 D versus Plano) whereas Blu-OLP, Smart Blue Filter and UV++Blue Control lenses with different powers significantly varied in their transmittance means ($p < 0.05$).

Post-hoc multiple comparisons between BBLs with the same power but of different brands showed there was no significant difference in the transmittance means of some BBLs: UV++Blue Control and Blue Guardian lens ($p = 0.447$, −2.00 D); UV++Blue Control and Blue Guardian lens ($p = 0.095$, +2.00 D); Blue Control and SeeCoat Blue UV lens ($p = 0.975$, +2.00 D); Blue Guardian and Crizal Prevencia lens ($p = 0.618$, +2.00 D); UV++Blue Control and Crizal Prevencia lens ($p = 0.481$, +2.00 D); SeeCoat Blue UV and Blue Control ($p = 0.171$, Plano); and Blue Guardian and Crizal Prevencia lens ($p = 0.071$, Plano), whereas a significant difference in the transmittance means was noticed in other BBLs ($p < 0.05$).

The statistical difference in the transmittance means in the wavelengths range (400–500 nm) was also investigated by comparing each BBL with the control lens using

BBL type	Lens power (D)	Relative change in blue perception ΔE_{sc} (%)	Relative change in scotopic sensitivity ΔE_r (%)	Relative change in circadian sensitivity ΔE_z (%)
Essilor (Crizal Prevencia lens)	–2.00 D	24.17	12.38	15.26
	Plano	17.56	8.25	10.28
	+2.00 D	23.76	11.88	14.80
Nikon lens (SeeCoat Blue UV)	–2.00 D	12.19	13.88	13.08
	Plano	12.19	15.13	13.86
	+2.00 D	11.36	13.38	12.62
JuzVision lens (UV++Blue Control)	–2.00 D	5.17	4.50	4.21
	Plano	6.82	6.00	5.45
	+2.00 D	8.26	7.00	6.39
GenOp lens (Blu-OLP)	–2.00 D	24.79	16.38	18.54
	Plano	28.10	18.50	20.87
	+2.00 D	35.95	23.88	27.10
Opticare (Blue Guardian)	–2.00 D	5.99	5.00	4.98
	Plano	5.37	5.00	4.52
	+2.00 D	8.88	7.75	7.48
Essilor (Smart Blue Filter)	–2.00 D	15.08	13.75	13.55
	Plano	11.57	10.38	10.12
	+2.00 D	11.36	10.13	9.81
Hoya (Blue Control)	–2.00 D	13.43	6.25	7.79
	Plano	11.16	5.25	6.70
	+2.00 D	11.57	7.25	8.72
Opticare (untinted control lens)	–2.00 D	9.09	8.88	8.88
	Plano	8.68	8.50	8.41
	+2.00 D	8.88	8.63	8.57

Table 3. The relative changes in the blue perception ΔE_{sc}, scotopic sensitivity ΔE_r and circadian sensitivity ΔE_z by weighting the attenuated transmitted light through each blue-blocking lens (BBL) with the spectral sensitivity functions given in the International Standard Commission International de l'Eclairage (CIE) TN 003:2015

independent samples t-test and Levenes test. The results of these tests showed that the transmittance mean of a control lens was significantly different from that for each BBL ($p \leq 0.05$ for all comparisons).

As the peak of the action spectrum to the photochemical damage is at 440 nm,[3] it is important to compare the mean transmittance of BBLs (400–500 nm) with their transmittance at only 440 nm to provide a description for the protective effect of those BBLs as shown in Figure 3A. This figure shows a large increase in blue light hazard prevention for Blu-OLP and Crizal Prevencia lenses, which transmitted the lowest percentage of light at 440 nm by 62–80 per cent. This provides a clear indication of the effectiveness of some BBLs in the protection of retinal cells from photochemical damage due to blue light exposure. The effectiveness of BBLs in reducing the peak of photochemical retinal damage was significantly correlated with their whiteness index with $r = 0.90$, $p < 0.05$, and the greatest correlation was shown for Blu-OLP and Crizal Prevencia lenses compared to other BBLs with and without powers as shown in Figure 3B.

Effect of BBLs on blue perception, scotopic vision and circadian rhythm

Figure 4 shows that a reduction in the blue-light transmission led to a decrease in light sensitivity to blue colours of approximately 5–36 per cent, impaired night vision by 5–24 per cent, and reduced the circadian sensitivity by 4–27 per cent (Table 3).

