

Blue Light and Digital Screens Revisited: A New Look at Blue Light from the Vision Quality, Circadian Rhythm and Cognitive Functions Perspective

Masoud Haghani (PhD)¹, Samaneh Abbasi (PhD Candidate)², Leila Abdoli (MSc)³, Seyedeh Fatemeh Shams (MSc)³, Batool Faegheh Baha'addini Baigy Zarandi (PhD)⁴, Nasrin Shokrpour (PhD)⁵, Atefeh Jahromizadeh (MSc)³, Seyed Alireza Mortazavi (MD)⁶, Seyed Mohammad Javad Mortazavi (PhD)^{7*}

ABSTRACT

Research conducted over the years has established that artificial light at night (ALAN), particularly short wavelengths in the blue region (~400–500 nm), can disrupt the circadian rhythm, cause sleep disturbances, and lead to metabolic dysregulation. With the increasing number of people spending considerable amounts of time at home or work staring at digital screens such as smartphones, tablets, and laptops, the negative impacts of blue light are becoming more apparent. While blue wavelengths during the day can enhance attention and reaction times, they are disruptive at night and are associated with a wide range of health problems such as poor sleep quality, mental health problems, and increased risk of some cancers. The growing global concern over the detrimental effects of ALAN on human health is supported by epidemiological and experimental studies, which suggest that exposure to ALAN is associated with disorders like type 2 diabetes, obesity, and increased risk of breast and prostate cancer. Moreover, several studies have reported a connection between ALAN, night-shift work, reduced cognitive performance, and a higher likelihood of human errors. The purpose of this paper is to review the biological impacts of blue light exposure on human cognitive functions and vision quality. Additionally, studies indicating a potential link between exposure to blue light from digital screens and increased risk of breast cancer are also reviewed. However, more research is needed to fully comprehend the relationship between blue light exposure and adverse health effects, such as the risk of breast cancer.

Keywords

Light; Smartphone; Circadian Clocks; Blue Light; Cognitive Functions; Vision Quality

Introduction

The circadian rhythm as a natural, internal process regulates the sleep-wake cycles; although circadian rhythms are endogenous, they are affected by external factors including light, temperature, and redox cycles [1]. All creatures such as humans have two timing systems as follows: **1**) it is in suprachiasmatic nuclei (SCN) that serve as “biological clocks” and regulate different daily rhythms such as sleep-

¹Department of Physiology, School of Medicine, Shiraz University of Medical Sciences, Shiraz, Iran

²Department of Medical Physics, School of Medicine, Mashhad University of Medical Sciences, Mashhad, Iran

³Department of Medical Physics and Engineering, School of Medicine, Shiraz University of Medical Sciences, Shiraz, Iran

⁴Department of Pharmacology, School of Medicine, Shiraz University of Medical Sciences, Shiraz, Iran

⁵School of Paramedical Sciences, Shiraz University of Medical Sciences, Shiraz, Iran

⁶School of Medicine, Shiraz University of Medical Sciences, Shiraz, Iran

⁷Ionizing and Non-ionizing Radiation Protection Research Center (INIR-PRC), School of Paramedical Sciences, Shiraz University of Medical Sciences, Shiraz, Iran

*Corresponding author: Seyed Mohammad Javad Mortazavi
Department of Medical Physics and Engineering, School of Medicine, Shiraz University of Medical Sciences, Shiraz, Iran
E-mail: mortazavismj@gmail.com

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wake cycle and reset daily with sunrise. Given this consideration, destruction of the SCN can lead to the complete impairment of a regular sleep-wake rhythm [2-5]. Thus, regular changes of light cause the adjustment of key body functions, including hormones secretion (such as melatonin and cortisol), awareness, body temperature, heart rate, and cognitive and behaviour function to be affected to be regulated due to sleep-awake adjustment [6-13]. As shown in Figure 1, the blue light emitted from digital screens can increase the risk of some cancers through affecting the melatonin level and biological rhythms. Given this consideration, digital screens as well as other sources of ALAN can affect the master clock located in the SCN of the hypothalamus and decrease the nocturnal melatonin synthesis in the pineal gland that causes disruption of circadian rhythms [14].

