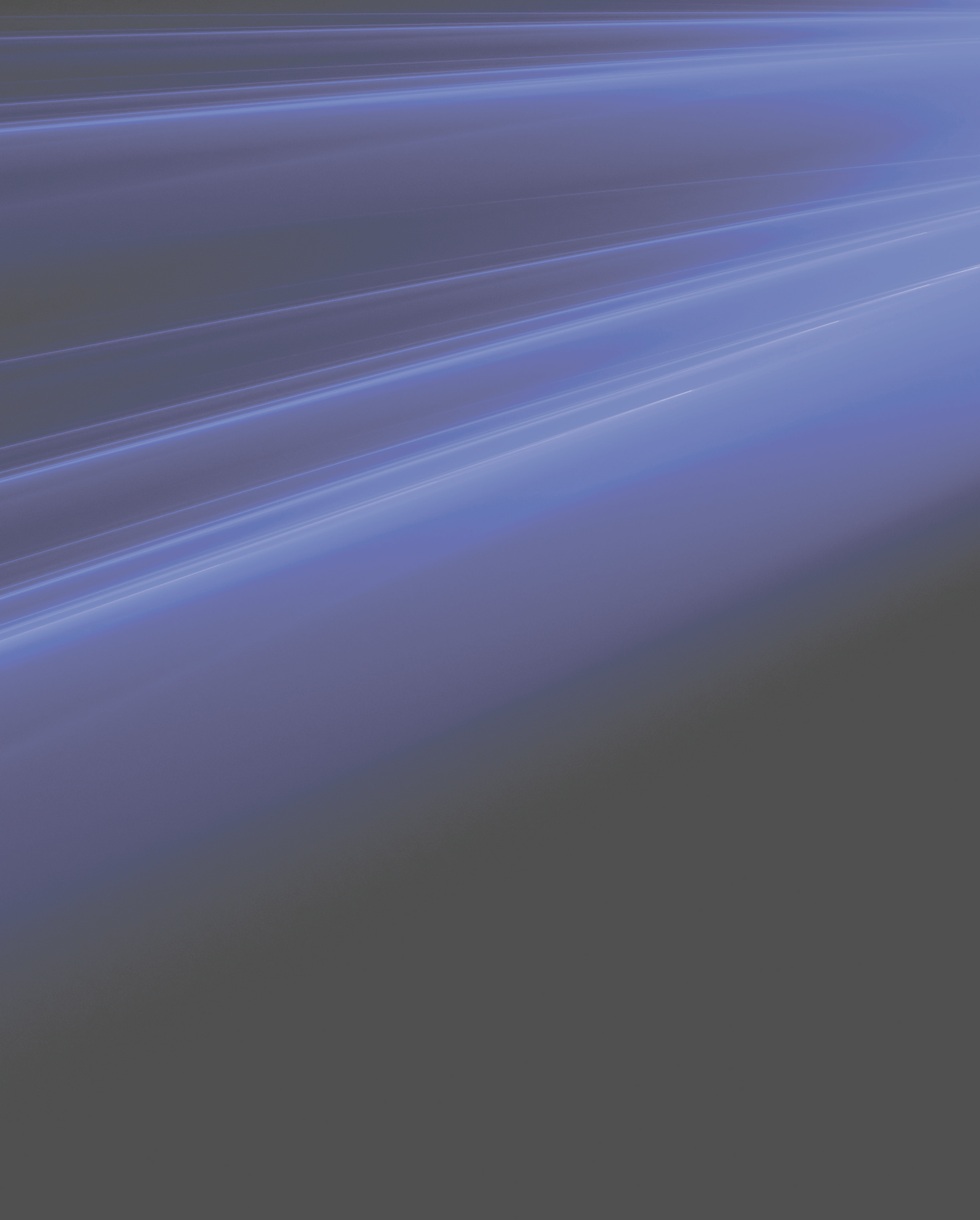


HOW TRANSITIONS® LENSES FILTER HARMFUL BLUE LIGHT

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Light-induced ocular damage has been investigated for decades in laboratory extensive work and several epidemiological studies. More recently, harmful effects of blue-violet light have been spotlighted by growing body of scientific research. Despite the eye's natural defense mechanisms, it has been evidenced that cumulative exposure to blue-violet light can contribute to long-term irreversible changes in the retina. When the most critical exposure occurs in outdoor conditions, Transitions® lenses can effectively filter harmful blue-violet light and consequently provide optimal photo-protection for the patient eyes.



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Light

The role of light in the visual experience

Light is essential to the development of visual function

Light is an element of life, a major environmental factor in human development. It plays a significant role in how we process sensory information, impacting our visual experience from the point of birth and throughout our lives.

Visual perception occurs when light strikes the retina of the eye. The pupil of the iris serves as the optical diaphragm of the eye affecting the path of light rays which are refracted by the cornea and the crystalline lens on their way to the retina. Numerous deprivation experiments have demonstrated that ocular growth and refraction development are regulated by visual information. Light is essential in providing this information on diurnal species by transmitting signals which are converted by the brain into visual perception. This acquisition of visual function is experienced as early as infancy and is essential to healthy development.

KEYWORDS

Blue Light, photochromic lenses, light filtering, sunlight, light exposure, Retina, AMD, photo protection, Transitions® Signature™, Transitions® XTRActive®

“Light plays a fundamental role in visual performance”

Light plays a fundamental role in visual performance

The iris acts as a natural optical diaphragm for expanding (dilation) or retracting (constriction) its central aperture. Depending essentially on lighting conditions and age, the diameter of the pupil ranges from 2mm to 8mm. Variations in the diameter of the pupil are caused by a movement reflex that regulates the light flux incident and, subsequently, visual performance. The visual system as a whole is sensitive over a wide range of light levels from starlight to bright sunlight but, despite the regulation of the pupil aperture, it cannot operate over the entire range simultaneously. An adaptation is required to adjust the light sensitivity of the visual system to different light levels. When the adaptation is in progress, visual performance is reduced. Once the process is complete, visual capabilities depend on the new level of light.

