THE EVOLVING SCIENCE OF BLUE LIGHT

TECHNICAL WHITE PAPER

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VISUAL BEHAVIOR AND ENVIRONMENT, A PARADIGM SHIFT

In the last 10 years, a transformation has taken place that has changed the lives of the world's population. Precisely, two events have occurred that have altered our visual behavior and environment unlike any others in human history.

First, mobile-connected digital devices including smartphones and tablets have become the mainstay of how we receive and transmit information. In 2014, a significant milestone was reached in that the number of mobile connected devices surpassed the number of people on the planet. By 2020, it is projected that there will be 1.5 mobile-connected devices per capita, approximately 11.6 billion devices, exceeding the world's projected population of 7.8 billion.[1]

Second, by legislation, incandescent light bulbs are being replaced with more energy-efficient CFL and LED bulbs. The energy savings is substantial; LED bulbs are 90% more energy-efficient than incandescent, and last 25 times longer. And the price of LED bulbs has also gone down, by 80% in the last five years. This phase-out of incandescent bulbs was completed in the United States in 2014, and the effort is continuing globally.[2]

Having instant access to information in the palm of our hands and reducing our carbon footprint with energy-efficient lighting are certainly advances in technology made with the best intentions. However, any time advances in technology are made, there may be unintended consequences. For example, with the automobile, we have had an increase in air pollution. With mobile-connected devices and energy-efficient lighting, we have had an unprecedented increase in blue light exposure. And it is blue light exposure that is an unintended consequence of this extraordinary change in our visual behavior and environment.

2016 REPORTS CAUSE FOR CONCERN

Two reports published in 2016, by The Vision Council and by VSP® Vision Care, demonstrate the enormity of this problem. What is interesting about the timing of these reports is that scarcely five years ago, the subject of blue light exposure and its effects on the eye were fringe topics in optometric education. However within the last five years, the amount of blue light education presented for ophthalmology, optometry, and opticianry has increased significantly. And it is not just professional awareness that has increased. Mainstream media reports have increasingly discussed the dangers that blue light exposure may pose.

According to The 2016 Vision Council report, 90% of Americans use digital devices for two or more hours per day, and 60% use them for five or more hours. Their report also states that 65% of Americans experience symptoms of digital eye strain. Additionally, they also found that 77% of individuals who suffer from digital eye strain use two or more devices simultaneously, and that women are more likely than men to use multiple devices. Yet 90% of patients do not speak with their eye care provider about digital device usage, and 27% are unaware that computer eyewear can protect against digital eye strain.[3]

90% of patients do not speak with their eye care provider about digital device usage.

The VSP report states that by the time the average American child reaches age 17, their eyes will have spent the equivalent of nearly six years looking at digital devices, equating to over a third of their lives. Most parents are concerned with their children's increasing screen time, with 44% stating they feel their kids are addicted to digital devices. Yet the majority, while perhaps having a parental inkling that something is wrong, are unable to identify the problem. Of the 1,194 parents interviewed by VSP that had children under 18 years of age, 58% had little to no awareness of the high-energy blue light that is emitted from digital devices and its potential impact on vision and health. Strikingly, only 10% of these parents had taken steps to protect their families against blue light.[4]

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WHAT IS BLUE LIGHT?

As inhabitants of the earth, we are surrounded by waves, some damaging, some benign. To understand which waves may cause harm, we need to think in terms of wavelength. The key to understanding this is that shorter wavelengths have higher energy with greater potential to cause damage, while longer wavelengths are relatively harmless. All waves are part of the electromagnetic spectrum. As seen in **Figure 1**, visible light wavelengths, those that we use for human vision, make up a very small portion of the total electromagnetic spectrum. The visible light spectrum consists of wavelengths from approximately 400nm to 750nm.

To put this in perspective, consider radio waves, which are long, low energy wavelengths that we are commonly exposed to. To demonstrate their low energy, consider entering an elevator while talking on a wireless phone. As the radio waves by which wireless phones operate are relatively long and weak, they may be unable to penetrate the concrete elevator shaft, and your call may be dropped.

