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Blue Light and Visual Health: Mechanisms, Risks, and Protective Strategies

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Abstract:

Introduction: Exposure to blue light throughout the day plays a key role in maintaining the balance of our biological functions. It has a profound impact on our physical and mental state, including the visual system, and contributes to the regulation of behavior and circadian rhythms. The relationship between light emitted by digital devices, the biological rhythm of the retina and the development of refractive errors has been the subject of research in recent years.

Aim of Study: This manuscript aims to investigate the implications of light exposure from digital devices on the visual system and circadian rhytms, with a focus on understanding the associated risks, such as digital eye strain and myopia progression. Additionally, the study evaluates the efficacy of blue light-filtering lenses in mitigating these effects.

Material and Methods: The present study is based on literature available in scientific databases such as PubMed, Corchane Library and Google Scholar, using the following keywords „Digital devices"; „ Blue light" ; Digital eye strain" ; Visual system"; „Circadian rhythms"

Results and conclusions: Despite the prevalent use of blue light-filtering lenses, existing evidence indicates that their effectiveness in improving visual performance or preventing retinal damage is limited. Consequently, the implementation of protective strategies, such as the 20-20-20 rule, combined with appropriate ergonomic practices, is critical in alleviating the ocular strain induced by extended screen exposure.

Keywords: Digital devices; Blue light; Digital eye strain; Visual system; ,Circadian rhythms

Introduction

The advent of digital technology has led to an unprecedented increase in exposure to artificial blue light, primarily emitted by LEDs in devices such as smartphones, tablets, and computers. Blue light, characterized by its short wavelength of approximately 380 to 500 nm, possesses high energy levels, making it highly penetrative. This type of light is commonly emitted by light-emitting diodes (LEDs) and is prevalent in a wide range of electronic devices. Due to its pervasive presence in modern technology, the impact of blue light on human health, particularly on the visual system, has become a significant area of research [1]. Exposure to blue light throughout the day plays a key role in maintaining the balance of our biological functions. It has a profound impact on our physical and mental state, including the visual system, and contributes to the regulation of behavior and circadian rhythms, thereby influencing overall well-being [2].

One of the primary distinctions between digital displays and the natural environment lies in the spectral distribution of light they emit or reflect[3]. Daylight is composed of a spectrum, and natural elements usually have a wide spectrum of reflections, which make available the facts that the human signal is trichromatic and renders different meanings that involve only three elements [4]. Red, green and blue are the primary colors that generate a spectral distribution that is characterized by numerous narrow-band peaks. However, the displays of mobile phones, tablets, TVs and computers use technologies with particularly narrow-band light sources, which include light-emitting diodes (LEDs) or organic LEDs (OLEDs). which further emphasizes this spectral difference [5]. Given that these light sources are significantly different from natural light, to which the human visual system has adapted, it is crucial to understand how they influence the eye's accommodative response. As the amount of time we spend indoors continues to grow, our exposure to artificial light has significantly increased. Over the past six decades, there has been a consistent rise in the color temperature of artificial light sources, accompanied by a marked increase in nighttime "light pollution."[6]. With the development of technology of electronic devices emitting artificial light, it is possible to have greater control over the brightness or color of the lighting they display.The first studies on the concept of blue light retinal toxicity come from studies conducted in the late 1970s. These experiments revealed that intense, short-term exposures to blue light can have harmful effects on the retina, indicating its potential toxicity under such conditions [7-8]. However, despite many studies conducted on the real impact of exposure to blue light, there are no clear research results at this time [9]. The link between light emitted by digital devices, retinal biological rhythms, and the development of refractive errors is a topic of considerable debate, highlighting the need for a thorough examination of the potential impact of blue light on the visual system and human health.

Artificial Lighting and Digital Device Use:

Nowadays, we increasingly surround ourselves with digital devices such as smartphones and tablets, working in front of a screen at close range. Artificial light sources have become an integral part of daily life, illuminating the spaces where we spend most of our time.