There are two primary lighting conditions with which the visual system has to deal: daylight (photopic) and night-time (scotopic). Between photopic and scotopic levels is a range called mesopic, which corresponds roughly to twilight. The human eye has three types of light sensitive cells (photoreceptors) in the retina – cones, rods and ganglion cells – that process sensory information (Table 1). Cones are highly concentrated in the central area of the retina (macula) and are responsible for providing daylight sharp image resolution and color detection. Rods are largely distributed in the periphery of the retina. Having

high sensitivity, they are required for scotopic vision but provide low resolution and lack of color information. The ganglion cells or ipRGCs (intrinsic photosensitive Retinal Ganglion Cells) express the melanopsin-based photopigment. These melanopsin ganglion cells are crucial for relaying light information from the retina to the brain to control circadian rhythms, pupillary light reflex, sleep and many other body functions. (Sand A. et al., 2012, Gronfier 2013).^[11, 09]

The sun is the most powerful source of light

The solar spectrum

The sun emits a tremendous amount of energy in the form of wide electromagnetic radiation. From cosmic rays to radio waves (Fig. 1), the majority of solar emissions are not visible to human photoreceptors. Only a thin portion – at wavelengths (λ) between 380nm and 780nm – provides the visible light that interacts with the eye's photoreceptors – enabling us to see the world. When visible solar radiation reaches the Earth's surface it is scattered throughout the atmosphere, especially in the blue-violet region corresponding to the shortest wavelengths (380-460nm) of visible light and subsequently to the highest energy.

OPERATING STATE	LUMINANCE RANGE	PHOTORECEPTOR	PEAK SENSITIVITY	CHARACTERISTICS
Photopic	$>3\text{cd/m}^2$	Cones	555nm	Fine resolution Good vision color
Scotopic	$<0.001\text{cd/m}^2$	Rods	507nm	No vision color Poor resolution Fovea "blind"
Mesopic	$>0.001\text{cd/m}^2 < 3\text{cd/m}^2$	Cones and Rods	Between 555nm and 507nm	Reduced color Reduced resolution

TAB.1| Summary of main lighting conditions (Boyce, 2001).^[6]

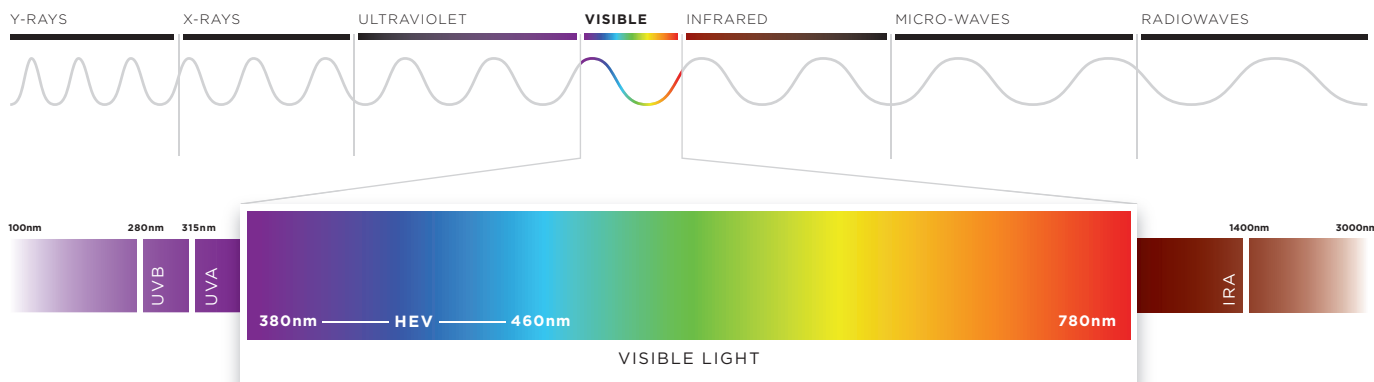


FIG.1 | Electromagnetic radiation and the visible spectrum

The risks associated to UV exposure

Beyond the visible spectrum, sunlight emits ultraviolet radiation with wavelengths shorter than 380nm – commonly referred to as UV – and infrared radiations with wavelengths greater than 780nm. Ultraviolet radiation arriving on earth surface is divided into UVB (280-315nm) and UVA (315-380nm). At sea level, about 10 percent of radiation is UV, 50 percent is visible and 40 percent is infrared.

Exposure to the sun for an extended period of time produces erythema and affects skin pigmentation, causing burning or tanning. Both UVA and UVB penetrate the atmosphere freely and play a critical role in advancing more severe health conditions like premature skin aging (ex: wrinkles) and certain skin cancers (ex: carcinoma) which can affect the eyelids and facial skin. In a healthy adult, more than 99 percent of UV radiation is absorbed by the anterior part of the eye (eyelid, ocular surface, crystalline lens). Exposure to ultraviolet radiation is well established as a major cause of eyelid malignancies, photokeratitis, climatic droplet keratopathy, pterygium and

cortical cataract (Yam 2014, Behar-Cohen et al. 2014).^[17, 3] There is insufficient evidence to support the proposal that Age-related Macular Degeneration (AMD) is related to UV exposure, and it is now suggested that AMD risk is probably more closely related to exposure to visible radiation, especially blue light (Yam 2014).^[17]

Blue light

The blue sky is evidence that blue light is present in direct sunlight. Since blue light is higher in energy than other wavelengths in the visible spectrum (Fig. 2), it scatters more throughout the atmosphere (Rayleigh scattering) and makes the sky appear blue. Blue light makes up 25-30 percent of daylight.

