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Eur. Phys. J. Plus (2019) **134**: 494 DOI 10.1140/epjp/i2019-12848-x

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Società Italiana di Fisica

Springer

Eur. Phys. J. Plus (2019) **134**: 494
DOI 10.1140/epjp/i2019-12848-x

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Mitigating retinal damage and circadian rhythm modification by blue-blocking spectacles lenses: evaluation parameters

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Received: 30 November 2018 / Revised: 23 May 2019

Abstract. It is well established that short-wavelengths visible radiation has the potential to damage the retina and pigment epithelium and there is evidence for the effect of the same wavelengths on the circadian cycle. The introduction of LED lamps and digital devices has dramatically increased human exposure to blue light. In the last two years, a number of novel blue-blocking ophthalmic lenses entered into the market with the aim to protect human retina preserving also circadian cycle, but unfortunately, there is a lack of clarity in factory communication in explaining how this lens works and should be used and prescripted. It is not evident for ophthalmologists which is the best lens depending on the needs of the patients. Due to the different effect of the blue light on ocular media and circadian rhythm, we have defined new separate indexes that could describe the level of protection of the lenses towards the retina and the circadian cycle under different lighting sources, *e.g.* daylight and tablet. These indexes can help in individuating the right lens for ocular protection. We have measured these indexes for many blue blocking lenses available on the market, evaluating the effect under daylight and during the use of digital devices. We also have evaluated the effect of these lenses on chromatic discrimination.

1 Introduction

The invention of the Light-Emitting Diode (LED) has completely changed the world of light sources. LEDs replaced the old type of light sources, and they are massively adopted in the production of screens of all kind of electronic devices with which many of us deal every day, such as TVs, PCs, smartphones, and tablets. A particularity of the commonly used white LED is its significant emission of short-wavelength blue light [1]. Thus, it is essential to fully understand the consequences of this type of radiation on our health.

Recent investigations on the *third retinal receptor* have pointed out the importance of *blue light* (*i.e.* short-wavelength visible radiation mainly in the range $400\,\text{nm} \leq \lambda \leq 450\,\text{nm}$) for our life cycles. Berson *et al.* [2] showed that this receptor has a significant impact on the control of the circadian cycle, *i.e.* the set of all the physiological cycles of our body within 24 hours, such as the regulation of arterial pressure or the production of melatonin. Several studies confirmed that an unnatural exposition to short-wavelength radiation could have a negative impact on our health (a similar effect is present also in vegetables production [3]). For example, insufficient exposure to blue light during the day is related to sleep disorders [4,5], while substantial exposure to blue light during the evening is known to cause the inhibition of melatonin production which damages the quality of sleep [6–8]. Lots of studies [9–22] have shown how an excessive and prolonged exposure to this kind of radiation can lead to the onset of ocular pathologies, such as senile macular degeneration or cataract.

Optical devices such as ophthalmic, contact, or intra-ocular lenses can be used as protection from the effects of the blue radiation. Due to the ubiquitous presence of LED devices, we witnessed an increasing interest around those aspects of blue light, with the result of the market introduction over the last few years of many blue-blocking ophthalmic lenses by lens manufacturers. This kind of lenses are more likely used and sold to reduced the eye strain caused by digital devices usage, but often they are marketed as blue-blocking lenses. However, there is still a debate

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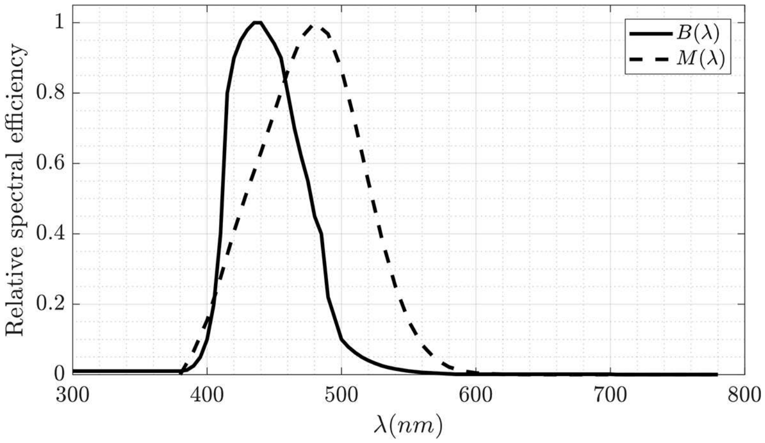