Neurological studies showed that there was a correlation between non-visual cognitive functions of the brain and subcortical areas such as the pulvinars, hypothalamus, and brainstem [15, 16]. 2) It is in striate-cortical loops and leads to passing time like passing minutes and

seconds [17]. Does light have effects on the brain of just sighted people or includes the same effects for blind people as well? Actually, there is still light effects, including the suppression of melatonin secretion and sleep disorders even without any ocular cells making images. There are two kinds of cells in the retina, including imaging and non-imaging cells which account for human vision and adjustment of key body functions, respectively. In addition to the image effects, non-image effects should be considered to evaluate the role of cones, rods, and *intrinsically photosensitive retinal ganglion cells* (ipRGCs) [18]. The cell called melanopsin in the retina [19, 20] is responsible for the adjustment of sleep rhythm and suppression of melatonin [3, 21], placed in retinal ganglion cells with high sensitivity to short-wavelength lights, especially blue light [18]. The melanopsin and their information are sent by the retinohypothalamic tract to the SCN. Due to blue-light stimulation, the message is sent to suprachiasmata to affect the pineal gland and then regulate melatonin secretion [22, 23]. Melatonin is released by the pineal gland and has different levels during the

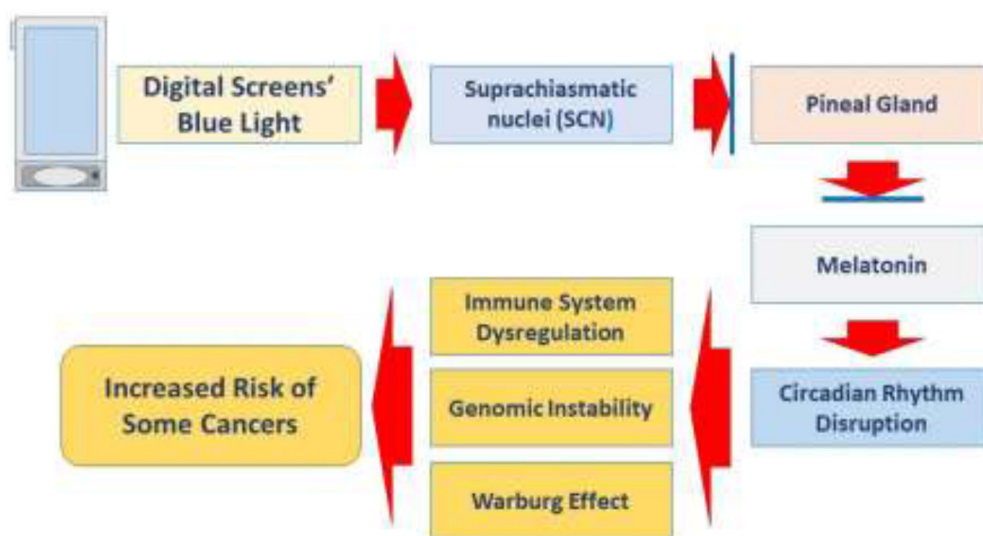


Figure 1: The short wavelength blue light emitted from digital screens can increase the risk of some cancers through affecting the melatonin level and biological rhythms. [This figure is modified from the original figure which appeared in a paper by Giudice et al., *Molecules* 2018, 23(6), 1308; <https://doi.org/10.3390/molecules23061308> [14]]

day since it is responsible for awareness level [24-27], regulating sleep-wake cycle, metabolism, and cognitive activity [28, 29]. Thus, its level decreases during the day due to activity and increases during the night [30, 31], so that this is a light-sensitive hormone [32, 33].