While blue light is emitted naturally by the sun, it can also be produced by numerous artificial light sources commonly found indoors. Light-emitting diodes (LEDs) are gaining an increased share of the domestic lighting market because of their high efficiency of luminance and low energy consumption. Widely found in digital screen technologies and displays, LEDs exhibit a high emission blue peak, centered at 430nm (Fig. 3).

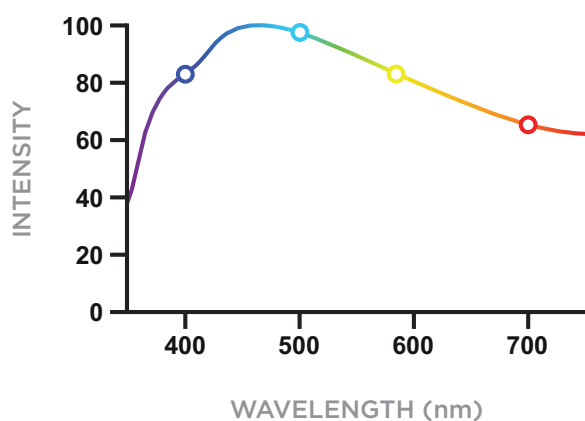


FIG.2 | Daylight source spectra

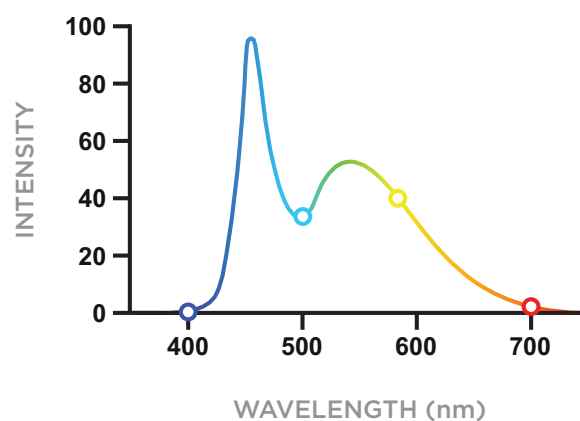


FIG.3 | Artificial cool white LED source spectrum

Harmful Blue Light

The phototoxicity of blue light

As a part of visible light, blue light passes through the eye structure, reaching the retina. Due to its higher level of energy than the other wavelengths in the visible spectrum, it is potentially harmful to the retina. Depending on exposure conditions (light intensity, duration, periodicity) it may induce different types of reactions, including photochemical lesions (Rozanowska et al., 2009)^[16]. Laboratory experiments showed that blue light is harmful (Sparrow et al., 2000)^[14] and particularly it has been demonstrated that exposure to blue violet light with a maximum peak centered on 435+/- 20 nm can induce irreversible cell death in the retinal pigment epithelium (RPE), located in the external layer of the retina (Arnault et al., 2013).^[11] These damages contribute to the aging process of the eye and may lead to the development of pathologies such as AMD, the major cause of blindness in the elderly in developed countries. In epidemiological studies addressing long term chronic exposure to blue light, the Beaver Dam Eye study demonstrated that there is a strong correlation between outdoor activities (sunlight exposure) and early incidence of AMD changes (Cruickshanks et al., 2001, Tomany et al., 2004).^[7, 15]

The different levels of blue light exposure

Amount of blue violet light is characterized by the intensity of emitted light of varied sources (Table 2). Sunlight is by far the strongest source of blue light at least 100 times greater than artificial sources (Fig. 4).

There is a significant difference in the level of blue light when facing into the sun (direct) and facing away from the sun (indirect). In actuality, no one looks directly at the sun since there is a natural aversion to sources of high glare.

Humans often make adjustments by moving their head or their eyes or by relying on automatic reflexes like blinking, squinting and pupillary constriction. The eye can be subject to more serious effects due to multiple reflections of sunlight onto white surfaces. For example, the reflection of the sun at noon on sand or snow can reach 10 times more luminance than the blue sky (Behar-Cohen et al., 2011).^[4]

The impact of blue-violet light exposure depends on the amount of total light reaching the retina: the retinal irradiance, which is characterized by the radiant flux (power) received by the retina per unit area. These values vary by the ocular media transmittance and – more importantly – by physical factors such as the eyelid position, which dictates the field of vision and the pupillary aperture, making ocular dosimetry far more complex than generally appreciated (Sliney 2001, 2005).^[12, 13] More investigations need to be done, but it seems reasonable to think that the level of retinal irradiance in the 435+/- 20 nm range is more important outdoors than indoors. Wearing appropriate glasses can be worthwhile to prevent from cumulative effects of light exposure.