Fig. 1. Comparison between $B(\lambda)$, blue light hazard function and M_λ, the ipRGCs response curve.

in the scientific community and no strict regulations on how short-wavelength visible light should be treated. Thus, it is not clear how lenses should protect us from the negative effects of the blue light (by blocking it) while preserving the positive effects on the circadian cycle. In this work, we propose a novel approach to characterise the interaction of lenses with blue light based on the introduction of two new numerical indexes, one devoted to retinal damage and one to circadian rhythm. We evaluate a set of commercially available lenses with different types of blue-blocking treatments, comparing them with a group of lenses without this type of treatment. None of the blue-blocking lenses claims to be medical devices, and thus they are not regulated by the Food and Drug Administration. Computing our indexes for the analysed lenses, we were able not only to compare treated and non-treated lenses but also to capture the heterogeneity of the behaviours of the different blue-blocking lenses.

The paper is structured as follows. In sect. 2, we briefly introduce the numerical parameters used for the analysis of the lenses, defining the two novel indexes we propose in this work. In sect. 3 we report the experimental settings, in sect. 4 we expose and discuss the results of this study, and sect. 5 concludes the paper.

2 Characterization of the interaction of lenses with blue-light radiation

In this section, we describe the proposed indexes to characterise the response of lenses to the exposure to blue light. One index, named *Retinal Index* (RI), is related to retinal damage. Another index, called *Non-Linear Circadian Index* (NLCI) wants to describe the effect of filters on human circadian rhythm. Our parameters are linked only to the lens, and not to ocular media and for this reason could be associated to the common indexes present in the Standard regulating in the world the possibility to market ophthalmic filters [23].

2.1 Retinal Index (RI)

The Retinal Index (RI) quantifies the possible damage of the retina due to the exposure to the short-wavelength radiation. We define

$$RI = \frac{\int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} T(\lambda)SP(\lambda)B(\lambda)\mathrm{d}\lambda}{\int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} SP(\lambda)B(\lambda)\mathrm{d}\lambda}\,, \tag{1}$$

where $T(\lambda)$ is *spectral transmittance* of a lens in the visible spectrum (380–780 nm), defined as the ratio between the transmitted flux and the incident flux [24], $SP(\lambda)$ is the spectrum of a generic illuminant, and $B(\lambda)$ is the *blue-light hazard function* (depicted in fig. 1). $B(\lambda)$ represents the risk of damaging the retina if exposed to a blue-light radiation [25]. RI ranges from 0 to 1, where an RI = 0 identifies a totally protective lens against the photochemical retinal damage due to blue light, while RI = 1 identifies a totally non-protective lens.

2.2 Non-linear circadian index (NLCI)

In 2010, Rea *et al.* [26] introduced a non-linear model that takes into account also “a subadditive, spectral opponent input to the ipRGCs from the blue-yellow channel, [...] a shunting inhibition and a one-way diode-like signal path whereby only depolarizing input from the S-cone bipolar to the ipRGCs is possible" [27]. Using this model, Rea *et al.* defined a quantity called *Circadian Light* (CL). Given

$$\begin{aligned} R &= \int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} P_\lambda V'_\lambda \mathrm{d}\lambda, \\ G &= \int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} P_\lambda M_\lambda \mathrm{d}\lambda, \\ B &= \int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} P_\lambda S_\lambda \mathrm{d}\lambda, \\ Y &= k\int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} P_\lambda V_{10\lambda} \mathrm{d}\lambda, \end{aligned} \tag{2}$$