Discussion

The present results confirm that all BBL types used in this study provide significant protection from photochemical retinal damage compared to the control lenses.

Based on the spectral transmittance analysis, Blu-OLP and Crizal Prevencia lenses offered substantially greater protection against hazardous short wavelengths of blue light compared to other BBLs.

The reduction in the ocular exposure to the blue light transmitted through BBLs is not only determined by the direct light measurement, but it is also determined by various parameters[34] such as the physical characteristics of the lens, frame, side shield structure and the wearers facial features as well as the back reflection. All these parameters can increase the amount of blue light hazard striking the eye, reducing their benefit. However, the influence of these parameters is beyond the scope of this investigation, since the only interest of the current study was to determine how much each BBL type could transmit the blue light.

The efficacy of the BBLs for visual and non-visual performance was theoretically evaluated which showed that the attenuated transmitted blue light through BBLs, resulted in a reduction in the S-cone (blue

perception), rod (scotopic), and ipRGC (circadian rhythm) sensitivities. These outcomes might have significant unintended effects on visual and non-visual behaviours, in particular BBLs with higher attenuation of blue light may pose a risk regarding their use during evening activities such as night time driving.

It is important to note that the actual effect of BBLs used in this study on the blue perception, scotopic, and circadian rhythm has not been fully characterised,[30,31] and needs to be empirically and clinically investigated to determine their effect on colour perception under different lighting conditions, the safety of wearing BBLs in low lighting conditions, lens wearing time, consequences of long-term use, and the possibility of BBLs in regulating circadian clock.

In conclusion, BBLs can provide some protection to the human eye from photochemical retinal damage by reducing a portion of blue light that may affect visual and non-visual performances such as those critical to scotopic vision, blue perception, and circadian rhythm. The present findings have obvious implications and are most useful for clinicians who may wish to recommend BBLs as a protective option for individuals who work in environments in which blue light is prevalent.

ACKNOWLEDGEMENTS

The authors of this study wish to thank Mr Justin Baker (JuzVision), Mr Tim Thurn (Essilor Australia) and Ms Dubravka Huber (Optometry Clinic, School of Optometry and Vision Science, UNSW Sydney) for providing BBLs used in this study. We thank Dr Kathleen Watt for valuable discussion.