Irradiance spectra of common artificial light sources (top) and direct and indirect sunlight (bottom)
Irradiance spectra of common artificial light sources (top) and direct and indirect sunlight (bottom)2

The eye’s natural protections against blue light

Physiological structures around the eye, like eyelids and eyelashes, provide some protection against intense light. The iris pupil also contributes by using constriction to decrease the amount of entering light. While UV transmittance is blocked primarily by the cornea and crystalline lens in healthy adults, blue light crosses over these struc-

SUN INDIRECT	PLASMA TV ⁽¹⁾	SMARTPHONE ⁽²⁾	LCD MONITOR ⁽³⁾	CRT MONITOR ⁽⁴⁾	FLUORESCENT LIGHT OVERHEAD ⁽⁵⁾
3.71	0.035	0.007	0.013	0.025	0.089
viewing distance: (1)=6ft (2)= 1ft (3)= 2ft (4)= 2ft (5)= 6ft facing					

TAB.2| 420-440 nm integrated Irradiance values (w/m²) of common artificial light sources against solar diffused light (Transitions Optical internal measurements)

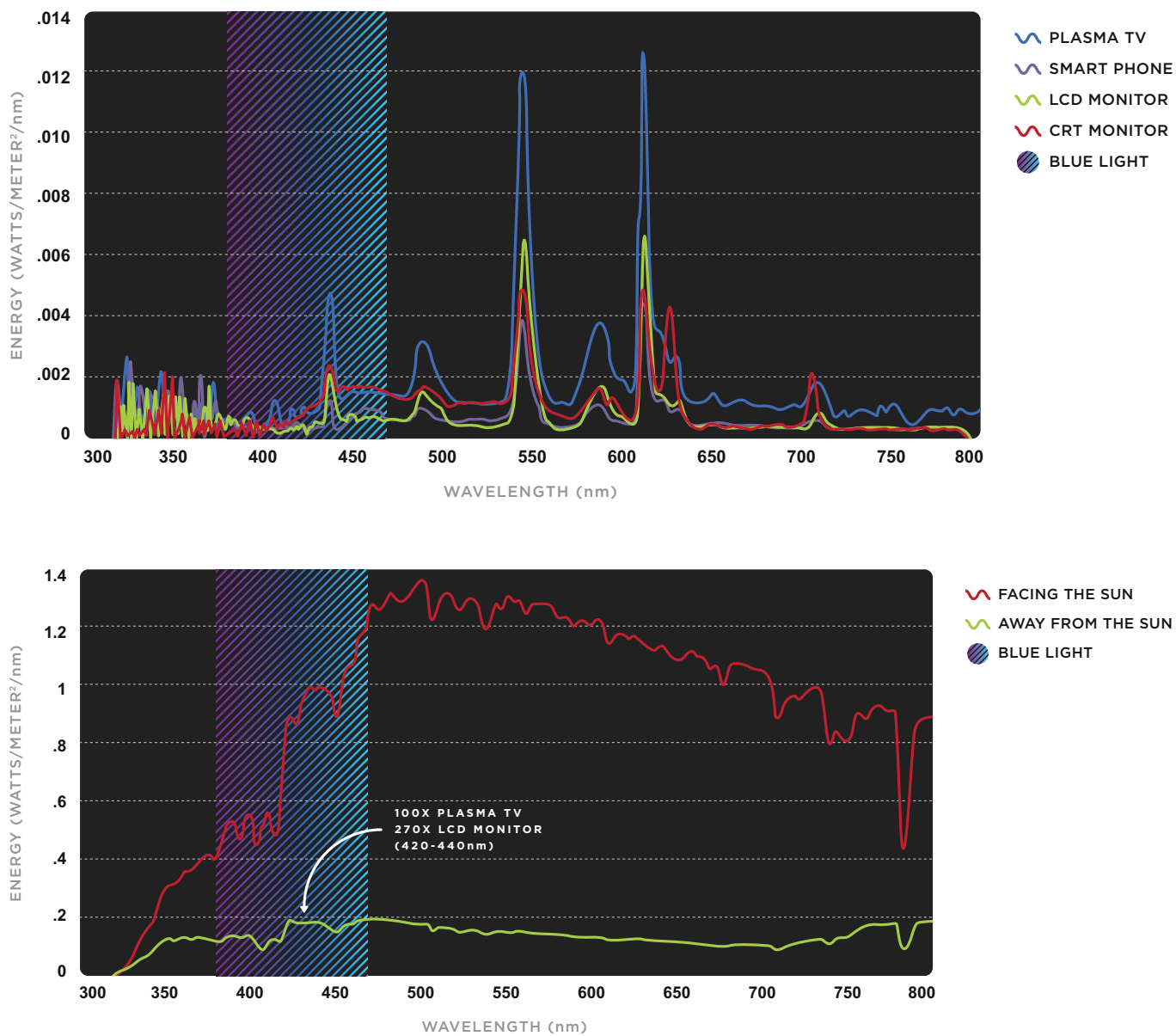


FIG.4 | Irradiance spectra of common artificial light sources (top) and direct and indirect sunlight (bottom). (Transitions Optical internal measurements)