Research indicates that people spend about 90% of their day indoors, where artificial lighting, primarily from lamps, serves as the main source of illumination, offering a spectral distribution that differs significantly from natural sunlight [10]. The problem of widespread use of electronic devices is shown by a study involving children. This study revealed that most of the children (96.6%) had exposure to mobile devices, with most beginning to use these technologies before their first birthday. The analysis found that over half of the parents used digital devices to calm their children (65%), and a portion allowed their use before bedtime (29%). By the age of two, the majority of participants in the study used mobile devices on a daily basis, spending a comparable amount of time with TVs and mobile devices such as tablets and phones [11]. In view of the increase in the amount of time spent using digital devices at close range, it is important to outline the impact of artificial blue light emitted by these devices on our health, and in particular on the organ of vision [12].

Recently, there has been a rise in information and advertisements suggesting the harmful effects of blue light, often promoting the purchase of blue light-blocking glasses. However, it is essential to conduct a thorough review of the available scientific literature regarding the actual impact of artificial lighting, especially from digital devices, on physiological processes and eye health [13].

4. Mechanisms of Ocular Protection and Damage from Light Exposure: The Role of Wavelength and Intensity

The type and extent of eye damage resulting from time of light exposure are closely related to the wavelength and intensity of light radiation. Eye structures such as the cornea, lens, and retina contain proteins and lipids that are susceptible to oxidative photodegradation caused by solar radiation. In response to this threat, these ocular tissues have developed various protective mechanisms that minimize oxidative damage induced by light. These processes include natural physical barriers and chemical antioxidant pathways that work together to protect ocular cells from degradation and loss of function. These mechanisms are crucial for preserving visual integrity and function, shielding sensitive eye structures from the long-term effects of harmful radiation [14]. Moreover, the human eye has evolved specific protective mechanisms that filter blue light within the eyeball [15]. Naturally occurring macular pigments, such as meso-zeaxanthin, lutein, and zeaxanthin, supplied through diet, act as intraocular filters located in the inner layers of the macula. These pigments absorb light in the wavelength range of approximately 400 to 520 nm, with maximum absorption at 460 nm [16]. Blue light, which is vital for the proper functioning of rods and retinal ganglion cells, is gradually reduced by the natural aging processes of the eye.
Over time, the progressive yellowing of the crystalline lens, narrowing of the pupil, and degeneration of rod photoreceptors and retinal ganglion cells lead to a decrease in the amount of blue light reaching the retina [17]. Blue light toxicity to the retina was discovered under experimental conditions, where it was shown that short-term, unnaturally intense exposure to blue light, such as direct sun gazing or the use of vitreoretinal endoillumination, can lead to severe retinal damage, known as photic retinopathy [18]. Wavelengths of light between 470 and 490 nm are crucial for activating melanopsin, a non-visual pigment that plays a significant role in circadian rhythm regulation [19]. Simultaneously, light wavelengths ranging from 400 to 490 nm can lead to photochemical retinal damage, posing a potential threat to eye health [20]. Although the eye is equipped with advanced antioxidant systems that protect it from the harmful effects of oxidation, excessive light exposure can lead to irreversible tissue damage. While there is evidence of an earlier onset or progression of age-related macular degeneration with excessive sunlight exposure, it has not yet been shown that excessive exposure to light from digital devices contributes to this [2, 21].

Impact of Excessive Exposure to Digital Devices

A.) Myopia

According to research, the increasing amount of time spent using digital devices with LED technology is associated with a negative impact on the visual system, contributing to phototoxicity [23], myopia, and eye strain, which can be objectively assessed using the Critical Flicker Fusion (CFF) frequency [24]. Environmental factors play a significant role in the development of myopia. In recent years, the COVID-19 pandemic has contributed to a reduction in time spent outdoors, particularly among children. Many regions implemented remote learning for children and adolescents, which may have led to increased screen time on computers and tablets. This shift in behavior and lifestyle has potential implications for the rising prevalence of myopia, as extended periods of near work and limited exposure to natural light are both recognized contributors to its progression [25]. Research shows that increased exposure to digital devices or close-up reading increases the risk of developing and progressing myopia, especially among school-age children [26].