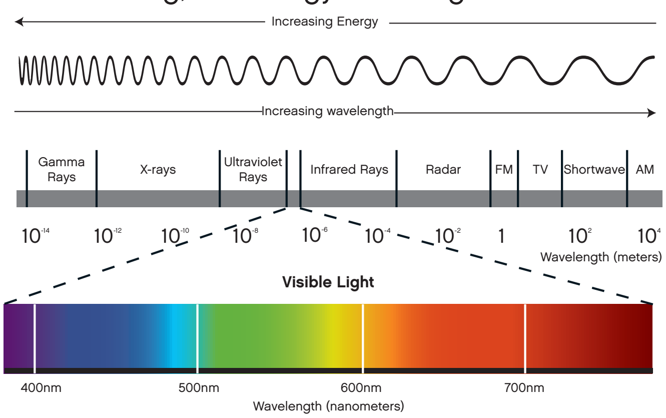


Figure 1: The electromagnetic spectrum. Note that as energy increases, the wavelengths get shorter. Blue light ranges from 400-500 nm, having the shortest wavelengths of visible light, thus having the highest energy.

Blue light is able to penetrate the cornea and lens and is incident on the retina and macula.

On the other hand, adjacent to the shortest visible light waves are ultraviolet (UV) wavelengths ranging from 100-400nm. UVB (280-315nm) and UVA (315-400nm) reach the earth by way of sunlight and are the highest energy waves that we are commonly exposed to; (UVC waves, from 100-280nm are blocked from reaching the earth by the atmosphere). It is well known that spending time unprotected in the bright sun can have a short-term result of sunburn, and a possible long-term result of skin cancer. Likewise, it has been shown that unprotected ocular exposure can lead to cancer of the eyelid, pinguecula, pterygium, and cataracts. However, the eye is relatively well-equipped to protect the most sensitive ocular tissues, the retina and macula, from UV light. The cornea and lens essentially block UV light from entering the posterior segment of the eye.

Blue light is defined as wavelengths from 400-500nm. Note that this is adjacent to UV light and has the shortest wavelength (thus the highest energy) of visible light. Blue light is able to penetrate the cornea and lens and is incident on the retina and macula.

CHANGES IN LIGHT EXPOSURE

In thinking about our sources of blue light, consider the evolution of illumination. It starts with the sun, which incidentally is still the strongest source of blue light, as seen in **Figure 2**. Early man had firelight to light the night, but firelight has a very low blue spectral emission. Man then learned how to put fire in a jar, and we had lamplight. General Electric introduced to market Thomas Edison's incandescent bulb in 1879. Fluorescent lighting was introduced in 1939. However, it has historically been used for commercial and industrial purposes, not to light our homes, thus humans have had minimal nighttime exposure.

However, with the advent of new technologies, our

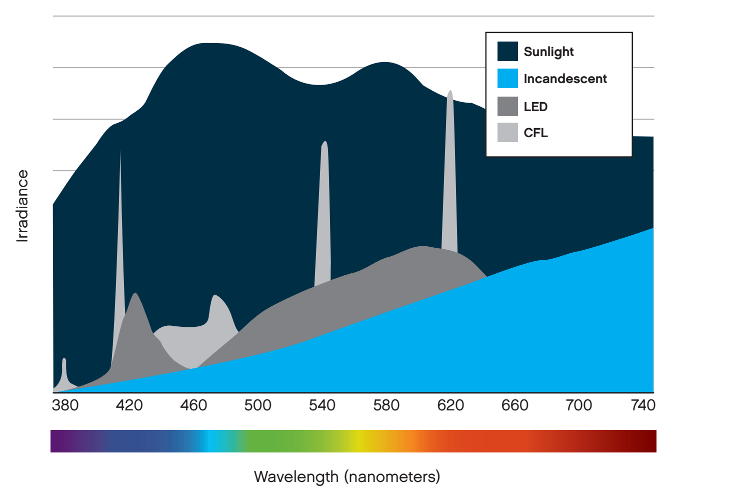


Figure 2: Visible spectra of common light sources. Note that sunlight is the strongest source of blue light we are exposed to, while incandescent light bulbs emit the least blue light of electric light sources.

exposure to blue light, especially at night, has steadily increased. The shift from incandescent to energy-efficient light bulbs has increased the amount of blue light we are exposed to in lighting our homes. Note the difference in blue light emitted from incandescent light bulbs versus energy-efficient CFL and LED light bulbs as seen in **Figure 2**. With the introduction of flat panel televisions and computer monitors in the late 1990s, the release of the iPhone® in 2007, the iPad® in 2010, and other similar handheld devices, our 24/7 blue light exposure has risen to unprecedented levels. Note the emission spectra of the previous and new generation of iPads shown in **Figure 3**.