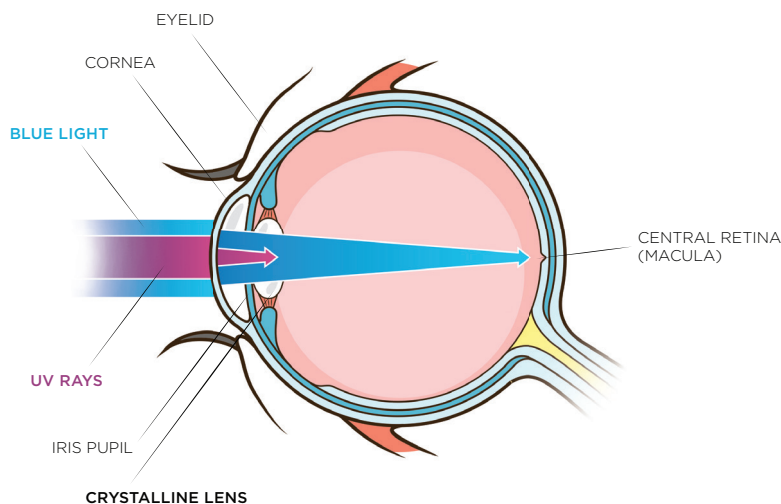


FIG.5 | UV and blue-violet light path into the human eye

tures to reach the fundus of the eye (Fig. 5). The amount of blue light reaching the retina depends on the age of the eye as, during a lifetime, there is a yellowing of the crystalline lens that would typically provide some absorption in the blue violet region. The central part of the retina is covered by yellow pigments (Macula Lutea), which serve as a filter for incoming blue light because its absorbance peak in this range (Haddad et al., 2006).^[10] Due to assorted factors, macular pigment density can be variable from one individual to another and its ability to absorb light evolves during a lifetime. The children are the most exposed to harmful blue light because they have larger pupil diameter, less concentration of macular pigment and the amount of blue light reaching the retina is 65 % while it is 40 % for adults (Behar-Cohen et al., 2015).^[5]

Technical optical solutions for Blue Light long-term prevention

With the potential risks associated with outdoor conditions described and the natural protections of the human eye discussed, we now turn our attention to the technical solutions available within the eyewear industry to prevent from the long-term effects of blue-violet light. UV protection in eyewear will not be reviewed here since most high-quality lenses today offer complete protection against UV up to 380nm.

1. Coatings

Anti-reflective interferential layers may be applied to ophthalmic lenses by evaporating transparent dielectric metal oxides to the anti-scratch coating on both the convex and concave sides of the lens. The coatings essentially involve stacks created by successive deposits. Processed under vacuum on a few hundred nanometers of low index material ($RI \sim 1.46$) and high index material ($RI \sim 2.2$) of desired thickness (Fig. 6), they provide anti-reflective properties within the visible region of the light spectrum. It is possible to design anti-reflective stacks that offer enhanced protection in the blue-violet light region by adding a specific reflection element at the wavelength to be rejected, in this case 380-460nm. The blue-filtering reflective properties can be effective up to 20 percent while keeping superior anti-reflective properties active within the entire remaining visible range. These ophthalmic lenses display high clarity indoors and outdoors, and offer reliable indoor protection against harmful blue-violet light emitted by electronic devices and artificial lighting while providing moderate outdoor protection as well.

Blue mirror effect of an anti-reflective coating (AR) reflectance spectra

2. Blue light absorption with dyes: yellow filters

Another way to prevent harmful blue-violet light from entering the eye is to reduce the unwanted wavelengths by absorbing them with yellow dye, a chemical compound

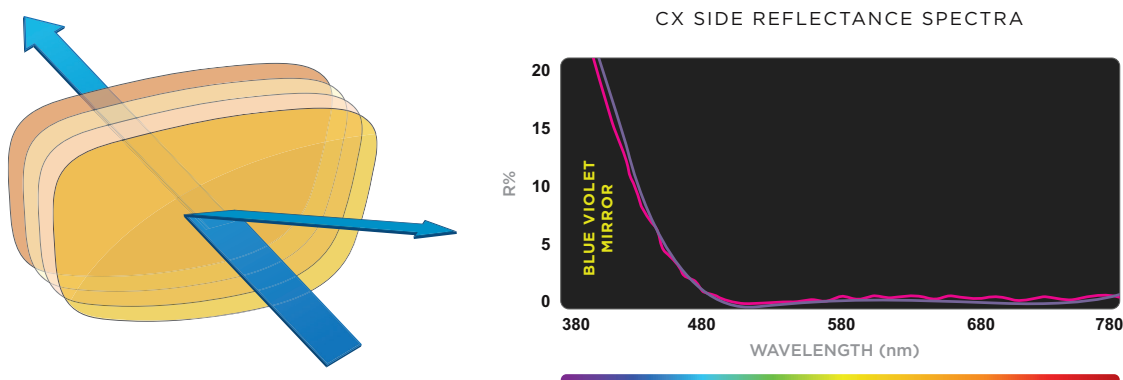


FIG. 6 | left: Blue mirror effect of an anti-reflective coating (AR) and its reflectance spectra (right)

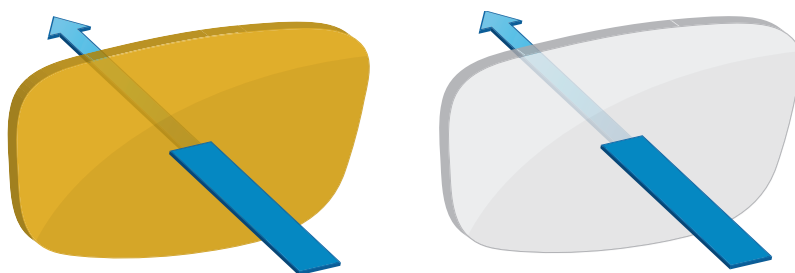


FIG. 7 | Blue light absorption with yellow dyes in substrate (left) and neutral color-balanced substrate (right)

whose structure allows absorption in the visible part of the light spectrum of its complementary color: in this case, blue. This is why most blue-absorbing lenses appear more or less yellow depending on the level of their blue-filtering properties. A highly-efficient blue-blocking lens would appear deep yellow, while a moderately efficient blue-blocking lens would appear merely yellowish.

The advantage of the yellow dye solution is that it can reduce a significant amount of blue light, but the intense yellow color is detrimental to its cosmetic appearance and detracts from human color perception. A highly intense yellow filter, for example, will induce color distortion despite the ability of the brain to adapt chromatically.

There is a way to circumvent the yellow color of an absorbing filter that involves “color balancing” the tint by adding a small proportion of another dye. The complementary dye absorbs in another region of the visible spectrum, creating a global neutral grey filter (Fig. 7). This solution is acceptable for low yellow colors – where color balancing can be efficient – but not possible for dark yellow tones. It should be noted as well that color balancing in general is detrimental to the global photopic transmission of a lens since it causes a loss of visible transmission (or clarity).