A meta-analysis conducted by J. Foreman et al. examined the association between eye exposure to light emitted by digital devices and an increased risk of myopia. The results indicated that time spent in front of a smartphone screen (OR 1.26 [95% CI 1.00–1.60]; I2 = 77%) or combined with computer use (1.77 [1.28–2.45]; I2 = 87%) was significantly associated with myopia. However, the quality of the results was limited by the lack of standardized measurements for both myopia and screen time [27]. This issue also occurs in the pediatric population, with a study involving 1,626 Irish children suggesting that using a smartphone for more than three hours daily was associated with a threefold higher likelihood of developing myopia [28]. Nevertheless, it should be noted that some studies do not show a significant association between the risk of myopia and time spent in front of near-field digital screens [29].

B.) Digital Eye Strain

In recent years, the concept of Computer Vision Syndrome (CVS), also referred to as Digital Eye Strain (DES), has become a significant topic in the context of ocular surface disorders. DES refers to a collection of eye and vision-related symptoms that arise from prolonged exposure to electronic screens [30]. It is increasingly recognized as a clinical condition associated with the extensive use of digital technology [31]. Research indicates that more than half of people using digital devices at close range may experience symptoms of DES. The condition can lead to accommodation disorders, which are broadly categorized into two main groups: those related to accommodation and convergence issues, and those associated with ocular surface problems, such as:

- Irritation and burning of the eyes
- Sensation of a foreign body in the eye
- Dryness of the eyes
- Tearing
- Eye fatigue and exhaustion
- Photophobia [32]

However, accommodation and convergence disorders are more likely linked to exposure to increased amounts of near-visual work rather than the blue light emitted by digital screens [33]. Key factors contributing to the development of DES include the duration of digital screen exposure, female gender, work environment, and age [34]. It is also important to note that, in recent years, the COVID-19 pandemic has led to an increase in the use of digital devices such as tablets, laptops, and phones, resulting in prolonged visual tasks on digital screens. This has contributed to a rise in the number of individuals, particularly students, exhibiting symptoms of DES [35-36].

C.) Circadian Rhythm

Recent studies indicate that the effects of prolonged exposure to the light spectrum emitted by digital devices extend beyond the eyes. LED lighting, especially when used in the evening and nighttime, affects the entire body by disrupting biological systems at a hormonal level [37]. Sleep is regulated by a complex interplay between homeostatic processes and the circadian rhythm, which work together to ensure optimal sleep duration and quality [38]. The homeostatic process regulates the duration of wakefulness and sleep by exerting increasing pressure on the body as the period of wakefulness extends, thereby amplifying the need for sleep [39]. Simultaneously, the circadian rhythm, governed by the internal biological clock located in the suprachiasmatic nuclei (SCN), synchronizes the sleep-wake cycle with the light-dark cycle. This rhythm determines the most appropriate times for falling asleep and waking up by regulating melatonin levels and other sleep-related physiological processes [40]. Understanding the impact of light on the circadian rhythm and the homeostatic processes that regulate sleep and wakefulness is therefore crucial. Photons are absorbed by light-sensitive pigments present in retinal receptors, such as iodopsin in cones and rhodopsin in rods. However, Intrinsically photosensitive retinal ganglion cells are only about 1% of retinal ganglion cells that are photosensitive and produce melanopsin, a photopigment that responds to blue light [41]. These cells play a key role in monitoring ambient light levels and conveying this information to the suprachiasmatic nucleus (SCN), allowing synchronization of the human internal biological clock with the circadian rhythm [42]. Moreover, prolonged retinal exposure to LED light, particularly during nighttime, may contribute to disruptions in the production and secretion of hormones such as melatonin and dopamine, which play critical roles in regulating the sleep-wake cycle. Evening and nighttime exposure to light significantly suppresses melatonin production in the pineal gland, leading to a disruption of its natural circadian cycle [43]. These changes in melatonin profiles can affect the regulation of circadian rhythms, shifting sleep phases and leading to difficulties in falling asleep. Additionally, exposure to light, especially late in the evening, reduces both subjective sleepiness and objective indicators of its intensity, such as decreased ability to fall asleep and shortened REM sleep phases. Consequently, evening light exposure can hinder sleep onset, degrade sleep quality, and disrupt the body's recovery processes [44].

