12-31-2023

The effects of blue light from digital displays on visual fatigue

Victor Taboadela
New Jersey Institute of Technology

Recommended Citation

Taboadela, Victor, "The effects of blue light from digital displays on visual fatigue" (2023). *Theses*. 2375.
https://digitalcommons.njit.edu/theses/2375

ABSTRACT

THE EFFECTS OF BLUE LIGHT FROM DIGITAL DISPLAYS ON VISUAL FATIGUE

by
Victor Taboadela

With the ever-increasing viewing time of digital displays, the potential effects of blue light emitted from these displays on eye health and eye fatigue are a real concern. This study presents a literature review of six laboratory studies conducted between 2014 and 2022 on the effect of using filters to attenuate the harmful effects of blue light. The review delves into smartphone and computer screen effects, recent literature reviews on blue light, and potential hazards associated with short-wavelength light. Although the majority of the studies recommended blue light filters, only three of the six laboratory studies (Shi et al. 2021, Tu et al. 2021, Lin et al. 2017) found significant positive effects.

A pilot study was conducted with six participants, focusing on the immediate effects of blue light exposure from an 18-inch screen of a laptop computer, while playing a graphic-based and a text-based game with three filter conditions, no-filter, an eyeglass filter, and a digital filter. Eye fatigue symptoms of tired eyes, sore eyes, dry eyes, and blurred vision showed a reduction of perceived ratings when blue light filters were used. Symptoms of tired eyes, and dry eyes reached a significant level of p-value < 0.5 improvement over no filter. The digital filter, which has not been tested before for computer screens, provided a statistically significantly better rating than the eyeglass filter.

While the results suggest an improvement for those using blue light filter technologies and may help to advocate for more blue light blocking technology in workplace design, the overall conclusion underscores the ongoing need for comprehensive research, considering limitations such as the small sample size of the pilot study and the absence of long-term effects research.

THE EFFECTS OF BLUE LIGHT FROM DIGITAL DISPLAYS ON VISUAL FATIGUE

by
Victor Taboadela

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Occupational Safety and Health Engineering

Department of Mechanical and Industrial Engineering

December 2023

APPROVAL PAGE

THE EFFECTS OF BLUE LIGHT FROM DIGITAL DISPLAYS ON VISUAL FATIGUE

VICTOR TABOADELA

Dr. Arijit Sengupta, Thesis Advisor Date
Associate Professor, Department of Mechanical and Industrial Engineering, NJIT

Dr. Athanassios Bladikas, Thesis Committee Member Date
Associate Professor, Department of Mechanical and Industrial Engineering, NJIT

Dr. Samuel C. Lieber, Thesis Committee Member Date
Associate Professor, School of Applied Engr & Tech, NJIT

BIOGRAPHICAL SKETCH

Author: Victor Taboadela

Degree: Master of Science

Date: December 2022

Date of Birth:

Place of Birth:

Undergraduate and Graduate Education:

- Master of Science in Occupational Safety and Health Engineering, Newark College of Engineering. New Jersey Institute of Technology, Newark, NJ, 2023.

- Bachelor of Science in Mechanical Engineering Technology, Newark College of Engineering. New Jersey Institute of Technology, Newark, NJ, 2021.

Major: Occupational Safety and Health Engineering

This research project is dedicated to my family, whose unwavering support and encouragement have been my steadfast pillars throughout this academic journey. Their love, understanding, and sacrifices have been a driving force behind my pursuit of knowledge. To my teachers, professors, and mentors, whose impact extends beyond the classroom, leaving an enduring impact on the lives of those they have guided, encouraging them to become future innovators, scientists, engineers, and leaders in the world and whose guidance has specifically illuminated my path and enriched my understanding, I express my deepest appreciation. This cumulative endeavor would not have been possible without the collaborative spirit of friends and colleagues who provided social support and inspiration along the way. This work stands as a testament to the collective strength of those who believe in the power of education and the transformative impact it can have on our lives.

ACKNOWLEDGMENT

I would like to acknowledge my advisor, Dr. Sengupta, whose guidance, expertise, and support have been instrumental throughout the journey of this thesis.