Color Filter Spectrum: New iPad and iPad 2

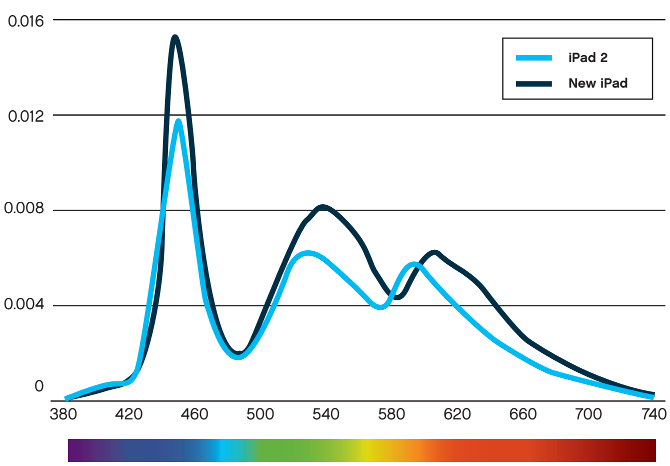


Figure 3: iPad 2 released March 2, 2011 vs. the New iPad with Retina Display released March 7, 2012. Note the increase in the spectral emission in the blue peak at 450 nm. Also note that there is almost twice as much blue light emitted as green light, and over four times as much blue light emitted as there is red light.[5]

HOW VISIBLE LIGHT BEHAVES IN THE EYE

In **Figure 4**, we can see that in the refractively corrected eye, green light (approximately 550nm) is in focus on the macula. Longer wavelength red light (670nm) is mildly hyperopically defocused, by approximately +0.50D. Shorter wavelength blue light (410nm) is significantly myopically defocused, by approximately -1.00D. This creates a violet-blue blur circle, or haze around the in-focus green component of light. This phenomenon is known as chromatic aberration and significantly affects visual quality.[6] Chromatic aberration contributes to the visual symptoms of disability glare, eye strain, and visual fatigue.

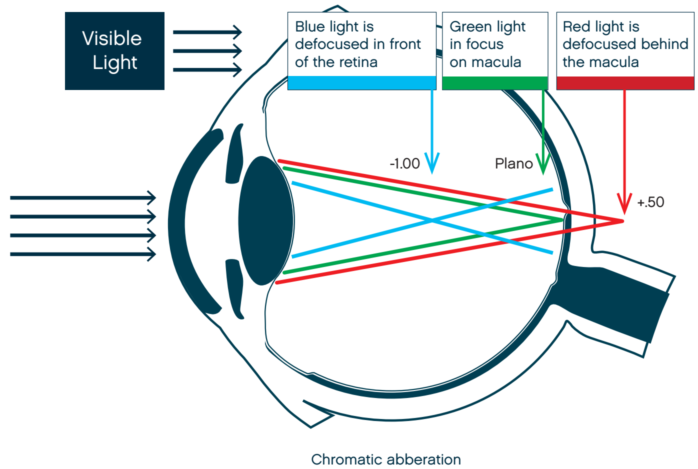


Figure 4: Blue light is myopically defocused, creating a blur circle on the retina surrounding the in-focus green component of visible light. This is known as chromatic aberration and degrades visual quality.

CAUSES OF DIGITAL EYE STRAIN

The Vision Council defines digital eye strain as "the physical eye discomfort felt by many individuals after two or more hours in front of a digital screen." In a survey conducted by VSP in 2016, 65% of eye care providers reported seeing an increase in patient complaints about eye strain, and 77% believe the symptoms are intensified by blue light exposure. Additionally, 78% report seeing an increase in effects from blue light exposure due to digital devices among their children patients.[7] Without intervention, reports containing statistics such as these will likely increase.

65% of eye care providers reported seeing an increase in patient complaints of digital eye strain.

The symptoms of digital eye strain from blue light can be broken down into three causes. In considering ways to alleviate symptoms, keeping these contributing factors in mind can guide treatment recommendations.

1. Proximity

The first of these causative factors is proximity. We tend to hold digital device screens closer to our eyes. This increases demands placed on our accommodation and vergence systems.