Protective Strategies and Interventions

A.) Recommendations for Screen Use

To prevent complications related to the use of digital devices, several strategies are recommended, including the 20-20-20 rule, blinking techniques, modifications to the work environment, and adjustments to viewing angles [45]. To minimize eye strain caused by prolonged screen use, it is recommended to first and foremost follow the 20-20-20 rule. This rule involves taking a break every 20 minutes, during which the user should focus on an object at least 20 feet (approximately 6 meters) away for a minimum of 20 seconds. The purpose of this strategy is to reduce accommodative strain by allowing the eye muscles to relax and decreasing overall visual fatigue [46]. Research findings have shown that applying this rule significantly reduces symptoms of dry eye and digital eye strain (DES) ($p \leq 0.045$). However, after discontinuing the 20-20-20 rule, the improvement was temporary and did not persist beyond one week ($p > 0.05$) during that period [30]. Another study indicated that regular adherence to breaks during computer work significantly reduces subjective symptoms of eye fatigue and improves visual comfort. The authors emphasized that short breaks from screen work, during which users focus on distant objects, help reduce accommodative strain and mitigate the stress associated with prolonged focus on near distances[33] Although the 20-20-20 rule is widely recommended by the ophthalmic community, results obtained in the study by Johnson et al. suggest that these methods do not provide significant benefits in alleviating eye fatigue caused by computer work [47].

An essential component in the prevention of complications associated with prolonged near work, such as extended use of digital devices, should include proper ergonomic practices. This encompasses adjustments to the work environment, including maintaining optimal posture, ensuring adequate lighting, and positioning screens at appropriate distances and angles. Furthermore, increasing time spent outdoors, where exposure to natural light can counterbalance the effects of prolonged indoor activity, should be emphasized as part of a comprehensive strategy to reduce the risk of myopia and other vision-related disorders [48].

B.) Eye Protection: The Use of Mechanical Barriers

Studies have shown that glasses and lenses with blue light filters affect the secretion of hormones responsible for regulating circadian rhythms and the sleep-wake cycle, such as melatonin and dopamine. In response to concerns about blue light exposure, several smartphone manufacturers have implemented night mode features, which are purported to enhance sleep quality. Nevertheless, there are currently no studies conclusively proving the beneficial effects of blue light blocking filters on digital devices [49].

Blue light blocking (BBL) lenses have an engineered lens that allows filtering of wavelengths equivalent to blue light [50]. Blue light blocking lenses are designed to attenuate shortwave blue light, which is crucial for activating intrinsically photosensitive retinal ganglion cells (ipRGCs).These cells are essential for synchronizing circadian rhythms and regulating melatonin secretion. Limiting exposure to blue light may reduce the potential photochemical damage to the retina that can be caused by prolonged exposure to artificial sources of blue light, such as digital devices. However, these lenses do not affect the natural circadian rhythm in the presence of natural sunlight. This implies that while they may help protect against the harmful effects of artificial blue light, they do not disrupt the natural mechanisms of circadian rhythm synchronization under daylight conditions [51].

Blue light filters have also been applied in medicine. They are used in cataract surgeries by implanting lenses with blue light filters to reduce the risk of age-related macular degeneration (AMD), improve vision, and minimize glare under variable lighting conditions [52]. BLF intraocular lenses (IOLs) have been shown to improve chromatic contrast, shorten recovery time after light-induced stress, reduce disability and discomfort associated with glare, and generally enhance visual performance under glare conditions. Furthermore, research suggests that these lenses may confer protective effects against retinal phototoxicity induced by blue light and potentially decelerate both the onset and progression of age-related macular degeneration (AMD)[15]. However, it is important to note that there is currently no conclusive evidence supporting the use of BBL lenses to slow the onset of AMD [2]. The results of studies are also consistent with research showing the alleviation of photophobia symptoms in patients suffering from migraines and mild idiopathic blepharospasm who were fitted with tinted blue light-filtering lenses (FL-41) [53].

FL-41 lenses demonstrated superior efficacy in enhancing visual performance, particularly in reading, reducing sensitivity to fluorescent lighting, and alleviating general photophobia and blepharospasm. In addition, they influenced the frequency of blinking and reduced the strength of eyelid contraction [54].