CL is defined as

$$CL = a_1 G - b_1 + a_2(B - Y) - b_2 - a_3\left(1 - e^{-\frac{R}{rodSat}}\right), \tag{3}$$

where P_λ is the spectral irradiance at the eye, $V_{10\lambda}$ is the large-field L+M cone spectral efficiency function [28], V'_λ is the rod spectral efficiency function [29], S_λ is the S-cone spectral efficiency function [30]. Relying on this definition, we define an index called NLCI as

$$\mathrm{NLCI} = \frac{\mathrm{CL}_{\mathrm{filtered}}}{\mathrm{CL}_{\mathrm{non\text{-}filtered}}}, \tag{4}$$

where $\mathrm{CL}_{\mathrm{filtered}}$ is the circadian light computed using the filtered spectral irradiance $P_\lambda = SP(\lambda)T(\lambda)$, with $SP(\lambda)$ being the spectrum of the used light source and $T(\lambda)$ the spectral transmittance of the filter. $\mathrm{CL}_{\mathrm{non\text{-}filtered}}$ is instead computed using the non-filtered radiation, that is, $P_\lambda = SP(\lambda)$.

The index NLCI ranges from 0 to 1, where 0 identifies a lens that completely blocks the effects of the blue light radiation on the circadian cycle, and 1 identifies a lens that does not interfere with those effects.

NLCI quantifies the ability of a lens to inhibit the effect of the light radiation on the circadian cycle. When using a lens with NLCI $= 1$, the natural circadian cycle could be altered by the exposure to the artificial blue light of digital devices, but the same lens allows the natural rhythm of the circadian cycle in the case of natural, solar light exposure. On the other hand, a lens with NLCI $= 0$ protects from the damages caused by the artificial blue light, but, at the same time, does not allow the natural blue light to influence the circadian rhythm.

2.3 UV transmission factor (τ_{UV})

To fully characterise the quality of a lens, we also measure and report the *Solar UV transmission factor*, τ_{UV} [23], defined as

$$\tau_{UV} = \frac{\int_{280\,\mathrm{nm}}^{380\,\mathrm{nm}} T(\lambda) W_\lambda(\lambda) \mathrm{d}\lambda}{\int_{280\,\mathrm{nm}}^{380\,\mathrm{nm}} W_\lambda(\lambda) \mathrm{d}\lambda}, \tag{5}$$

where $T(\lambda)$ is the spectral transmittance of a lens, and $W_\lambda(\lambda)$ is the weighting function for UV transmission as defined by the European Regulation UNI EN 1836. This index takes into consideration the percentage of ultraviolet radiation that a medium can transmit.

3 Experimental settings

For this study, we analysed 16 commercially available blue-blocking lenses from 8 different companies and 5 lenses without any blue-blocking treatment. The characteristics of the analysed lenses are reported in table 1.

We measured the spectral transmittance $T(\lambda)$ using the spectrophotometer *Perkin Elmer Lambda 1050 UV/Vis/NIR* double-beam with integrating sphere. Since we were interested in the behaviour of the lenses in the visible and UV spectra, we measured $T(\lambda)$ for $280\,\mathrm{nm} \leq \lambda \leq 830\,\mathrm{nm}$, with a stride of $5\,\mathrm{nm}$, in order to obtain a good compromise between measuring times and preciseness, as suggested by the principal ISO regulations. For each lens, we computed RI, CII, and NLCI using two different illuminants $SP(\lambda)$, the spectrum of the standard illuminant D65 ($\mathrm{W/m^2nm}$) defined by the International Commission on Illumination (CIE) [31], and the spectral emission of an LCD screen ($\mathrm{W/m^2nm}$), in particular, the one of an iPad. By changing the illuminant, it is possible to study the behaviour of a medium when exposed to different type of radiation. We also computed and reported τ_{UV} for each lens. The MATLAB code for the computation of the indexes is publicly available[1].

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[1] `https://github.com/reginacomparetto/retinal-and-circadian-indexes.`

Table 1. List of all the analysed lenses. When available, we also report their refractive indexes (n), whether they had a blue blocking treatment (BB), the RI and NLCI computed with the standard illuminant D65 and the spectral emission of an LCD screen, and the UV Transmission Factor τ_{UV}.