In a 2011 study published in Optometry and Vision Science, it was demonstrated that mean working distance is decreased when viewing digital devices. In comparison to the 16" distance that a typical adult holds hard copy text when using a smartphone, working distances decreased. Their findings showed that when viewing a text message, working distance decreased to 14.25", and when viewing websites, to 12.68". They state that these closer working distances will place increased demands on ocular accommodation and vergence, especially with extended viewing time. Consequently, symptoms of visual discomfort may be exacerbated when compared to the longer viewing distances found when reading hard copy material. They conclude that practitioners need to consider closer distances adopted while viewing material on smart phones when examining patients, and prescribe refractive corrections based on closer working distances. In other words, standard age-appropriate add powers need to be increased to adjust for closer working distances, especially when treating patients presenting with asthenopia associated with digital device usage.[8]

2. Intensity

The intensity of light from digital devices entering our eyes is dependent on the distance we are holding the device from our eyes. If you are familiar with lighting and photography, you know that the Inverse Square Law states that the intensity of a light source is equal to one over the distance squared. What this means concerning light exposure is that a child holding an iPhone or iPad at 8" is getting approximately four times the light, including blue light, as an adult holding the same device at 16". And as discussed above, adults are holding smartphones closer for viewing text messages and websites, increasing the light intensity their eyes receive. This added light intensity can affect the feeling of fatigue we experience from using digital screens.

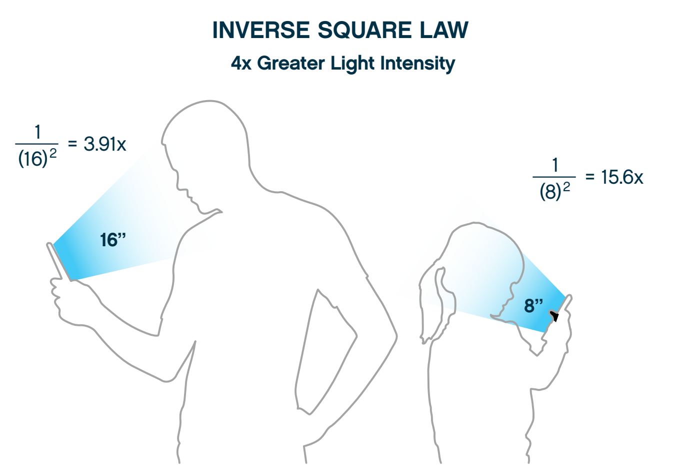


Figure 5: Inverse Square Law
Intensity = 1 / Distance^2 - A child holding a digital screen at eight inches is getting approximately four times the blue light intensity as an adult holding the same device at 16 inches.

3. Frequency and Duration of Exposure

The number of times during the day that we look at digital screens and the amount of time spent looking during each episode affect symptoms of digital eye strain. Evidence of increasing frequency and duration of exposure to handheld digital devices is all around us; just observe tables of people in restaurants all looking at their smartphones. More formally, a recent report showed that in 2014, the minutes per day spent looking at mobile digital devices surpassed the number of minutes spent looking at a TV screen.[9]

Another study compared time spent per adult in the U.S. viewing digital media by the type of device in 2008 and 2015. In 2008, the average adult spent 2.7 hours viewing digital media, 80% of which was spent on a desktop or laptop computer, 12% on a mobile device and 9% on other connected devices (such as GPS units). By 2015, the time the average adult spent viewing digital media had increased to 5.6 hours. However, the time spent viewing desktop or laptop computers had shrunk to 42% of the total, and mobile device usage had increased to 51%. Other connected devices stayed fairly stagnant at 7%.[10]

This increased frequency and duration of device exposure, coupled with closer proximity of mobile devices, is likely a contributing factor to the increase in reports of digital eye strain symptoms by patients.

SPECTACLE LENSES FOR REDUCING DIGITAL EYE STRAIN

The ophthalmic marketplace has responded admirably in an attempt to alleviate the growing problem of digital eye strain. The number of lens designs for specifically absorbing or reflecting blue light has steadily increased since 2012. However, what has not been clearly revealed by most manufacturers is how their specific lens design reduces blue light incident on the retina. Specifically, lens manufacturers have not disclosed what wavelengths are affected and to what degree. Certainly, an eye care provider would not prescribe an anti-infective or glaucoma medication without knowing its mechanism of action, its safety profile, and potential side effects. Therefore, to understand how these lenses alleviate digital eye strain, it is important for manufacturers to provide the spectral transmittance curves for their products.