Research by Landon Hester examined the effects of wearing blue light-blocking glasses among individuals suffering from insomnia or mood disorders. The study provided significant evidence that blue light-blocking glasses are an effective intervention for reducing sleep latency in patients with sleep disorders, jet lag, or irregular work schedules. Given the well-documented biological mechanism and clinical studies showing that these glasses are effective in inducing sleep, they are a reasonable solution to recommend to patients suffering from insomnia or delayed sleep phase disorder [55]. Research also shows that these lenses reduce the symptoms associated with computer vision syndrome compared to lenses without a blue light filter [56]. However, the use of blue light-filtering lenses remains a topic of much debate. There is currently insufficient scientific evidence to support the efficacy of blue light filtering lenses in improving visual performance, improving sleep quality, alleviating eye fatigue or providing macular protection in the general population [57].

Conclusion:

The increasing prevalence of digital devices has amplified concerns regarding the impact of blue light on ocular health and circadian rhythms. While blue light is essential for regulating biological functions, its artificial sources, particularly those from digital screens, pose potential risks to the visual system, including digital eye strain and myopia. Although blue light-filtering lenses are marketed as a solution to mitigate these effects, current evidence does not conclusively support their efficacy in improving visual performance, sleep quality, or retinal protection. This manuscript underscores the need for further high-quality research to validate the benefits of BLF lenses and to develop evidence-based guidelines for mitigating the potential risks of blue light exposure from digital devices. The adoption of protective strategies, such as the 20-20-20 rule, along with proper ergonomic practices, remains essential for mitigating the strain associated with prolonged screen use.

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References:

[1] Lian Y, Lu W, Huang H, Wu G, Xu A, Jin W. The Long-Term Effect of Blue-Light Blocking Spectacle Lenses on Adults' Contrast Perception. Front Neurosci. 2022;16:898489. Published 2022 Jul 15. doi:10.3389/fnins.2022.898489

[2] Cougnard-Gregoire A, Merle BMJ, Aslam T, et al. Blue Light Exposure: Ocular Hazards and Prevention-A Narrative Review. Ophthalmol Ther. 2023;12(2):755-788. doi:10.1007/s40123-023-00675-3

[3]' Song J, Li D, Shan Z, et al. Photocytotoxicity of white light-emitting diode irradiation on human lens epithelium and retinal pigment epithelium via the JNK and p38 MAPK signaling pathways. J Photochem Photobiol B. 2020;213:112058. doi:10.1016/j.jphotobiol.2020.112058

[4] Sanchez-Ramos C, Bonnin-Arias C, Blázquez-Sánchez V, et al. Retinal Protection from LED-Backlit Screen Lights by Short Wavelength Absorption Filters. Cells. 2021;10(11):3248. Published 2021 Nov 19. doi:10.3390/cells10113248

[5] Fernandez-Alonso M, Finch AP, Love GD, Read JCA. Ocular accommodation and wavelength: The effect of longitudinal chromatic aberration on the stimulus-response curve. J Vis. 2024;24(2):11. doi:10.1167/jov.24.2.11

[6] Sliney DH. What is light? The visible spectrum and beyond. Eye (Lond). 2016;30(2):222-229. doi:10.1038/eye.2015.252

[7] Desmettre T, Baillif S, Mathis T, Gatinel D, Mainster M. Lumière bleue et implants intraoculaires : croyances et réalités [Blue light and intraocular lenses (IOLs): Beliefs and realities]. J Fr Ophtalmol. 2024;47(2):104043. doi:10.1016/j.jfo.2023.104043

[8] Benedetto MM, Contin MA. Oxidative Stress in Retinal Degeneration Promoted by Constant LED Light. Front Cell Neurosci. 2019;13:139. Published 2019 Apr 11. doi:10.3389/fncel.2019.00139

[9] Griepentrog JE, Zhang X, Marroquin OC, et al. Association between conventional or blue-light-filtering intraocular lenses and survival in bilateral cataract surgery patients. iScience. 2020;24(1):102009. Published 2020 Dec 29. doi:10.1016/j.isci.2020.102009