However, this hormone has the maximum and minimum level in the red and green light, respectively [13, 34]; the minimum light needed to suppress the melatonin level is considered 1000 lux [35]. Moreover, melatonin decreases and reaches the time of day for people exposed to bright light during the night [27, 33, 35-38]. Therefore, if the light becomes brighter during the night, melatonin decreases more [24]. In addition to regulation, melatonin hormone adjusts the intraocular pressure. Based on the study conducted on rabbits from New Zealand, yellow filters for blue light lead to decreased intraocular pressure [39]. Sleep disorder is a common problem in teenagers and adults [40]. According to a study carried out on 35 healthy adults, who were exposed to either blue (469 nm) or amber (578 nm) wavelength light for 30 minutes in a darkened room, followed immediately by functional magnetic resonance imaging (fMRI), the blue light group were faster in their responses on the N-back task. These participants also showed increased activation in the dorsolateral and ventrolateral prefrontal cortex compared to those in the amber light control group [41]. Wood, Rea et al. showed that the melatonin level decreased after 2 h in people exposed to light emitted from the laptop [42]. Temperature of light exposed to people affects the melatonin as well as wavelength. Furthermore, it was shown in some studies that people, who were exposed to high-temperature light, had higher levels of awareness, especially children and teenagers [36, 43, 44]. In accordance with a study carried out by Lee Matsumori et al., for children and adults exposure to 3000-6200 K light with 6200 K resulted in suppression of melatonin secretion in children at night, more than adults, and also blue light emitted from LED was more

effective [45]. Thus, based on the findings, it is better to use low-temperature light at night since high-temperature light leads to sleep disorders. Furthermore, 16 healthy women were exposed to lights with 2700-6500 K temperature; people exposed to light with 6500 K temperature had less awareness compared to the others [31].

The question is whether exposure to bright light can cause an increase and decrease in awareness and drowsiness, respectively, as caffeine. The use of caffeine is common in the world, so that many studies on it show that caffeine has the same effects as light on behavior and personality [46]. According to studies carried out on the light and caffeine separately and comparatively, there was a decrease in the level of melatonin and body temperature for people who used 200 mg caffeine two times a night or those who were exposed to light with an intensity more than 2000 lux.

A study found that caffeine intake and bright light exposure, both individually and combined, suppressed melatonin and attenuated the normal nighttime drop in temperature [47].

The question is why the effects of light are less on adults, especially old people, in comparison with children, especially kids? Does the brain lose excitability during the time or are there other factors to make this stability? Increasing age was associated with changes in the brain function, and the most important change reduces the ipRGCs cells [48]. Based on the studies carried out so far, reduced cells, which are responsible for the non-visual response of the brain [49, 50], result in delivering low light into SCN [51-53]. Age-related disrupted sleep is linked to changes in the timing of circadian rhythms, with studies suggesting decreased sensitivity of the aging circadian pacemaker to light [54]. In this paper, we aimed to review the bio-effects of exposure to blue light on human cognitive functions and vision quality. Moreover, studies indicating a potential link between exposure to blue light from digital screens and an increased risk of

breast cancer are also reviewed.

Discussion

The effective factor of light

Studies that have been carried out reveal that there are three important factors affecting our response to light, namely wavelength, radiation duration, and light intensity. These factors control our cognitive functions and tasks [13, 55-58].

The effective factor of wavelength

Based on some studies carried out on radiation transmitted to human naturally or artificially during the day, short-wavelength visible lights (<500 nm) in comparison with long-wavelength ones (>500 nm) caused drowsiness [7, 15, 36, 59, 60] and awareness to decrease and increase, respectively [7, 61, 62]. Blue light, with 460 nm, is considered as light with a short wavelength. The shorter the wavelength, the higher the energy. It is revealed that blue light has more detrimental effects on the light receptor cell in comparison with green and white lights [63]. In the past, the only source for blue light was the sun; however, nowadays, there have been many sources, including laptops, digital TVs, and computers, the most important of which are smartphones and laptops [64, 65]. The studies show that the use of systems mentioned above in the evening affects sleep, waking, health, and reaction time [60, 66-68].