I would like to express my sincere appreciation to the members of my thesis committee, Dr. Bladikas and Dr. Lieber, for their valuable time, thoughtful insights, and constructive criticism.

I am immensely thankful to NIOSH for providing financial support during the course of this research and throughout my graduate studies. The fellowship not only alleviated some of the practical challenges but also allowed me the freedom to dedicate more time and resources to the scholarly pursuits inherent in this thesis.

This accomplishment would not have been possible without the support of EOP. Their support and resources to students, including myself, who may face economic, educational, and social challenges that could otherwise impede the pursuit of higher education have been critical in my ability to get where I am today.

Lastly, I extend my appreciation to all those who have contributed to this endeavor, directly or indirectly. Your support has played a pivotal role in shaping the outcome of this thesis, and for that, I am truly grateful.

TABLE OF CONTENTS

Chapter **Page**

1 INTRODUCTION……………………………………………………...……………….. 1

1.1 Background…………………………………………………………………..… 1

1.2 Mechanism of Eye Fatigue and Eye Injury……………………………….……… 3

1.3 Objective Of The Review And Study……………………………………….. 8

2 LITERATURE REVIEW…………………………………………………..…….…... 9

2.1 Recent Literature Reviews on the Effects of Blue Light…………………..…….. 8

2.2 Smartphone Screen Blue Light……………………………………………… 13

2.3 Computer Screen Blue Light ……………………………………………….. 20

2.4 Analysis of Literature Review……………………………………………….. 25

3 PILOT STUDY ON BLUE LIGHT EFFECTS ON FATIGUE/PRODUCTIVITY….. 29

3.1 Method Of Experiment ………………………………………….…………… 29

3.2 Results………………………………………………………….……….……... 32

3.3 Comparison Of Study…………………………………………….…………… 35

4 CONCLUSION…………………………..………………………...…………… 36

References……………………………………………………………….. 38

LIST OF TABLES

Table **Page**

2.1 Meta-Analysis of Recent Studies On The Blue Light Effects of Smartphone and Computer Display……………………………………………… 26

3.1 Comparison of Fatigue Ratings…………………….……………………….. 34

LIST OF FIGURES

Figure **Page**

1.1 Sunlight’s SPD vs Artificial LED-Based Light SPD. 2

1.2 Functions of the extraocular muscles. 4

2.1 Visual Fatigue Symptoms vs Display Type. 15

2.2 SPD of Regular LCD vs SPD of Blue Light Shifted LCD. 18

2.3 Subjective Visual Fatigue Survey Results. 19

2.4 Wavelength Transmission Amongst Research Groups. 20

2.5 Questionnaire of visual fatigue and discomfort. 22

3.1 BLS “Spot the difference game” sample.. 29

3.2 Sample random collection of characters presented in the Pseudo-text game. 30

3.3 The average change in symptom ratings after playing the “Spot the Difference” game. 33

3.4 The average change in symptom ratings after playing the “Pseudo-text” game.. 33

CHAPTER 1

INTRODUCTION

In the twenty-first century, workers are exposed to several different kinds of digital display technologies both in and out of work. In particular, the widespread use of digital devices has significantly increased exposure to blue light, which at a wavelength of 400-490 nm makes it a high-energy visible (HEV) light (Yang *et al.*, 2018). This light is emitted by screens of digital devices such as smartphones, tablets, laptops, and computer monitors usually at artificially high spectral power distribution (SPD). SPD measures the radiation emitted by a light source at each wavelength.

It is important to understand that this plays a big role in how we perceive colors via our photoreceptors since each receptor follows a different sensitivity curve. The smaller the wavelength, the more health effects there are on the eye due to the increased amount of energy per photon. For example, gamma rays and X-rays are known to be damaging to DNA and carcinogenic due to their ionizing ability. This ionization causes electrons to be removed from atoms and molecules which in turn have severe health effects.

Blue light, however, is on the non-ionizing radiation side of the spectrum. Still, it sits closest to the ionizing of visible light, next to ultraviolet (UV) light, which is also linked to various health-related issues. The artificially high spectral power distribution of blue light emissions from a digital screen as compared to that of natural sunlight is shown in figure 1.1.