			D65 Illuminant		iPad LCD Illuminant		
Lens	n	BB	RI	NLCI	RI	NLCI	$\tau_{UV}\%$
1	1.50	y	0.77	0.79	0.78	0.62	3.1
2	1.50	y	0.86	0.90	0.92	0.89	3.3
3	–	y	0.86	0.89	0.88	0.80	1.7
4	–	y	0.90	0.91	0.90	0.83	4.9
5	–	y(a)	0.10	0.19	0.09	0.04	0.0
6	1.50	n	0.84	0.86	0.85	0.80	4.8
7	1.59	y	0.79	0.82	0.81	0.68	0.0
8	1.74	y	0.79	0.82	0.85	0.75	0.0
9	1.60	y	0.74	0.77	0.77	0.62	0.0
10	1.67	y	0.78	0.82	0.83	0.72	0.0
11	1.59	y	0.85	0.88	0.92	0.89	0.0
12	1.60	y	0.83	0.86	0.91	0.87	0.0
13	1.67	y	0.82	0.86	0.91	0.87	0.0
14	1.50	y	0.84	0.86	0.90	0.83	0.0
15	1.50	y	0.75	0.82	0.92	0.90	0.0
16	1.60	y	0.80	0.86	0.96	0.95	0.0
17	1.60	y	0.82	0.87	0.97	0.95	0.0
18	–	n	0.97	0.97	0.98	0.96	5.2
19	1.50	n	0.88	0.89	0.89	0.84	2.8
20	1.50	n	0.87	0.88	0.88	0.81	2.8
21	1.50	n	0.92	0.92	0.92	0.89	66.7(b)

(a) Lens 5 is an orange-tinted lens.

(b) Lens 21 is a non-organic glass lens without any treatment.

4 Results

The computed indexes for all the lenses and both the illuminants are reported in table 1. Lens 5 is an orange lens, not claimed as a blue blocker. Obviously, such a lens is very protective from the harmful effect of blue light on the retina, but we have to take into account that this lens can create problems on colour vision (as we show later), and its effect on the reduction of luminance could be excessive. Moreover, such a lens is handy outside, but it is not suitable for indoor use.

4.1 Indexes correlation

Figure 2 shows the scatter plot of RI and NLCI of various lenses computed using the spectral emission of an LCD screen. We can see that the Retinal Indexes of the blue-blocking lenses generally have lower values than the ones of non-treated lenses, even if this is not true in every single case. Instead, examining the values of NLCI, we notice a larger dispersion that is not reported by lens manufacturers. Lenses with a different NLCI should be used for different needs, *e.g.* lower NLCI lenses might be used with electronic devices in the evening to prevent sleep disorders, while they are not recommended in the day-light in order to preserve the natural circadian cycle. On the other hand, a lens with a lower RI is crucial during solar light exposure, because solar light has a greater damaging power on the retina with respect to an LCD screen. It is important to note that the damage is strictly related to the intensity of radiation. The parameters should be used as an instrument to compare lenses in a particular situation and not to compare different sources with the same lens. Nevertheless, lens manufactures generally advertise lenses with blue-blocking treatments as globally protective against blue light without distinguishing those aspects. Moreover, some lenses marketed as a