UNDERSTANDING SPECTRAL TRANSMITTANCE CURVES

A spectral transmittance graph (**Figure 6**) places the percentage of light transmitted along the y-axis (vertical axis). This can also be thought of as the inverse of light attenuation; that is to say, if a lens provides 20% transmittance at a given wavelength, then that same lens is also attenuating 80% of light at that same wavelength. The x-axis (horizontal axis) of the spectral transmittance graph represents wavelength. In regards to digital eye strain, shorter wavelengths are further out of focus in front of the retina.

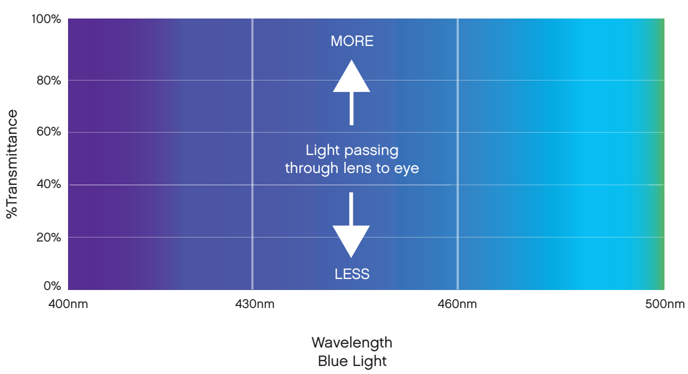


Figure 6: In defining how a spectral transmittance graph denotes the properties of a given spectacle lens, note that a higher transmittance value along the x-axis indicates more light is passing thorough the lens.

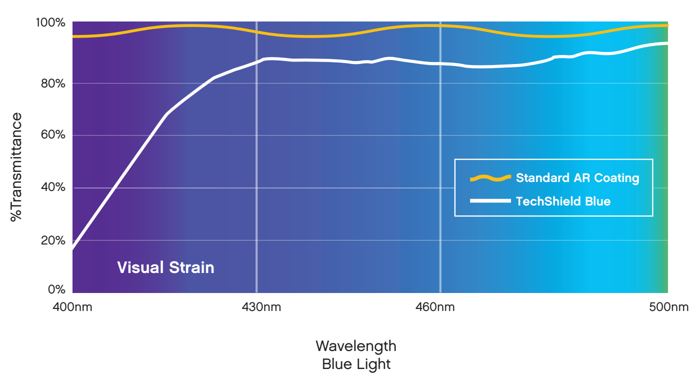


Figure 7: The yellow line represents a standard AR coating, the white line represents Tech Shield Blue.

The spectral transmittance graph in **Figure 7** shows two curves. The yellow curve is a standard AR coated lens. Note how essentially 98-99% of light at all wavelengths is transmitted through the lens. The white curve represents the multifunctional AR coating, TechShield™ Blue. Notice how the shortest, highest energy wavelengths are attenuated as transmittance is low in the 400-415nm range.

Currently available ophthalmic lenses make claims of protection, and some make claims of being optically clear. As a prescriber, it is important to understand how the various lens products prescribed actually affect blue light transmittance as well as other wavelengths.

In **Figure 8**, this particular lens seems to have fairly strong blue light attenuation through the 440nm range. Notice the dip in transmittance starting at 460nm, with the trough maximized at 510nm and extending through 600nm. Essentially this lens is blocking a key component of light for vision, green light in the 540-560nm ranges.

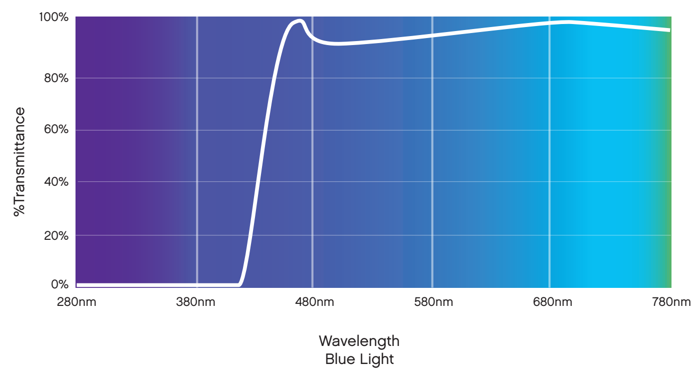


Figure 8: One manufacturer's claim of a "clear" lens, results in a dip in transmittance below 90% from 490-540 nm. Will this result in diminished visual performance?