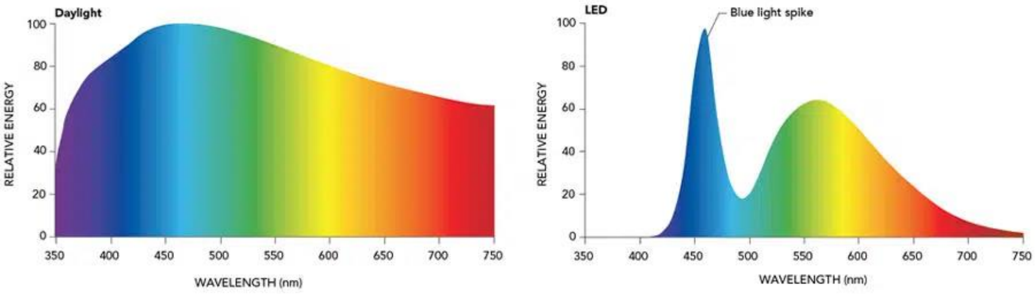


Figure 1.1 Sunlight's SPD vs Artificial LED-Based Light SPD.

Source: Eyesafe, 2023, https://eyesafe.com/chapter-2/

The relative energy of blue light spikes to 100% for lights from light emitting diode (LED) as opposed to natural daylight.

Glare is another factor that produces visual discomfort and occurs when the light entering the eyes impedes vision. It has been shown that light sources with controlled illuminance tend to be perceived with more glare-based discomfort when they contain higher levels of blue light wavelength distribution. (Bullough, 2020)

So, with the increasing screen time for workers and the general public concerns about the potential effects of blue light on visual fatigue and eye health have arisen and with them the rise of a whole market of blue light filters in the form of glasses, screen overlay films, and various software that all claim to help with the reduction of eye fatigue and sustained visual wellbeing.

1.2 Mechanism of Eye Fatigue and Eye Injury

The physiological component of visual fatigue can vary quite a bit depending on the type of fatigue being induced. As an overview of how the eyes function physiologically, the cornea works in conjunction with the lens by bending light into the eye. Light is perceived as color because the lens behind the cornea refracts light to focus it on the retina. Blue light, like all visible light, is refracted by these structures to reach the retina which is lined with special light-sensitive cells called photoreceptors (Sánchez López *et al*, 2022). These receptors are the photopic cones composed of red, green, and blue cones that allow us to see color in lighter settings and the scotopic rods that allow us to see in low-light environments like at night. Three types of cones are sensitive to different wavelengths. They are S-cones, M-cones, and long L-cones. S-cones are most sensitive to shorter wavelengths, which is why they are predominantly relevant to blue light. The mechanism of damage to these cones is called photochemical damage, which occurs when molecules absorb photons and undergo chemical reactions. These reactions often involve the breaking or rearranging of chemical bonds. The molecules must absorb a specific amount of energy, corresponding to the energy of the absorbed photons, to initiate these reactions.

The eye's intrinsic mechanical functions largely depend upon the ciliary muscle, which is a muscle inside the eye that controls the lens to adjust its focus. The more the ciliary muscle contracts the more a focus effect is produced while less focus effect is produced from the relaxation of the ciliary muscle (Rehman *et al.*, 2022). Contraction creates a more convex lens shape thus aiding the eye in viewing closer objects while relaxation results in a flatter lens and thus aiding in viewing objects at a distance. Sporadic contraction and relaxation and prolonged periods of contraction of the ciliary muscle create more visual fatigue due to the overexertion of the muscle. This type of visual fatigue has been studied using electroencephalography (EEG) to measure it quantitatively by placing sensors on the scalp over the brain's occipital lobe which houses the visual cortex and recording the brain event-related potential (ERP) across the alpha, beta, and delta band signals.