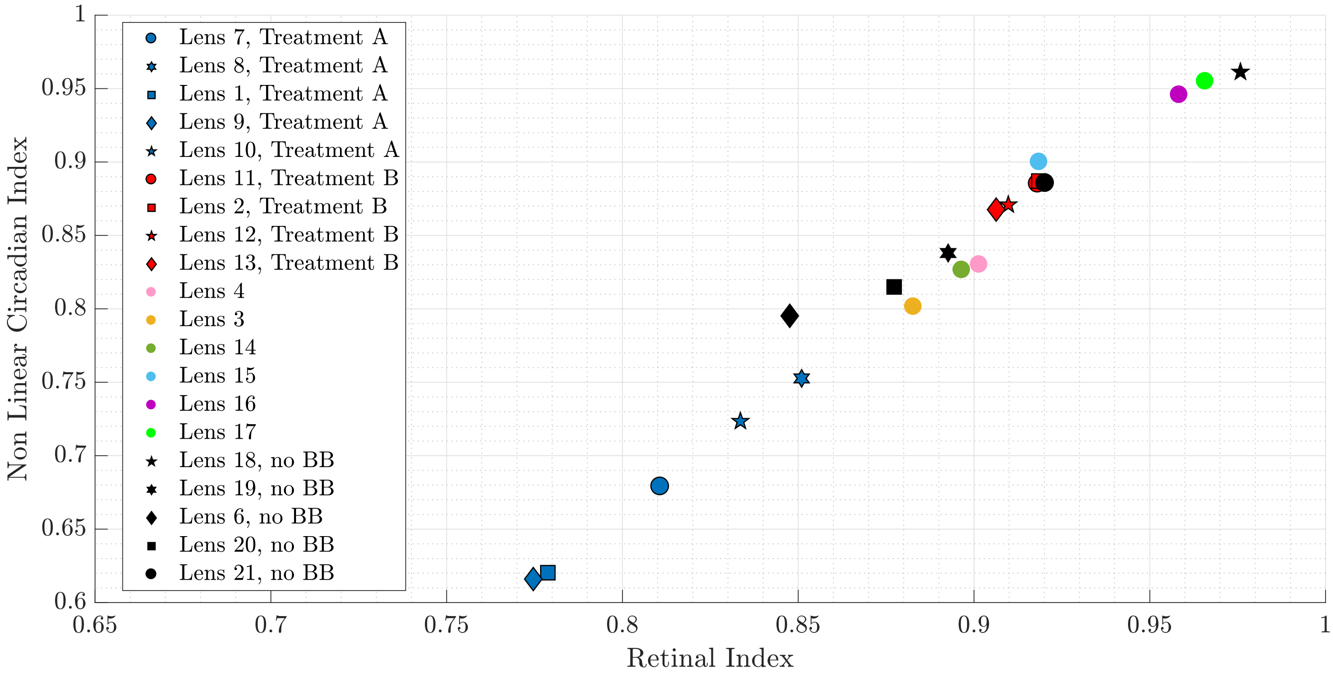

Fig. 2. Scatter plot of RI and NLCI of some of the evaluated lenses. The reported indexes are calculated using the spectral emission of an LCD screen. All the blue-blocking lenses are the coloured ones, the non–blue-blocking lenses are the black ones, the lenses with the dark blue symbols have the Treatment A, and the ones with the red markers have the Treatment B.

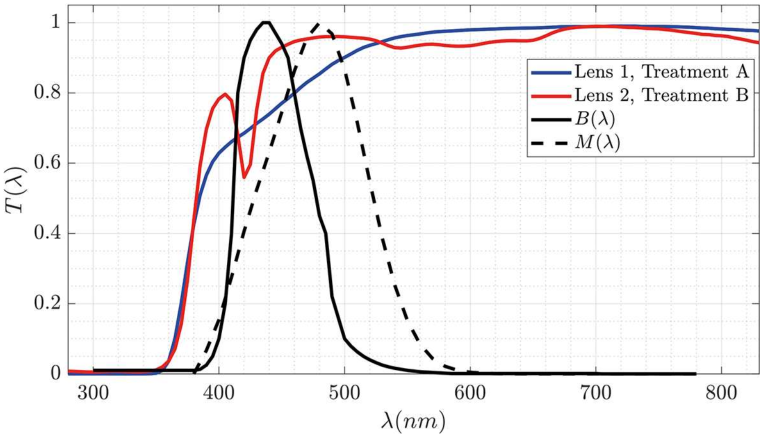

Fig. 3. Comparison between $B(\lambda)$, M_λ, and the spectral transmittance $T(\lambda)$ of two blue-blocking lenses (Lens 1 and 2) of the same material, but with two different treatments (Treatment A and Treatment B highlighted in fig. 2).

blue blocker have a behaviour comparable to a non-treated one (see Lens 3 and Lens 4 in fig. 2). We can observe that there is a positive correlation between the RI and NLCI. This is reasonable since the peak values of $B(\lambda)$ and M_λ (on which the definitions of RI and NLCI are based) are near in the spectrum, and there is a significant overlap of the areas under the two curves (see fig. 1). This means that the two aspects of the blue light, the effect on the circadian cycle and the damages of the retina, are difficult to separate.