Scholkmann et al. conducted a study on 14 healthy adults exposed to red, green, and blue lights to evaluate the effect of light on the brain hemodynamic system at the visual cortex (VC) and pre-frontal cortex (PFC) using the fNIRS technique. Results obtained are as follows: **1)** all kinds of light have effects on the VC and the only light, impacting the PFC, is blue, **2)** the activity of heartbeat depends on light, and **3)** brain hemodynamic response and rate changes depend on the gender [69]. It is worth noting that the daily exposure to short wavelength blue light has been reported

to be involved in modulating functional brain responses within the amygdala and PFC [70]. The PFC is associated with a variety of higher cognitive functions [71]. The significant role of PFC in personality development is well documented. Some studies show that the cognitive and emotional functions of the PFC develop in remarkable synchrony with its structural development [72]. It has been shown that people exposed to red light in the early night have better sleep quality [10].

The effect of intensity and duration of irradiation

The fact that humans are sensitive to light means that even small changes in the amount of light in a room (usually between 90-180 lux) can greatly affect how alert they feel and their corresponding brain activity during the early part of the night [73]. Many studies were done on the importance of exposure time and light intensity since researchers did not know which one (exposure time and light intensity) was more important. In a study, 56 healthy adults were exposed to bright and poor light in different times and intensities, including 1, 2, and 3 h and 2000, 4000, and 8000 lux, respectively. Exposure time was more important than light intensity. Therefore, it was effective to use moderate light for a long time to do phototherapy for people suffering from sleep disorders [56].

Another question asked is whether light intensity has an effect on the body temperature. Melatonin levels were investigated on 15 people at pre-and post-exposure with light intensity of 500, 1000, and 5000 Lux during 1700-2500 h. Findings showed that 500 lx could be considered as the threshold for significant melatonin suppression, temperature enhancement, and increased alertness [74]. High awareness and short response time were made at high-temperature light like daytime temperature (2568 k) [75]. Similarly, children exposed to blue light with 1000-lux intensity during less than 1 h are able to answer the mathematical questions better and have short-

er reaction times in comparison with people exposed to red light with the same properties [7]. People were exposed to blue light and then asked mental and mathematical tests; results obtained using fMRI showed they had more mind activity and answered computational questions faster than others did [62, 76-78].

The effect of shift working

Night-shift working can cause synchronization of biological clock and sleep-wake cycle to be lost; thus, drowsiness increases and efficiency decreases. On the other hand, there are some problems due to daytime sleep and the body wants to get ready for work [79-83]. It has been nowadays called night-shift working [84]. Studies conducted on people with night-shift working revealed that people who are exposed to blue light 500 lux with 7 h night-shift working had less drowsiness and more awareness [7]. Based on the studies carried out by Campbell et al. on 25 healthy adults exposed to light with 8 h night shift, it was revealed that people exposed to 1000 lux light had more awareness [61]. Moreover, it has been revealed that workers, wearing blue light filter sunglasses, have been suffering fewer sleep disorders [85, 86].

Filtration

The maximum injury to the eyes can be caused by the exposure to short-wavelength light. According to advancements in the electronic industry, there are some theories about the effects of filters such as the advantageous or disturbing effects of filters. Filters considered as lenses are of three types: spectacle lenses utilized in glasses, contact lenses, and intra-ocular lenses.

There was no significant difference in the criteria showing the effect of digital systems on the eyes. Other studies show that glasses with filtered blue light are useful to prevent blue light, especially at night and before sleeping [87]. A study on 48 healthy adults exposed to blue light emitted from smartphones indicated that the use of smartphones without filters caused delayed sleep-phase disorder (DSPD)

about 20.84 ± 9.15 min; however, blue and amber filters cause DSPDs about 15.26 ± 1.04 min and 26.33 ± 1.59 min, respectively. Because blue light suppresses melatonin, an amber filter probably improved sleep via melatonin secretion [60]. Furthermore, in a study, the students were asked who got into the college and suffered from DSPDs, to use glasses with a blue filter while working with digital systems at night. According to the results, sleep hours, and mental and emotional activities had an improvement [7, 88].