A lens can also be surface tinted by dipping an uncoated lens substrate or a tintable coated lens in a water dye solution at an elevated temperature.

Another solution is to cast lenses with monomers that already contain yellow dyes – and its color balancing agents – in the original formulation. In this case, only light tints are achievable since darker tints would lead to a non-homogeneous appearance from center to edge due to

differences in prescription lens thickness (high-minus and high-plus finished lenses).

3. Sunwear

Sunwear lenses are commonly grouped by ISO 8983-3 standards as class 3, providing 10-15% of photopic transmission (T_v), or the darker class 4 category ($T_v < 8\%$).

In the case of prescription eyewear, sun lenses are essentially made by diffusing a mixture of dyes in a polymer substrate or in a tintable coating. For the plano sunwear business, coloring is achieved by mass mixing an injection mold of polycarbonate for instance. Polarized lenses are made by using dichroic dyes in pre-formed stretched films or encapsulated wafers. The dyes are generally a mixture of primary colors in different combinations to achieve the desired hues based on the principle of subtractive color mixing (Baillet et al., 2008).^[2] The most common hues are brown and grey.

In the fashion and high-performance sunwear business, one finds mirrored lenses manufactured on the principle of interferential light rejection stacks and/or a mix of tinting by absorption and rejection mirror technologies.

By definition and usage, sun lenses are made exclusively for outdoor purposes. The dark intensity of the lenses, both plano and Rx, allows very good protection against blue light, especially by brown lenses where the yellow dye content in the mixture is in the majority (Fig. 8).

Sun lenses in brown and grey showing that, at equal photopic transmission (15% T_v), the brown lens filters more blue light than the grey lens, as it contains more yellow dyes in its formulation

**„Depending on exposure blue light
may damage the retina“**

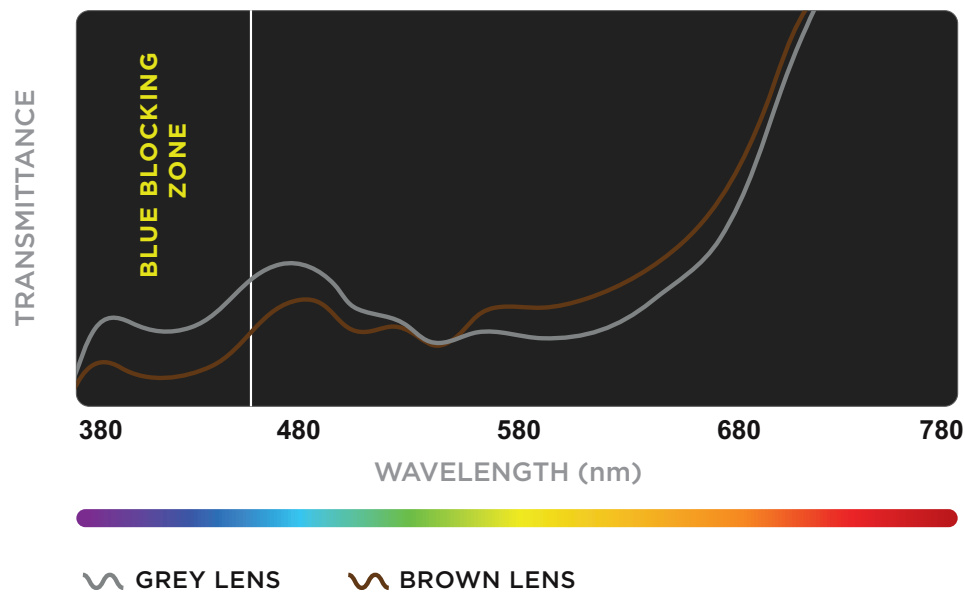


FIG. 8 | Sun lenses in brown and grey showing that, at equal photopic transmission (15% Tv), the brown lens filters more blue light than the grey lens, as it contains more yellow dyes in its formulation