In fig. 3, the two curves $B(\lambda)$ and M_λ are shown together with the spectral transmittance of two chosen lenses (Lens 1 and 2). These lenses are two samples of the same material and made by the same company, but with two different blue-blocking treatments, which we refer to as *Treatment A* and *Treatment B*. We can observe that the spectral transmittance of the lens with Treatment B reaches a high value near the higher point of M_λ curve ($450\,\mathrm{nm} \leq \lambda \leq 500\,\mathrm{nm}$); thus, it has a higher $NLCI_{LCD}$ than the lens with Treatment A. On the other hand, a side effect of Treatment B is that the spectral transmittance near the peak of the $B(\lambda)$ curve ($400\,\mathrm{nm} \leq \lambda \leq 450\,\mathrm{nm}$) is equally high, yielding a higher RI_{LCD} with respect to Treatment A. However, we can notice that there is a clear depression in the spectral transmittance under the $B(\lambda)$ curve right before its peak, which prevents the retinal index to increase further.

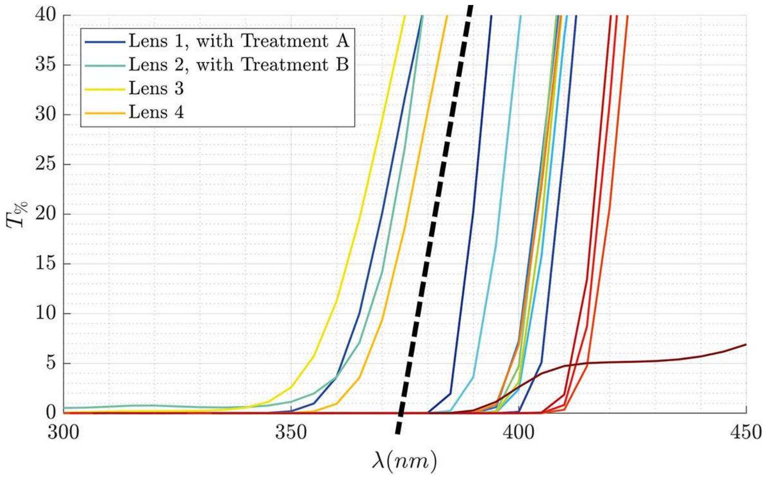

Fig. 4. The detail of the spectral transmittance of all blue-blocking lenses around the cut-off wavelength λ_{cut}.

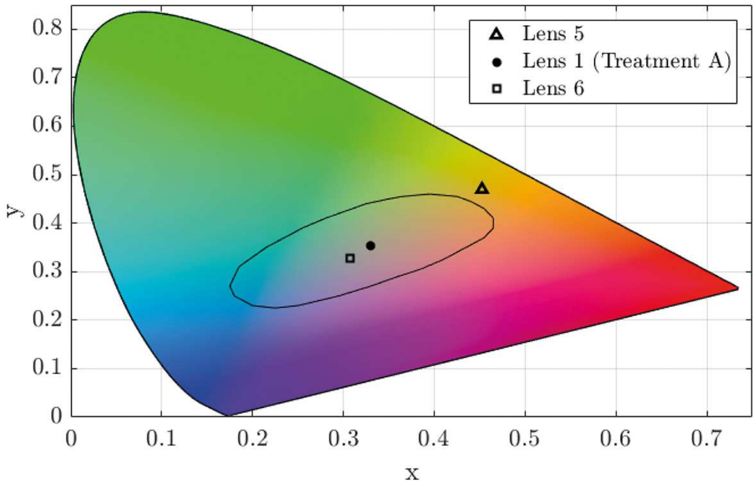

Fig. 5. The CIE colour space chromaticity diagram. The points represented three out of all the analysed lenses with and without blue-blocking treatment. The CIE spectral locus was generated using the software described in [32].