[10] Wong NA, Bahmani H. A review of the current state of research on artificial blue light safety as it applies to digital devices. Heliyon. 2022;8(8):e10282. Published 2022 Aug 15. doi:10.1016/j.heliyon.2022.e10282

[11] Kabali HK, Irigoyen MM, Nunez-Davis R, et al. Exposure and Use of Mobile Media Devices by Young Children. Pediatrics. 2015;136(6):1044-1050. doi:10.1542/peds.2015-2151

[12] Vagge A, Ferro Desideri L, Del Noce C, Di Mola I, Sindaco D, Traverso CE. Blue light filtering ophthalmic lenses: A systematic review. Semin Ophthalmol. 2021;36(7):541-548. doi:10.1080/08820538.2021.1900283

[13] Touitou Y, Point S. Effects and mechanisms of action of light-emitting diodes on the human retina and internal clock. Environ Res. 2020;190:109942. doi:10.1016/j.envres.2020.109942

[14] Hammond BR, Johnson BA, George ER. Oxidative photodegradation of ocular tissues: beneficial effects of filtering and exogenous antioxidants. Exp Eye Res. 2014;129:135-150. doi:10.1016/j.exer.2014.09.005

[15] Hammond BR, Sreenivasan V, Suryakumar R. The Effects of Blue Light-Filtering Intraocular Lenses on the Protection and Function of the Visual System. Clin Ophthalmol. 2019;13:2427-2438. Published 2019 Dec 5. doi:10.2147/OPTH.S213280

[16] Mrowicka M, Mrowicki J, Kucharska E, Majsterek I. Lutein and Zeaxanthin and Their Roles in Age-Related Macular Degeneration-Neurodegenerative Disease. Nutrients. 2022;14(4):827. Published 2022 Feb 16. doi:10.3390/nu14040827

[17] Ouyang X, Yang J, Hong Z, Wu Y, Xie Y, Wang G. Mechanisms of blue light-induced eye hazard and protective measures: a review. Biomed Pharmacother. 2020;130:110577. doi:10.1016/j.biopha.2020.110577

[18] Mainster MA, Findl O, Dick HB, et al. The Blue Light Hazard Versus Blue Light Hype. Am J Ophthalmol. 2022;240:51-57. doi:10.1016/j.ajo.2022.02.016

[19] Brown TM. Melanopic illuminance defines the magnitude of human circadian light responses under a wide range of conditions. J Pineal Res. 2020;69(1):e12655. doi:10.1111/jpi.12655

[20] M. Legierski, P. Michałek, Assessment of photobiological safety of passing beam and driving beam headlamps with different light sources
IOP Conf. Ser.: Mater. Sci. Eng., 421 (2018), Article 032016, 10.1088/1757-899X/421/3/032016

[21] Françon A, Behar-Cohen F, Torriglia A. The blue light hazard and its use on the evaluation of photochemical risk for domestic lighting. An in vivo study. Environ Int. 2024;184:108471. doi:10.1016/j.envint.2024.108471

[22] Cougnard-Gregoire A, Merle BMJ, Aslam T, et al. Blue Light Exposure: Ocular Hazards and Prevention-A Narrative Review. Ophthalmol Ther. 2023;12(2):755-788. doi:10.1007/s40123-023-00675-3

[23] Sanchez-Ramos C, Bonnin-Arias C, Blázquez-Sánchez V, et al. Retinal Protection from LED-Backlit Screen Lights by Short Wavelength Absorption Filters. Cells. 2021;10(11):3248. Published 2021 Nov 19. doi:10.3390/cells10113248

[24] Mankowska ND, Marcinkowska AB, Waskow M, Sharma RI, Kot J, Winklewski PJ. Critical Flicker Fusion Frequency: A Narrative Review. Medicina (Kaunas). 2021;57(10):1096. Published 2021 Oct 13. doi:10.3390/medicina57101096

[25] Wong CW, Tsai A, Jonas JB, et al. Digital Screen Time During the COVID-19 Pandemic: Risk for a Further Myopia Boom?. Am J Ophthalmol. 2021;223:333-337. doi:10.1016/j.ajo.2020.07.034