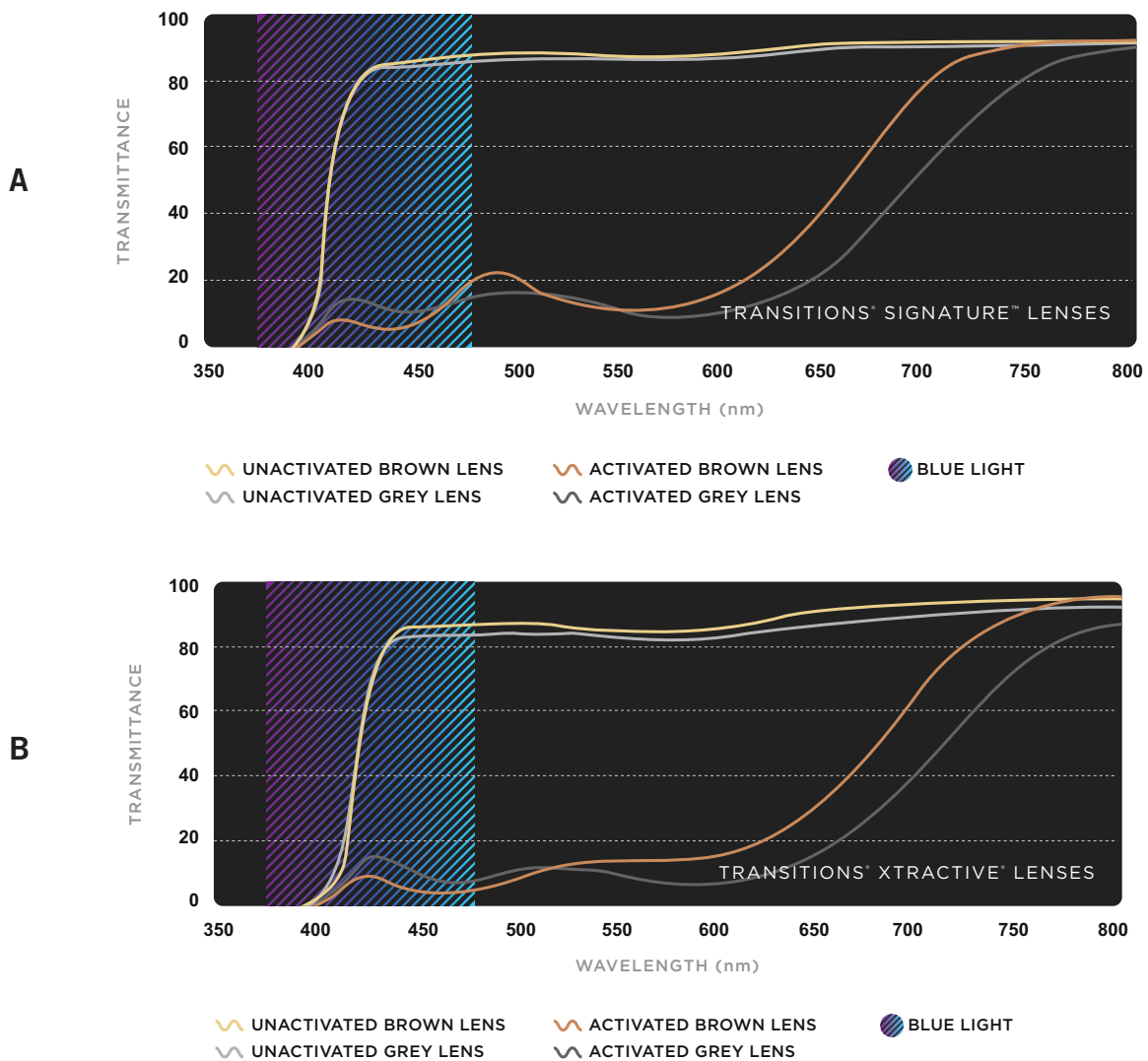


FIG. 9 | Overlay of un-activated and activated spectra of Transitions® Signature™ grey and brown lenses [A] and Transitions® XTRActive™ grey and brown lenses [B]

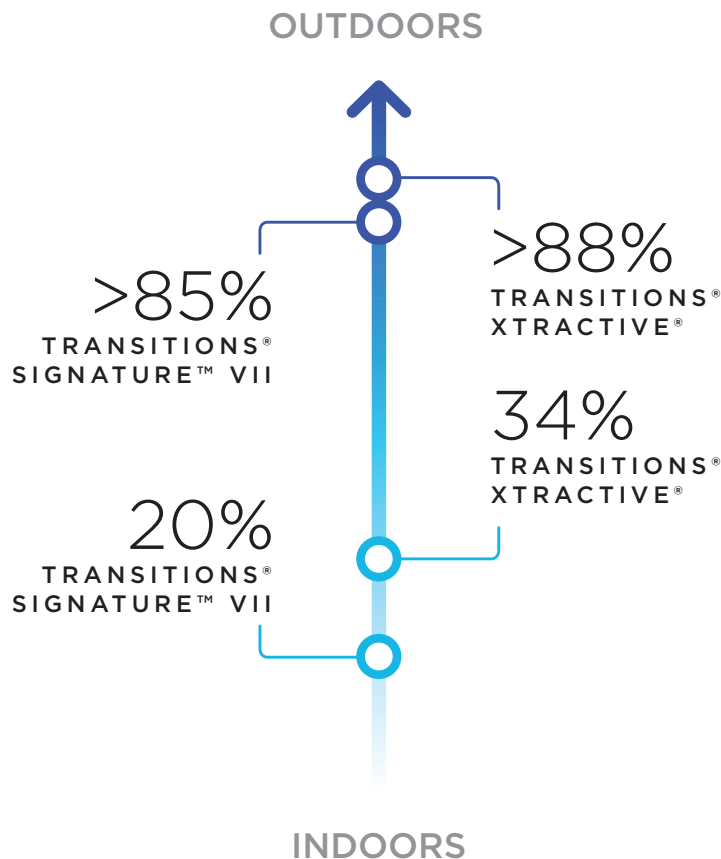


FIG. 10 | Blue filtering protection offered by Transitions® lenses at 23°C (ISO 8980-3 calculation 380nm-460 nm range)

4. Photochromic lenses

Photochromic lenses are non-permanent tinted filters containing photochromic dyes made from molecular structures that are reversible under the action of light (DÜrr et al., 1990).^[8] Their tint or color is obtained through the same principle of color-subtractive mixing as sunwear lenses.

There are, however, several notable differences in manufacturing technologies, including the cast in place (CIP) process wherein photochromic dyes are added to the monomers before polymerization, and the imbibition process, where photochromic dyes are absorbed into the surface of a lens. In these first two examples, a dedicated polymer allows the photochromic mechanism and movements to occur, and requires different polymers for each refractive index (for prescription lenses). The coating technology, meanwhile, wherein photochromic dyes are added to a coating deposited by dip – or preferentially, by spin – allows the process to be substrate independent. Photochromic lenses are highly efficient in protecting against glare, since their darkness (photopic transmission) automatically adjusts to the amount of outdoor light, whether overcast, in shadow or in bright sunlight. Because they always acclimate to various lighting levels, they help the visual system to adapt instantaneously without compromising visual performance or comfort.