The extrinsic movements of the eye are controlled by various extraocular muscles around the eye via the annular tendon that each serve different functions concerning the type of movements such as the medial and lateral rectus for adduction, the inferior and superior rectus for depression, and elevation, and the inferior and interior obliques for excyclotorsion and incyclotorsion. Below is a figure that shows the functions of extraocular muscles.

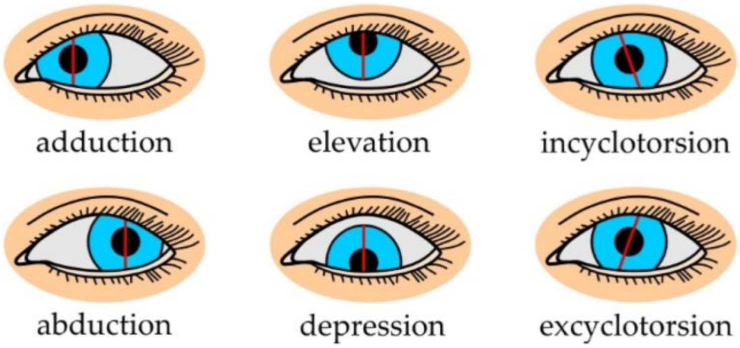


Figure 1.2 Functions of the extraocular muscles.

Source: Iskander *et al.*, 2018

Increased fatigue can also occur when eyes are kept out of a "neutral" position for extended periods like if they are kept adducted or elevated for too long. This type of visual fatigue has been studied using electromyography (EMG) to measure it quantitatively by using an electrode inserted into the muscle to record its electrical activity.

The groundwork definitionally for visual fatigue can be laid out by the following: “Visual fatigue does not occur instantaneously, visual fatigue should be distinguishable from mental workload demands, visual fatigue can be overcome by rest, visual fatigue should be discernible from any adaptive response of the visual system, symptoms of asthenopia are the main reason for assuming the existence of visual fatigue, symptoms of asthenopia can be caused by nonvisual factors” (Megaw, 1995). Visual fatigue caused by blue light may be a serious issue affecting millions across the globe so preventative measures involving best practices and technological solutions are key strategies for managing this problem.

An article by Youssef *et al.* (2011) reviewed the potential damage to the retina caused by exposure to various types of light, with a particular focus on blue light. The study investigates the mechanisms through which light, especially in the blue spectrum, can lead to retinal damage and provides insights into the role of oxidative stress and photoreceptor cells in this process. The study explains the concept of light-induced damage to the retina, known as retinal light toxicity. It is photochemical damage rather than photomechanical or photothermal that drives the function behind this retail light toxicity.

Photochemical damage involves chemical reactions initiated by the absorption of light energy and is sensitive to the wavelength of light making blue light a primary suspect in potential damage. Photomechanical damage is caused by rapid heating, expansion, and shock wave generation, and it is less sensitive to wavelength. Photothermal damage is initiated by the generation of heat through light absorption and is utilized in various medical and industrial applications where controlled heating is beneficial. It discusses how the retina is vulnerable to damage from excessive or prolonged exposure to light, particularly high-energy visible light such as blue light. The mechanisms through which light, and blue light, in particular, can cause retinal damage is the role of oxidative stress, where the production of reactive oxygen species (ROS) can lead to photoreceptor cell death and retinal injury.

Photoreceptor cells, such as rods and cones, may experience degeneration that can result from prolonged light exposure. The research here underscores the potential risk of blue light exposure from digital screens, LED lighting, and other sources and suggests that protecting the eyes from excessive blue light exposure, such as using blue light-blocking filters or reducing screen time, may help mitigate the risk of retinal damage.

Blue light has also been linked to the disruption of the circadian rhythm by suppressing the amount of melatonin that is released by the body. Melatonin is a hormone that helps us sleep at night and when it is suppressed this causes restlessness. (Wong & Bahmani, 2022). As a result of this, the time of day during exposure is an important variable to control for an experimental study. The focal point of relevant symptoms will derive from computer vision syndrome which is usually said to be caused by the hyper-focusing of the eyes, resulting in less blinking and irritation; however, research on blue light itself inducing these symptoms is still largely in the works and inconclusive.