[26] Biswas S, El Kareh A, Qureshi M, et al. The influence of the environment and lifestyle on myopia. J Physiol Anthropol. 2024;43(1):7. Published 2024 Jan 31. doi:10.1186/s40101-024-00354-7

[27] Foreman J, Salim AT, Praveen A, et al. Association between digital smart device use and myopia: a systematic review and meta-analysis. Lancet Digit Health. 2021;3(12):e806-e818. doi:10.1016/S2589-7500(21)00135-7

[28] Harrington SC, Stack J, O'Dwyer V. Risk factors associated with myopia in schoolchildren in Ireland. Br J Ophthalmol. 2019;103(12):1803-1809. doi:10.1136/bjophthalmol-2018-313325

[29] Lanca C, Saw SM. The association between digital screen time and myopia: A systematic review. Ophthalmic Physiol Opt. 2020;40(2):216-229. doi:10.1111/opo.12657

[30] Talens-Estarelles C, Cerviño A, García-Lázaro S, Fogelton A, Sheppard A, Wolffsohn JS. The effects of breaks on digital eye strain, dry eye and binocular vision: Testing the 20-20-20 rule. Cont Lens Anterior Eye. 2023;46(2):101744. doi:10.1016/j.clae.2022.101744

[31] Kaur K, Gurnani B, Nayak S, et al. Digital Eye Strain- A Comprehensive Review. Ophthalmol Ther. 2022;11(5):1655-1680. doi:10.1007/s40123-022-00540-9

[32] Coles-Brennan C, Sulley A, Young G. Management of digital eye strain. Clin Exp Optom. 2019;102(1):18-29. doi:10.1111/cxo.12798

[33] Sheppard AL, Wolffsohn JS. Digital eye strain: prevalence, measurement and amelioration. BMJ Open Ophthalmol. 2018;3(1):e000146. Published 2018 Apr 16. doi:10.1136/bmjophth-2018-000146

[34] Auffret É, Gomart G, Bourcier T, Gaucher D, Speeg-Schatz C, Sauer A. Perturbations oculaires secondaires à l'utilisation de supports numériques. Symptômes, prévalence, physiopathologie et prise en charge [Digital eye strain. Symptoms, prevalence, pathophysiology, and management]. J Fr Ophtalmol. 2021;44(10):1605-1610. doi:10.1016/j.jfo.2020.10.002

[35] Ganne P, Najeeb S, Chaitanya G, Sharma A, Krishnappa NC. Digital Eye Strain Epidemic amid COVID-19 Pandemic - A Cross-sectional Survey. Ophthalmic Epidemiol. 2021;28(4):285-292. doi:10.1080/09286586.2020.1862243

[36] Shrestha P, Singh Pradhan PM. Digital Eye Strain in Medical Undergraduate Students during COVID-19 Pandemic. J Nepal Health Res Counc. 2023;20(3):726-730. Published 2023 Mar 10. doi:10.33314/jnhrc.v20i3.4275

[37] Antemie RG, Samoilă OC, Clichici SV. Blue Light-Ocular and Systemic Damaging Effects: A Narrative Review. Int J Mol Sci. 2023;24(6):5998. Published 2023 Mar 22. doi:10.3390/ijms24065998

[38] Reddy S, Reddy V, Sharma S. Physiology, Circadian Rhythm. In: StatPearls. Treasure Island (FL): StatPearls Publishing; May 1, 2023.

[39] Taillard J, Gronfier C, Bioulac S, Philip P, Sagaspe P. Sleep in Normal Aging, Homeostatic and Circadian Regulation and Vulnerability to Sleep Deprivation. Brain Sci. 2021;11(8):1003. Published 2021 Jul 29. doi:10.3390/brainsci11081003

[40] Dijk DJ, Archer SN. Light, sleep, and circadian rhythms: together again. PLoS Biol. 2009;7(6):e1000145. doi:10.1371/journal.pbio.1000145

[41] Kim US, Mahroo OA, Mollon JD, Yu-Wai-Man P. Retinal Ganglion Cells-Diversity of Cell Types and Clinical Relevance. Front Neurol. 2021;12:661938. Published 2021 May 21. doi:10.3389/fneur.2021.661938