4.2 Relation to UV transmittance

In fig. 4, the spectral transmittances of all the analysed lenses with blue-blocking treatment are shown, with particular attention to the cut-off wavelength. We notice that four lenses (Lens 1 to 4) have a lower cut-off wavelength and thus present a higher UV transmission factor τ_{UV}. Despite being advertised as a protective lens with blue-blocking treatment, Lens 4 has the highest values of RI_{LCD} and τ_{UV} among all lenses with blue-blocking treatment; thus it offers minimal protection against the effects of the exposure to blue light. Lens 1, which is the one with the Treatment A, has a lower value of RI_{LCD} and $NLCI_{LCD}$, but still has a high value of τ_{UV}, which is comparable to one of lenses without blue blocking treatment. It is important to notice that the values of RI and NLCI are independent of τ_{UV}; thus the proposed indexes are not meant to describe in any way the behaviour of the sample to the ultraviolet radiation.

4.3 Chromaticity of lenses

In fig. 5, we highlight the chromatic coordinates of three lenses of interest in the CIE colour space chromaticity diagram. The curve in the centre of the diagram delimits the set of chromatic coordinates for which the colour perception is not altered [33]. We observed that lenses with blue-blocking treatments do not lead to an altered colour perception; in fact, all blue-blocking lenses fall inside the delimited area. Lens 1, treated with Treatment A, is the most yellow lens out of all the ones in the acceptance area; still, it is very near in the chromaticity space to Lens 6, a non-treated lens which is the most white of all the analysed lenses. The only lens that lies outside the acceptance area is Lens 5. Since it is an orange-tinted lens, we expected it to alter the perception of colour. This also accounts for the low values of RI_{LCD} and $NLCI_{LCD}$, since the strong orange tint blocks the majority of the blue radiation. All the other lenses had colour coordinates that lie approximately between the coordinates of Lens 1 and Lens 6.

5 Conclusions

In this work, we proposed two numerical indexes, namely the Non-Linear Circadian Index and the Retinal Index, to quantify the effects of the exposure to short-wavelength visible radiation to the human health. Given a lens, the first index summarises the impact of the transmitted light on the circadian cycle, while the second summarises the risk of retinal damage when exposed to same transmitted radiation.

Using these indexes, we performed a comparative analysis between commercially available lenses with blue-blocking treatment and non-treated lenses.

The results showed that there is a large dispersion of behaviours among different treatments. Our proposed indexes are able to capture those differences efficiently, and they could be useful as a metric to characterise blue-blocking optical media.

Differently from the already proposed index measuring global blue light transmission, we argue that having two separated metrics could help to identify the optimal lens for a particular usage easily. While it is always desirable to have a lens protecting from retinal damage, *i.e.* with a low RI, we may want to choose whether to block the effects of blue light on the circadian cycle (with a low NLCI) or not to (with a high NLCI), depending on the needs of the user. As seen in table 1, all the examined lenses presented values of RI and NLCI significantly higher than 0.5. RI and NLCI equal to 0 (the higher blocking power) is possible by completely blocking the blue light, but a lens with this kind of spectrum would not be suitable for the daily use.

Lens transmittance cannot determine the circadian impact of radiation completely, due to some factors strictly related to the person (as, *e.g.* transmittance of ocular media) and due to the same saturation effect depending on illuminance level [34,35].

Nevertheless, our indexes could be useful for evaluation of lenses present in the market. In the future it is very important to achieve, in order to obtain a validation of our results, a comparison with experimental results made on retinal cells *in vitro*. In order to encourage further research in this field, we released the data and MATLAB code to compute the proposed indexes and to replicate the experimental results.

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