OTHER FACTORS TO CONSIDER

When discussing blue light's effect on the eye, there are three areas of concern. Digital eye strain, the main focus of this paper, can be linked to exposure to blue light simply due to the natural physiologic properties of the inner workings of the eye. However, blue light is also now generally accepted as a causative factor for the development of age-related macular degeneration (AMD). Additionally, blue light exposure after sundown has been shown to interfere with the natural circadian rhythm or sleep-wake cycle. No discussion on the effect of blue light on the eye is complete without mentioning the latter two.

AMD: NATURAL AND ARTIFICIAL BLUE LIGHT

Human studies examining sunlight exposure and development of AMD point towards this causal relationship. A study of Chesapeake Bay watermen revealed that among those with moderate to severe AMD, a higher than normal amount of time was spent in the sun in the 20 years preceding diagnosis.[11] The Beaver Dam Eye Study found that subjects exposed to five or more hours of sunlight per day while in their teens and thirties, versus subjects exposed to two hours or less per day, on average developed AMD 10 years earlier in life.[12]

Currently, there are no FDA-cleared lens products on the market that are clinically proven to reduce the risk of developing AMD.

At present, there are no direct human studies linking blue light exposure from digital screens or energy-efficient lighting with development of AMD. However, in vitro studies using human and animal tissue, as well as in vivo studies using animal models, are showing retinal damage when exposed to artificial blue light sources. In a 2014 study, retinal injury in a rat model was assessed as caused from exposure to LED and CFL lighting at domestic levels. At nine days after exposure, functional, histological, and biochemical damage was observed.[13]

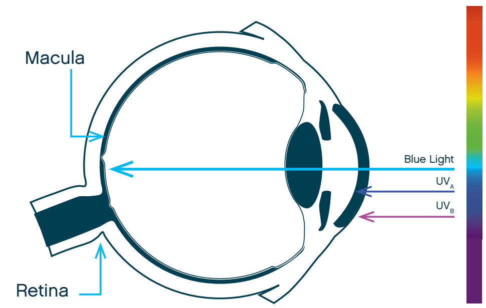
It must be taken into account that long-term data regarding human exposure to artificial blue light sources is not available. We are less than 10 years into an unprecedented shift in lighting environment and visual behavior.

The question yet to be answered in connection with exposure to artificial blue light is at what intensity, proximity, and duration of exposure might retinal damage leading to AMD occur? While the answer is currently unknown, well-designed longitudinal studies should be undertaken to provide an answer.

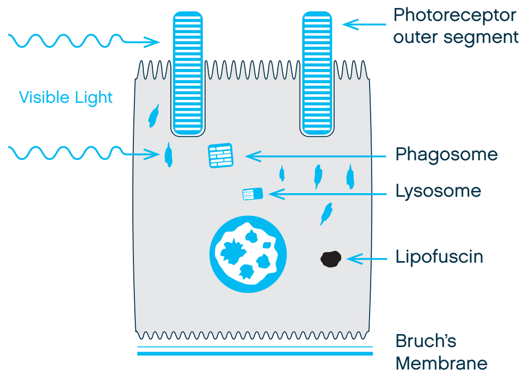
In the meantime, it must be understood that currently, there are no FDA-cleared spectacle lens products on the market that are clinically proven to reduce the

AMD AND THE BLUE LIGHT HAZARD

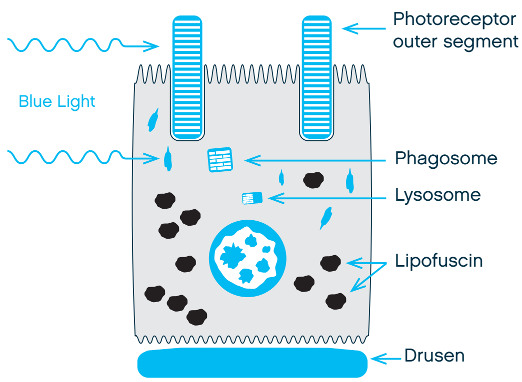
The cornea and crystalline lens provide the eye's natural protection of the retina from high-energy UV light. Unless this defense is overwhelmed, as in staring at the sun, essentially only visible light enters the eye and is incident on the retina and macula.



The diagram below represents a young retinal pigment epithelial (RPE) cell.