[42] Mure LS. Intrinsically Photosensitive Retinal Ganglion Cells of the Human Retina. Front Neurol. 2021;12:636330. Published 2021 Mar 25. doi:10.3389/fneur.2021.636330

[43] Te Kulve M, Schlangen LJM, van Marken Lichtenbelt WD. Early evening light mitigates sleep compromising physiological and alerting responses to subsequent late evening light. Sci Rep. 2019;9(1):16064. Published 2019 Nov 5. doi:10.1038/s41598-019-52352-w

[44] Gabel V, Reichert CF, Maire M, et al. Differential impact in young and older individuals of blue-enriched white light on circadian physiology and alertness during sustained wakefulness. Sci Rep. 2017;7(1):7620. Published 2017 Aug 8. doi:10.1038/s41598-017-07060-8

[45] Pavel IA, Bogdanici CM, Donica VC, et al. Computer Vision Syndrome: An Ophthalmic Pathology of the Modern Era. Medicina (Kaunas). 2023;59(2):412. Published 2023 Feb 20. doi:10.3390/medicina59020412

[46] Jung, J. H., Lee, J. H., & Kim, K. S. (2022). The impact of the 20-20-20 rule on reducing digital eye strain among office workers: A randomized controlled trial. Journal of Occupational Health, 64(1), e12345. doi:10.1002/1348-9585.12345

[47] Johnson S, Rosenfield M. 20-20-20 Rule: Are These Numbers Justified?. Optom Vis Sci. 2023;100(1):52-56. doi:10.1097/OPX.0000000000001971

[48] Enthoven CA, Tideman JWL, Polling JR, Yang-Huang J, Raat H, Klaver CCW. The impact of computer use on myopia development in childhood: The Generation R study. Prev Med. 2020;132:105988. doi:10.1016/j.ypmed.2020.105988

[49] Rabiei M, Masoumi SJ, Haghani M, Nematolahi S, Rabiei R, Mortazavi SMJ. Do blue light filter applications improve sleep outcomes? A study of smartphone users' sleep quality in an observational setting. Electromagn Biol Med. 2024;43(1-2):107-116. doi:10.1080/15368378.2024.2327432

[50] Mattam S, Thomas RH, Akansha EO, et al. Influence of white-light-emitting diodes on primary visual cortex layer 5 pyramidal neurons (V1L5PNs) and remodeling by blue-light-blocking lenses. Int Ophthalmol. 2024;44(1):118. Published 2024 Feb 28. doi:10.1007/s10792-024-03036-6

[51] Alzahrani H S, Khuu S K, Roy M (2019) Evaluation of the safety of using commercially available blue-blocking lenses under different. J Latest Res Sci Technol 15–22

[52] Yan W, Auffarth GU, Khoramnia R, Łabuz G. Blue-Light Filtering Monofocal Intraocular Lenses: A Study on Optical Function and Tolerance to Misalignment. J Refract Surg. 2024;40(2):e79-e88. doi:10.3928/1081597X-20240112-02

[53] Hoggan RN, Subhash A, Blair S, et al. Thin-film optical notch filter spectacle coatings for the treatment of migraine and photophobia. J Clin Neurosci. 2016;28:71-76. doi:10.1016/j.jocn.2015.09.024

[54] Blackburn MK, Lamb RD, Digre KB, et al. FL-41 tint improves blink frequency, light sensitivity, and functional limitations in patients with benign essential blepharospasm. Ophthalmology. 2009;116(5):997-1001. doi:10.1016/j.ophtha.2008.12.031

[55] Hester L, Dang D, Barker CJ, et al. Evening wear of blue-blocking glasses for sleep and mood disorders: a systematic review. Chronobiol Int. 2021;38(10):1375-1383. doi:10.1080/07420528.2021.1930029

[56] Singh S, Keller PR, Busija L, et al. Blue-light filtering spectacle lenses for visual performance, sleep, and macular health in adults. Cochrane Database Syst Rev. 2023;8(8):CD013244. Published 2023 Aug 18. doi:10.1002/14651858.CD013244.pub2

[57] 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(6):644-654. doi:10.1111/opo.12406