One of the most important questions, which has been posed recently, is whether lens replacement leads to damage to the retina in eyes surgery such as cataract surgery, which is more common [89-91]. It has been concluded that a new lens causes the retina to attract more light in lens replacement for cataract surgery. There are different lenses which decrease this damage; thus, it would be better to use a lens which filters the UV light [92-94].

In a study, two groups, including young and old people with natural lens (NL) and second lens after cataract surgery, multifocal and/or toric intraocular lenses (IOLs), were exposed to blue and orange lights after cataract surgery. According to the results, blue light causes cognitive activities of the brain to be balanced, especially in the hippocampus, singular and frontal cortex. However, no difference was seen between IOL and NL. Based on regression analysis, brain interactions were not related to the age for different lights in old age [95].

Lenses that filter blue light may prevent the detrimental macular changes of the retina. There are some studies, answering important questions such as: based on the effects of blue light, can the lens which filters the blue light be the best choice now? or do blue light filters affect people's sight at night? The balance between light receptors and light protection is important [96-98].

Studies carried out so far show that the use of these lenses not only do not cause any chang-

es in eye vision but also are the best choice for people with risk of macular degeneration [90, 99-102], which occurs with increasing age in many advanced societies [103-106]. The problem of driving with the high light condition was addressed using lenses with blue filters [107, 108]. However, filtering light causes some defects in people's vision, including a disorder of color perception and adjusting rhythm hours, and the poor performance of low light condition [109, 110]. Eyeglasses with UV filtered lenses work in wavelengths between 415 and 455 nm, and this range can show detrimental effects of blue light. These glasses have more advantages in comparison with intraocular lenses, including filtering a part of the spectrum and passing another part of it [111, 112].

The results of all studies mentioned above are summarized in Table 1.

The characteristics of blue light, such as irradiation duration, light intensity, and wavelength, affect performing tasks and cognitive functions. Based on the results reviewed in this paper, blue light is associated with more detrimental effects compared to other wavelengths. Moreover, exposure time seems to be of more crucial importance compared to light intensity. Individuals exposed to blue light at intensity of 500 lux during 7 h night-shift working had more awareness and less drowsiness. Moreover, based on studies carried out on students who suffered from DSPDs and wore glasses with blue filters during working with digital systems at night, sleep hours, emotional and mental activity were improved.

ALAN increases the Risk of Breast and Prostate Cancers

A study conducted by Mortazavi *et al.* suggests that exposure to blue light emitted from digital screens, particularly at night, can increase the risk of breast cancer. The study used machine learning models to predict breast cancer risk in women exposed to blue light from digital screens [122]. According to a study published in the International

Journal of Basic and Medical Sciences, women with hereditary breast cancer predispositions should avoid using their smartphones, tablets, and laptops at night. The study predicted that short-wavelength visible light from these devices can disrupt the secretion of melatonin and cause circadian rhythm disruption, which can increase the risk of breast and ovarian cancers in women with mutations in the BRCA1 and BRCA2 genes [123]. SAR Mortazavi and his colleagues have studied the health effects of blue light over the past several years [124-130]. To reduce the risk of breast cancer in women with hereditary predispositions, AR Mortazavi and SMJ Mortazavi have recommended to avoid exposure to light at night, including domestic light and light from digital screens such as smartphones, tablets, and laptops.

It is worth noting that exposure to light at night can disrupt the secretion of melatonin and cause circadian rhythm disruption, which can increase the risk of breast cancer. A case-control study on 894 healthy controls and 211 patients with breast cancer showed that excessive smartphone use significantly increased the risk of breast cancer, particularly for participants with smartphone addiction, a close distance between the breasts and smartphone, and the habit of smartphone use before bedtime [131]. Women who work or are exposed to high levels of light at night, such as factory workers and doctors, are also at increased risk of breast cancer. A study conducted by Harvard scientists on 3,549 breast cancer cases over 2,187,425 person-years, [132] showed that exposure to residential outdoor light at night could contribute to invasive breast cancer risk. Moreover, a systematic review and metaanalysis showed that indoor exposure to light at night was associated with 13% higher risk of breast cancer [133]. An ecological study also showed that artificial light at night was significantly associated with lung, breast, colorectal, and prostate cancers [134].