In response to light, photoreceptor outer segments are shed into RPE cells, phagocytized, and digested in lysosomes. Free radicals deteriorate lysosome function and become lipofuscin, containing the chromophore A2E. A2E generates free radicals in response to blue light, creating more lipofuscin.



As we age, continued blue light exposure results in accumulation of more lipofuscin, eventually resulting in RPE cell damage and malfunction, with secondary inflammation extruding the RPE cell's contents leading to the formation of drusen.

risk of developing AMD. To avoid imparting a false sense of security, clinicians should refrain discussing blue light lenses as protective against AMD.

BLUE LIGHT AT NIGHT

Since the discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs) in 2002, scientific knowledge regarding blue light at night has steadily increased. Although research on these cells and their function is still in its infancy, it is understood that ipRGCs exert some degree of control over circadian, pupillary light reflex, neuroendocrine, and neurobehavioral response. Several studies point to blue light with wavelengths between 459-484nm as having the most effect on ipRGCs in regard to regulating the sleep wake cycle.[15]

Peculiarly, and seemingly promoted by the ophthalmic industry, these upper bands of blue light wavelengths that are longer than 455nm have been described as 'good blue light.' Some ophthalmic lens manufacturers proclaim that while their lenses filter out some of the 'bad blue light' (between 400-450nm) they allow this 'good blue light' to pass through to keep the wearer alert and enhance their mood. However, and perhaps disingenuously, what they fail to mention is that unless a spectacle lens is specifically treated to reduce blue light above 455nm, all spectacle lenses allow 'good blue light' to pass through. And although in theory this is true, the question becomes at what point in the day is this 'good blue light' no longer good?

Currently, there are no FDA-cleared spectacle lens products on the market that are clinically proven to alleviate sleep deficiency.

Historically, human exposure to blue light at night was relatively low. Daytime exposure to blue light, particularly in the upper range, would trigger our internal clock to suppress melatonin secretion, keeping us alert and awake. As evening would fall, lack of blue light would allow for secretion of melatonin with subsequent onset of sleep (**Figure 9**). However with advancements in technology, our evening exposure to blue light is at levels never before experienced by mankind. Electronic screens on our smartphones, tablets, and computers, as well as LED and CFL light bulbs, all emit light in this upper blue (459-484nm) spectral range.

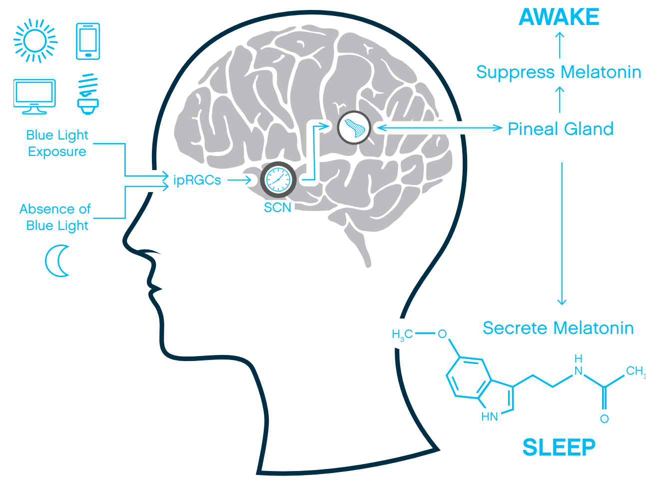


Figure 9: Blue light incident on ipRGCs, whether from natural sunlight or artificial sources, sends a signal along the retinohypothalamic tract to the suprachiasmatic nucleus, the body's internal clock. In response to this blue light stimulation, the SCN signals the pineal gland to suppress melatonin secretion, evoking wakefulness. In the absence of blue light, which has historically been in the evening, the SCN would signal the pineal gland to secrete melatonin, allowing for sleep.