It has been suggested by some studies (Tu *et a*l., 2021) that this HEV blue light can penetrate deeper into the eye compared to other kinds of wavelengths which may induce some level of retinal damage via photochemical damage which could then lead to ocular diseases such as age-related macular degeneration (ARMD) but with much of the exposure to blue light being recent the long term effects are largely unknown. Of course, this should all raise concerns for the safety and health workers since it can ultimately cause them pain and discomfort both physically and mentally which in turn can lower health, happiness, and productivity which in turn begs the question of blue light's impact in all of this. Ultimately the goal of this research is to further understand and detail how to optimize workstations, occupational environments, employee behaviors, or supplemental equipment revolving around the use of digital display technologies to help keep workers from any distress that blue light exposure may cause.

1.3 Objective of the Study

Thus far optimization of digital display workstations typically revolves around parameters like screen size, resolution, viewing distance, screen type, and screen curvature which have yielded all sorts of best practices including increasing blinking frequency and utilizing proper lighting conditions as well as reducing screen glare (Hamada et al.,2019). In this research, presents a study the potential effects that artificial blue light exposure on health, productivity, and visual fatigue through both a review of the current literature and a pilot study. Visual fatigue, in this case, will refer broadly to the types of eye strain or discomfort after extended periods of screen time, inducing what is referred to as computer vision syndrome. This is usually denoted by the symptoms of dry eyes, blurred vision, headaches, and neck pain.

CHAPTER 2

LITERATURE REVIEW

This literature review aims to provide a comprehensive exploration of the existing body of knowledge on the subject of blue light and its relationship to visual fatigue. By examining relevant studies, methodologies, and findings, this review seeks to illuminate the current state of understanding regarding the potential effects of blue light exposure on visual comfort and fatigue. Furthermore, it will assess the implications of these findings for both an individual worker's well-being and the broader societal context, considering the implications for workplace modification to ensure health and productivity are optimized.

2.1 Recent Literature Reviews on Effects of Blue Light

A review of the current state of blue light from digital screens by Wong and Bahmani (2022) discusses the impact of blue light on different components of the eye, particularly the ocular surface, anterior ocular structures (cornea and conjunctiva), and the lens. They discuss how overexposure to blue light from LEDs has been linked to apoptosis (cell death) and oxidative damage to the cornea in mice, as well as a reduction in cell viability in human corneal and conjunctival epithelial cells. They also mention the concerns that blue light may exacerbate dry eye disease symptoms, but admit the evidence is still mixed. The study also highlights the debate around blue-filtering intraocular lenses during cataract surgery and their potential impact on age-related macular degeneration and other ocular processes.

They found that some studies indicate elevated contrast sensitivity under blue illumination, but blue light's impact on visual performance remains uncertain due to their inability to isolate all factors and pinpoint an exact mechanism of action. Here, they state filtering blue light from screens or devices does not seem to significantly affect visual acuity or contrast sensitivity. They touch on the blue light effect on the circadian rhythm and conclude that exposure to blue light during the day can have beneficial effects on alertness, mood, and productivity but during the evening exposure to blue light, especially from digital devices, can negatively affect the sleep-wake cycle and sleep quality.

They conclude that the low-intensity blue light from digital devices doesn't seem to have an immediate impact on our eyes but that there's a lack of comprehensive, high-quality research on the long-term effects under relevant conditions. Current findings from blue-light-filtering studies suggest that blue light may not significantly harm our eye health or protect against digital eye strain or age-related macular degeneration. However, further research is necessary. A deeper understanding of how artificial blue light influences human health is crucial for safely integrating new technologies into our daily lives.

Another review article of blue light effects by Bullough (2000) discusses the potential hazards associated with short-wavelength light generally but digital display applications specifically. Here they discuss The American Conference of Governmental and Industrial Hygienists (ACGIH) and the Illuminating Engineering Society of North America (IESNA) standards and recommendations to specify exposure limits to different forms of radiation, including optical radiation (light, infrared, and ultraviolet). The review highlights that short-wavelength light, including blue light, can cause photochemical damage to the retina. The ACGIH has established maximum exposure limits to energy in this part of the spectrum known as the blue-light hazard limit and that the IESNA has developed algorithms for calculating the blue-light hazard based on ACGIH recommendations and a framework for classifying and labeling light sources based on their potential risk. The study also provides information and data for lighting specifiers, illuminating engineers, and equipment designers.