Table 1: Summary of the studies conducted on the health effects of exposure to blue light

Author(s)	Factor	Sex	Participant's Number	Results
Kozaki, et al. [33]		Male	12	There was not any noticeable difference in concentration of melatonin before and after exposure to high-time light correlated to bluish white light, for individuals involved in the study and exposed to conditions of different light.
Cajochen, et al. [13]		Male	10	In the late evening, exposure to 2 h of monochromatic light with 460 nm led to a noticeable suppression of melatonin in comparison with 550 nm monochromatic light associated with heart rate, a great warning response and incremental temperature of core body.
Killgore, et al. [30]		-	26	For individuals exposed to a 30min of amber light and blue light, and followed by functional MRI throughout working memory, there was no significant difference in levels of melatonin in the morning at the group level. There was a decrease in salivary melatonin for individuals, which was associated with great increases in activation, within the left dorso-medial in addition to right inferior lateral prefrontal cortex.
Vandewalle, et al. [59]	Effect of wavelength	-	17	For individuals who listened to emotional as well as neutral vocal stimuli in addition to being exposed to changing 40s of green or blue ambient light, there was an increase in reply to emotional stimuli in the area of the voice of the temporal cortex in addition to the hippocampus due to blue light.
Alkozei, et al. [78]		-	30	For individuals who received blue light, it was revealed that there was noticeable recall of long-delay verbal compared to those who were exposed to amber light.
Vandewalle, et al. [113]		-	27	The impacts of 1 min of low-intensity blue as well as green lights exposure were compared based on responses of the brain. After sleep, blue light, in the morning, in comparison with green light, causes an increase in brain responses in the ventrolateral and dorsolateral prefrontal cortex in addition to the intraparietal sulcus.
Cajochen, et al. [73]		Male & female	23	Individuals involved in the study were exposed to illuminances, which ranged from 3 to 9100 lux for 6.5 h during the early biological night, after getting exposed to <3 lux for many hours. There was a decrease in EEG activity in the frequencies of theta-alpha and self-reported sleepiness.
Te Kulve, et al. [31]	Effect of light intensity, duration, and temperature	female	16	Individuals involved in the study were exposed in two parts, including 2700K and 6500K light (both 55 lx). Reaction time was lower for 6500K exposure; however, the temperature of the body core was higher under 6500 K. Reaction time was related to heat loss although this relation did not clarify why the reaction time was for 2700 K.
Smolders and de Kort [43]		-	30	Results revealed there was no significant activating and even subtle performance degrading effects in the relatively high related color temperature (2700 K vs. 6000 K, 500 lx) condition but higher subjective importance in condition of the 6000 K in the morning. Participants involved in the study registered their mood in addition to the light settings as less positive in the 6000 K vs. 2700 K condition.
Chellappa, et al. [114]		male	16	For individuals involved in the study and exposed to the light of 40 lux at 6500K and at 2500K for 2 hours in the evening, exposure to light at 6500K made greater melatonin suppression associated with improved subjective warning
Dai, et al. [115]		male	12	For individuals involved in the study and exposed to changing levels of intensity of light and quantity, containing exposure to white and blue LEDs, there was non-visual effects of pulsed light on physiological function established not by quantity but the emitted light intensity, with relatively higher levels of intensity, which produce more noticeable physiological changes.