The advantage of photochromic lenses like Transitions® Signature™ lenses is that they are dark outside when sunlight is bright and intense, so they offer a high level of blue light filtering much like regular sun lenses. They can be worn all the times and offer good indoor protection against artificial blue lights with no aesthetic drawbacks such as residual yellow color (Fig. 9).

As described before, color-balancing can help to limit the yellowish aspect of a given filter. For photochromic lenses, where a very low level of yellowness needs to be overcome, the smart color balancing is put to full use. Only a slight amount of dyes are used to deceive the eye (and subsequently the brain) to offset the yellowish aspect induced by chemical species providing the blue blocking properties.

A specific family of high technology products like Transitions® XTRActive® lenses, which allow activation of the photochromic molecules behind the windshield of a vehicle, present the unique advantage of having a light tint indoor and a strong tint outdoor, leading to enhanced blue light-filtering at all times (Fig. 9 and 10) thanks to specific proprietary photochromic molecules that intrinsically absorb in the blue region of the visible spectrum.

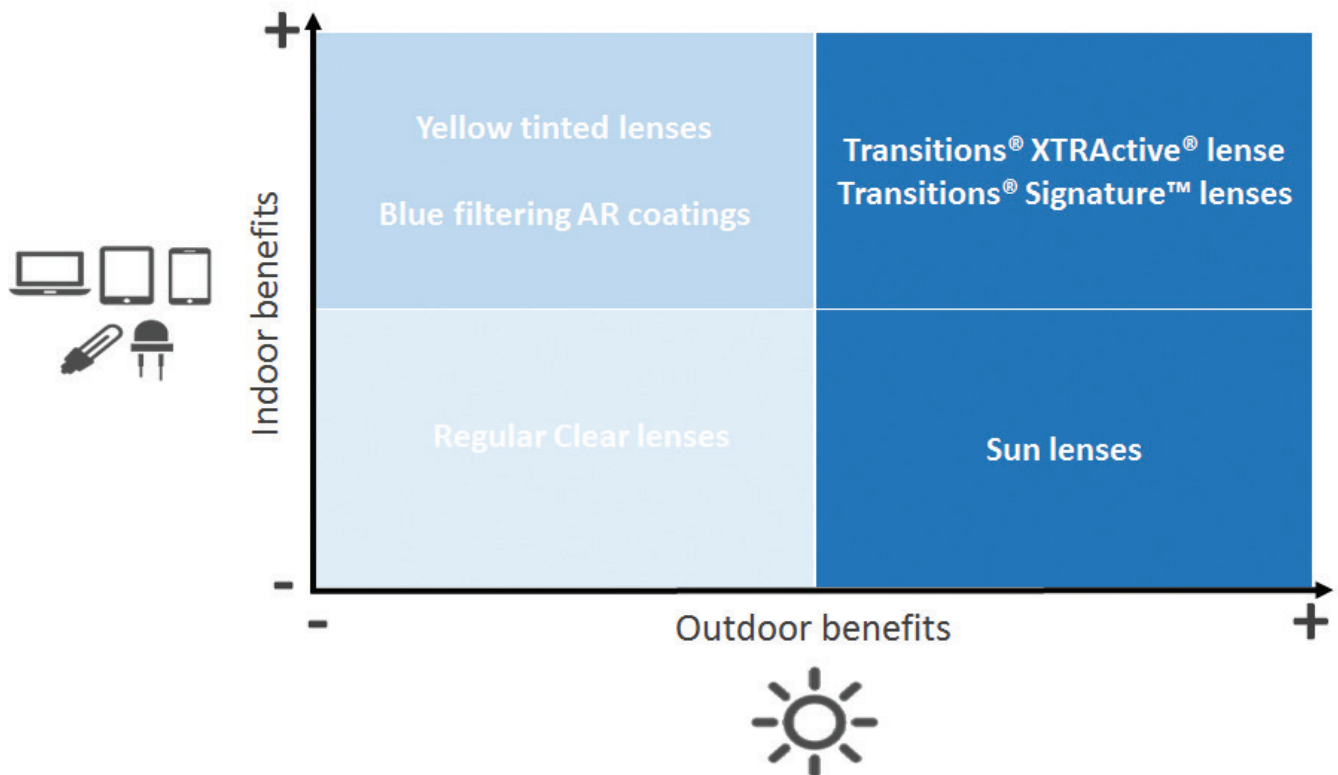


FIG. 11 | Blue light benefits delivered by different optical solutions in the eyewear industry

Conclusion

Visible light reaching the retina is essential for visual perception. Despite several self-protection mechanisms, the retina in the human eye can be exposed to light levels that exceed its natural defenses and can cause long-term irreversible damage. The lifelong buildup of light-induced phototoxicity can contribute to age-related changes and retinal cell degeneration.

Preventing excess exposure and accumulation of blue-violet light indoors – and especially outdoors – during one’s life seems like common sense.

Transitions® photochromic lenses – and, in particular, Transitions® XTRActive® lenses – offer the optimum visual experience, regardless of lighting conditions, while providing an ideal protection against blue-violet light under all circumstances (Fig. 11). •



KEY TAKEAWAYS

- Light plays essential role in the development of visual function and visual performance
- The sun is the most powerful source of light
- Blue light is higher in energy than the other wavelengths in the visible spectrum
- Depending on exposure blue light may damage the retina
- Eyewear industry provide different solutions for blue filtering such as antireflective coatings, yellow absorbing filters, sun lenses and photochromic lenses
- Transitions® photochromic lenses offer the optimal visual experience and ideal protection against harmful blue light

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