The mechanisms for retinal damage, which include the aforementioned mechanical, thermal, and photochemical damage, suggest a focus on photochemical damage for blue light exposure. It discusses that photochemical lesions on the retina result from chemical reactions due to light exposure, particularly short-wavelength light. They suggest that specific population groups might be more susceptible to this retinal damage, such as the elderly, infants, recipients of prosthetic lens transplants, and people with aniridia (Missing or damaged iris condition). They highlight that individuals within these groups should take precautions to minimize exposure. They also examine specific applications, including exposure to daylight and sunlight, medical examination and surgical lights, endoscopic fiber optic instruments, bilirubin phototherapy units, dental photopolymerization units, argon lasers, studio and theatrical floodlights, and quartz linear lamps. For each application, it provides recommendations for minimizing potential risks and ensuring safety. For example, they suggest that argon laser applications utilize protective eyewear to prevent inadvertent specular reflections from causing accidental exposures and for studio/theatrical floodlight applications to limit the direct observation of high-intensity light sources to no more than a few minutes each day to reduce the risk of photochemical damage.

A review done by Munsamy *et al.* (2022) aimed to examine the effects of digital blue light from LED displays on the eyes. It analyzed 37 peer-reviewed studies published over the last 25 years which were narrowed down to 5 main studies involving various electronic devices with LED displays, predominantly computer screens. Participant ages ranged from 18 to 55 years, with equitable gender representation. Three of the five accepted studies indirectly measured the effects of digital blue light using blue-blocking spectacle lenses. One study directly exposed participants to modified 3D videos with reduced blue light, and the fifth study was a review of existing research. Two studies explored the effects of digital blue light on critical flicker frequency (CFF).

CFF, also known as critical flicker fusion, is a measure used to assess the temporal resolution of the human visual system. It determines the highest frequency of flickering at which an individual can perceive a steady or continuous light, without perceiving any flicker or discontinuity. CFF tends to decrease when visual fatigue arises since the eyes become less tolerant of rapid flickering or changing light. It is measured by gradually increasing the flicker frequency of a light source until the individual can no longer perceive it as steady but instead perceives it as flickering.

Both studies demonstrated that blue-blocking spectacles reduced the decrease in CFF, implying that blocking short-wavelength light mitigates eye fatigue and visual discomfort related to digital blue light. Another study assessed digital blue light's impact on the near point of convergence (NPC), saccadic eye movements, and blink rate. It found that reducing blue light from videos led to a reduction in the change in NPC, suggesting that blue light may affect 3D content recognition. The study concluded that blocking short-wavelength blue light, such as with blue-blocking spectacles, alleviated visual discomfort and digital eye strain. However, the review identified a research gap, particularly the absence of in vivo studies on the exposure of digital blue light to the human retina, which is necessary to validate findings from animal studies that have found blue light to cause photochemical damage to the eyes.

Ultimately, this review offers insights into the impact of digital blue light on the human eye and vision, particularly in terms of visual discomfort and the potential advantages of blue-blocking spectacles. Nevertheless, it underscores the urgency for more research, particularly in vivo studies, to better understand how digital blue light affects the human retina.

2.2 Smartphone Blue Light Effects

In a study by Shi *et al* (2021) they measured visual fatigue after using 3 different types of smartphone screens (LCD, blue-shifted LCD, and OLED) using both subjective and objective testing methods. Among these were self-perception-based questionnaires in addition to electroencephalographs and other clinical parameters like distance visual acuity (BCDVA), critical flicker frequency (CFF), and tear break-up time (TBUT) all of which are related to visual fatigue. Visual acuity tests are conducted using a test sheet with letters of varying sizes in rows, the subject stands 20 feet away and reads the letter off row by row. A decrease in acuity can be linked to a fatiguing effect. Critical flicker frequency is tested using a machine to measure the point at which the eye perceives a “flicker” as a solid light. A smaller CFF typically is related to increased fatigue and decreased alertness due to impaired temporal sensory perception. Tear break-up time is measured by putting a sodium fluorescein dye into the eyes and observing how long it takes without blinking for dry spots to appear on the eyes. This is widely used as a test for dry eyes and so is a good indicator of a prominent visual fatigue symptom.