REFERENCES

1. Solomon SG, Lennie P. The machinery of colour vision. *Nat Rev Neurosci* 2007; 8: 276–286.
2. Chellappa SL, Steiner R, Blattner P et al. Non-visual effects of light on melatonin, alertness and cognitive performance: can blue-enriched light keep us alert? *PLoS One* 2011; 6: e16429.
3. Wu J, Seregard S, Algvere PV. Photochemical damage of the retina. *Surv Ophthalmol* 2006; 51: 461–481.
4. O'hagan J, Khazova M, Price L. Low-energy light bulbs, computers, tablets and the blue light hazard. *Eye (Lond)* 2016; 30: 230–233.
5. Augustin AJ. The physiology of scotopic vision, contrast vision, colour vision, and circadian rhythmicity: can these parameters be influenced by blue-light-filter lenses? *Retina* 2008; 28: 1179–1187.
6. Mainster MA, Sparrow J. How much blue light should an IOL transmit? *Br J Ophthalmol* 2003; 87: 1523–1529.
7. Zhou J, Sparrow JR. Light filtering in an RPE culture model. *Optom Vis Sci* 2011; 88: 759–765.
8. Ham W, Ruffolo J, Mueller H et al. Histologic analysis of photochemical lesions produced in rhesus retina by short-wavelength light. *Invest Ophthalmol Vis Sci* 1978; 17: 1029–1035.
9. Fletcher AE, Bentham GC, Agnew M et al. Sunlight exposure, antioxidants, and age-related macular degeneration. *Arch Ophthalmol* 2008; 126: 1396–1403.
10. International Commission on Non-Ionizing Radiation Protection. ICNIRP guidelines on limits of exposure to incoherent visible and infrared radiation. *Health Phys* 2013; 105: 74–96.
11. Commission International de l'Eclairage. *Photobiological Safety of Lamps and Lamp Systems*, Vol. 27. Geneva: Commission International de l'Eclairage, 2006. p. 62471.
12. Bower B, Bylsma LM, Morris BH et al. Poor reported sleep quality predicts low positive affect in daily life among healthy and mood-disordered persons. *J Sleep Res* 2010; 19: 323–332.
13. Blask DE, Sauer LA, Dauchy RT et al. New insights into melatonin regulation of cancer growth. In: *Melatonin after Four Decades*. Boston, MA: Springer, 2002. pp. 337–343.
14. Reiter RJ, Tan D-X, Korkmaz A et al. Obesity and metabolic syndrome: association with chronodisruption, sleep deprivation, and melatonin suppression. *Ann Med* 2012; 44: 564–577.
15. Dominguez-Rodriguez A, Abreu-Gonzalez P, Sanchez-Sanchez JJ et al. Melatonin and circadian biology in human cardiovascular disease. *J Pineal Res* 2010; 49: 14–22.
16. Cho K. Chronic 'jet lag' produces temporal lobe atrophy and spatial cognitive deficits. *Nat Neurosci* 2001; 4: 567–568.
17. Ostrin LA, Abbott KS, Queener HM. Attenuation of short wavelengths alters sleep and the ipRGC pupil response. *Ophthalmic Physiol Opt* 2017; 37: 440–450.
18. Chen D-C, Huang K-L, Lee S-L et al. Blue light blocking lenses measuring device. *Procedia Eng* 2016; 140: 17–29.
19. Hiromoto K, Kuse Y, Tsuruma K et al. Colored lenses suppress blue light-emitting diode light-induced damage in photoreceptor-derived cells. *J Biomed Opt* 2016; 21: 035004–035004.
20. Kimberly B, James RP. Amber lenses to block blue light and improve sleep: a randomized trial. *Chronobiol Int* 2009; 26: 1602–1612.
21. Henriksen TE, Skrede S, Fasmer OB et al. Blocking blue light during mania markedly increased regularity of sleep and rapid improvement of symptoms: a case report. *Bipolar Disord* 2014; 16: 894–898.
22. Phelps J. Dark therapy for bipolar disorder using amber lenses for blue light blockade. *Med Hypotheses* 2008; 70: 224–229.
23. Eperjesi F, Fowler CW, Evans BJ. Do tinted lenses or filters improve visual performance in low vision? A review of the literature. *Ophthalmic Physiol Opt* 2002; 22: 68–77.
24. Rosenblum Y, Zak P, Ostrovsky M et al. Spectral filters in low-vision correction. *Ophthalmic Physiol Opt* 2000; 20: 335–341.
25. Wolffsohn J, Dinardo C, Vingrys A. Benefit of coloured lenses for age-related macular degeneration. *Ophthalmic Physiol Opt* 2002; 22: 300–311.
26. Clark BA. Colour in sunglass*. *Optom Vis Sci* 1969; 46: 825–840.
27. Clark BA. The luminous transmission factor of sunglasses. *Optom Vis Sci* 1969; 46: 362–378.
28. Lockley SW. Safety considerations for the use of blue-light blocking glasses in shift-workers. *J Pineal Res* 2007; 42: 210–211.
29. Aarnisalo EA. Effects of yellow filter glasses on the results of photopic and scotopic photometry. *Am J Ophthalmol* 1988; 105: 408–411.
30. Lawrenson JG, Hull CC, Downie LE. The effect of blue-light blocking spectacle lenses on visual performance, macular health and the sleep-wake cycle: a systematic review of the literature. *Ophthalmic Physiol Opt* 2017; 37: 644–654.
31. Downie LE. Blue-light filtering ophthalmic lenses: to prescribe, or not to prescribe? *Ophthalmic Physiol Opt* 2017; 37: 640–643.
32. Sliney DH. Radiometric quantities and units used in photobiology and photochemistry: recommendations of the commission Internationale de l'Eclairage (international commission on illumination). *Photochem Photobiol* 2007; 83: 425–432.
33. Price LL, Peirson SN. The first international workshop on circadian and neurophysiological photoreception, 2013: a physicist's perspective on the construction of standard units. *Light Eng* 2014; 22: 8–35.
34. Hall GW, Schultmeyer M. The FUBI system for solar rating nonprescription eyewear. *Optometry* 2002; 73: 407–417.