Author(s)	Factor	Sex	Participant's Number	Results
Sasseville and Hébert [85]		-	4	Individuals involved in our study and exposed to ambient blue-green light as well as light throughout various times, blue-blockers had to be used outside after the night shift. At least, melatonin of 3 individuals involved in the study had moved by 2 h. As there was an increase in the performance at the fourth night, an enhancement in parameters of subjective vigilance as well as sleep from the third night was observed.
Thome, et al. [116]		male	10	Individuals, who worked from 18:00-6:00 h had a 6-sulphatoxymelatonin acrophase of 11.7 ± 0.77 h (mean \pm SEM, decimal hours), although it was noticeably 14.6 ± 0.55 h ($p=0.01$) for shift workers who worked 19:00-07:00 h. Circadian phase was later; in addition, objective sleep was shorter with the 19:00-07:00 h compared to the 18:00-06:00 h shift plan.
Gumenyuk, et al. [117]	effect of light on shift workers	-	10	5 asymptomatic night workers in addition to night shift workers, who met diagnostic criteria during shift work disorder, were involved in the study, and stayed in a room, which was dim light and private during the study period of 25 h. Concentrations of melatonin as well as light intensity were measured. There was not any noticeable relationship between melatonin as well as sleep duration, and also, there was no similar relationship between melatonin as well as physical activity. Based on the analysis of the levels of salivary melatonin, the circadian rhythms did not change for night workers, which means production of peak melatonin occurs at night.
Grundt, et al. [118]		female	61	There was a random selection of participants to receive either filtered light or standard indoor light at night shift. Levels of salivary melatonin as well as alertness were investigated every 2 h at the first night shift of every study period. At the baseline night polysomnography, all sleep efficiency and time sleep were noticeably declined and intervening wake times noticeably had an increase with a mean 40 min than baseline. During the night and both conditions, subjective sleepiness had an increase.
Rahman, et al. [119]		-	9	With associated glare, the margin of safety was statistically noticeably greater in the study group compared to the control group. In the comparison glare and no-glare conditions, the study group showed noticeably lower glare susceptibility and effect on intersection approach speech compared to the control group in addition to fewer collisions with the oncoming car.
Gray, et al. [107]		-	34	For glare, patients who took IOLs test had noticeably more safety margins compared to those taking control IOLs and noticeably lower glare susceptibility. In glare and no-glare situations, patients with IOLs test showed noticeably lower glare susceptibility compared to those with control IOLs.
Gray, et al. [108]		-	33	The individuals involved in the study were accidentally allocated to put on blue blocking (BB) glasses or placebo (clear glasses) from 18:00 to 8:00 h. The mean sleep efficiency of the BB group was noticeably higher than the placebo group.
Henriksen, et al. [120]	effect of blue light filtration	-	-	Patients finished a program of CBT-I group therapy with groups accidentally assigned to condition of "active" (glasses with blue-light filtering) or condition of "placebo" (glasses without any properties of filtering). When the comparison of results in both groups was done before and after treatment, separately, important differences were seen also in the active group. No significant differences were detected in the placebo group. In addition, in active group, there was a marked decrease of subjective sleep latency and an increase of subjective whole sleep time without any changes in objective sleep length of time, which, in the placebo group, was noticeably shortened.
Janku, et al. [121]		Male & female	30	

MRI: Magnetic Resonance Imaging, EEG: Electroencephalogram, LEDS: Light Emitting Diodes, SEM: Scanning Electron Microscope, IOLs: Intraocular Lenses, CBT-I: Cognitive Behavioral Therapy for Insomnia

Conclusion

Due to factors such as increasing use of digital screens at night and urban light pollution, modern life is linked to significant interruptions in light-dark cycles. Blue light from digital screens is associated with a wide variety of problems ranging from macular degeneration, and cataracts to poor sleep, mental health problems and even increased risk for some cancers. Given this consideration, understanding the effects of exposure to blue light on the circadian rhythm is of crucial importance. More research is needed to fully comprehend the relationship between blue light exposure and adverse health effects, such as the risk of breast cancer.

Authors' Contribution

SMJ. Mortazavi designed the review study. SMJ. Mortazavi, M. Haghani and SAR. Mortazavi supervised the review process. M. Haghani, S. Abbasi, L. Abdoli and SF. Shams have equally contributed to this work. All authors have contributed to the gathering of the data, interpretation of the findings, and writing/reviewing of the current manuscript and read, modified, and approved the final version of the manuscript.

Conflict of Interest

SMJ. Mortazavi, as the Editorial Board Member, was not involved in the peer-review and decision-making processes for this manuscript.

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