Studies show we are all sleeping less than previous generations,[16] and our technology boom of the last 10 years is feeding into this. It has become routine for many to check their social media accounts or email just before bed. The Vision Council's 2016 Digital Eye Strain Report states that 83% of adults in their twenties use their smartphone as an alarm clock; in other words they are going to sleep with their phones. In fact, a 2015 study looked at the use of light-emitting eBooks before bed. Compared to those reading a paper book, the eBook group (they read from an iPad) had reduced evening sleepiness, took longer to fall asleep, had reduced melatonin secretion, had phase delay of their circadian clock, and had reduced next-morning alertness.[17]

Additionally, sleep deficiency from blue light at night has been linked with adverse health consequences, including greater risk of obesity, diabetes, heart disease, and stroke. Children that don't get enough sleep may have difficulty focusing or become hyperactive, mimicking symptoms of attention-deficit hyperactivity disorder (ADHD). And perhaps even more ominous, the World Health Organization has declared night shift work a known and probable carcinogen.[18]

Furthermore, in 2012, the American Medical

Association issued a policy statement regarding nighttime lighting as harmful to human health and may have potential carcinogenic effects.[19] An excerpt from this states: "In various laboratory models of cancer, melatonin serves as a circulating anticancer signal and suppresses tumor growth" and "epidemiological studies support the hypothesis that nighttime lighting and/or repetitive disruption of circadian rhythms increases cancer risk; most attention in this arena has been devoted to breast cancer." One such study using a rodent model demonstrated that light exposure at night reduced circulating melatonin levels, negating the effects of the anticancer drug Tamoxifen. However when these light-exposed rats were given melatonin, the effect of the Tamoxifen was restored.[20]

To reduce blue light exposure at night, particularly the longer wavelengths associated with ipRGC function and melatonin regulation, two approaches can be considered. The first would be to reduce the amount of blue light entering the eye in the evening through the use of spectacle filters. However, there are currently no FDA-cleared lens products available that are clinically proven to adequately regulate melatonin secretion to help alleviate sleep deficiency. The second would be to reduce the amount of blue light emanating from the source. Simply turning down screen brightness on one's smartphone or tablet will lower the intensity of blue light being emitted. Additionally, there are apps available such as f.lux and Apple's Night Shift that reduce the overall amount of blue light radiated from the screen. This second option is likely the best choice when providing medical advice to patients who inquire about blue light as it relates to sleep.

THE FUTURE

Gordon Moore, the co-founder of Intel®, made a prediction in 1965 that computing power would double every two years. This prediction has become known as Moore's law and has held true some 50 years later. This ongoing change in technology is the predicator of the unprecedented change in visual behavior and environment discussed at the beginning of this paper. After all, without the growth of processing that powers our electronic screens, we would not be discussing blue light. Rapid changes in technology are not likely to slow down, and with them, new challenges as to how this technology will affect eyesight and human health must be considered.

Wearable technology such as virtual reality and augmented reality that moves computer screens to within a couple inches of the eye is likely one of the next challenges we will face. As eye care providers, we may be asked to solve the functional and safety issues that will arise by moving a blue light source so close to the eye. However, as a profession, we don't want to bring about fear and create an adversarial relationship with device makers. Rather we should strive to work with the device industry, using our expertise in eye care to devise the best possible solutions for ocular comfort and protection, while imparting the best visual experience that technology will allow.

In the last five years, we have seen the advent of blue light education for providers along with the introduction of blue light lenses. It has been somewhat of a connect-the-dots period with theories put forth on whether our increased blue light exposure will lead to an increased incidence of AMD, sleep deficiency with its related health consequences, and increased digital eye strain. And while not wrong, as hypotheses are the basis of scientific discovery, the research to back up the theories is in its infancy. While inferences and perhaps claims may be made regarding spectacle lenses, screen covers, and apps protecting the eye from AMD and sleep disruption, the proverbial proof is in the pudding, and the pudding is not yet ready to serve; further research is required.

In the meantime, it is appropriate to discuss blue light lens options with patients in terms of prevention of digital eye strain. Virtually all blue light lens designs filter most strongly in the shortest part of the blue light spectral range. Based on optical principle, filtering these shortest blue light wavelengths can alleviate the visual and asthenopic symptoms associated with electronic screen usage. So the tools are available to improve the visual comfort and quality for patients viewing what has become a part of everyday life. As an eye care provider, now is the time to learn about the options available to reduce blue light. Then, based on careful consideration of product specifications and solid research, you can decide which solutions are best for your patients.

WRITTEN BY GARY MORGAN, OD

Dr. Gary Morgan has been in private practice for over 20 years in Arizona. During his career, Dr. Morgan has pioneered the use of groundbreaking ophthalmic devices, products, and techniques in a clinical setting. A lifelong advocate for innovation and education within the field of optometry, Dr. Morgan serves in a technical advisory capacity to several of the leading industry manufacturers.

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