In the results they noted that LCD screens use liquid crystals that are lit up from behind to generate images on the display, blue shifted LCDs use similar technology with the crystals entering the blue phase which typically helps the display images at a higher frame rate. OLED screens on the other hand are composed of many individual organic materials that are directly lit by electricity to produce images. This means that LCDs are transmissive displays because they require an external light source to display an image while OLEDs are emissive because they light up independently. These differences in themselves present various factors that could affect visual fatigue such as contrast ratio and refresh rate. Blue-shifted LCDs are screens that have had their blue light output altered and for the purpose of this review will be compared to that of the LCD.

As controls for this study, all the screens were kept at the same viewing distance/angle, brightness, and color temperature. The spectral power distribution was evaluated for each screen. The SPD measures the amount of radiation emitted by a light source at each wavelength. They noted that these play a role in how we perceive colors via our photoreceptors since each receptor follows a different sensitivity curve. Each participant was given a questionnaire and had their ocular parameters measured four times in the experiment at 0, 30, 60, and 90 minutes during which three 30-minute videos were shown. The measurements were taken at the start of the first video and then at the end of each of the videos. In their results, they found that time increases fatigue consistently across all the screens. They found conflicting results between some of their survey questions regarding different types of perceived visual fatigue like dryness vs blurred vision. On the quantitative measurements, the CFF revealed that the LCD had the worst performance but in terms of the TBUT, the OLED exhibited the worst performance. These results showed good agreement with the results of the questionnaire.

Regarding the EEG, the blue-shifted LCD induced the least visual fatigue while the OLED caused the largest visual fatigue. Overall the symptoms for each of the three screens were graphed using the figure 2.1 below.

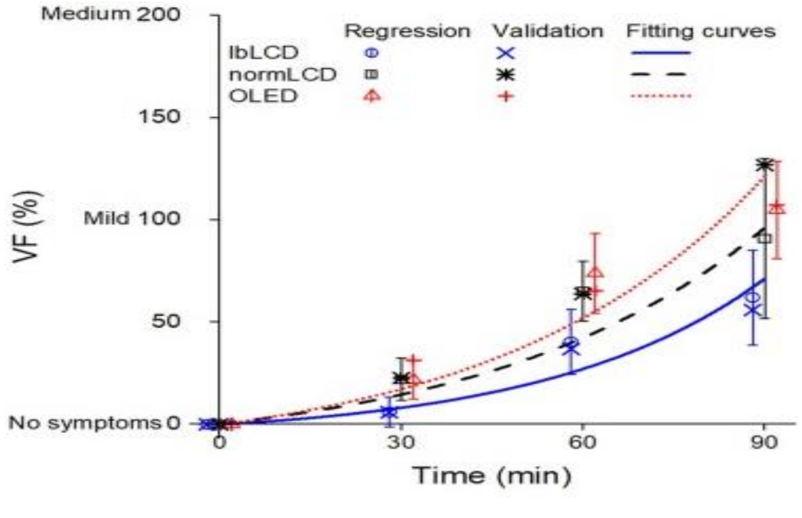


Figure 2.1 Visual Fatigue Symptoms vs Display Type.

Source: Shi *et al*, 2021

The study concluded that the spectral light distribution may be a possible explanation for the visual fatigue differences among the three smartphone displays. They suggest based on these results that a “light shift of the blue light peak toward a longer wavelength is recommended for reducing visual fatigue” (Shi *et al*, 2021). For further research on this subject, this study should consider the potential extra “flicker” that certain OLED smartphones sometimes have that could have skewed the results.

In the study by Chiu & Liu (2019) they analyzed the effects of blue light from three different smartphone configurations for their effects on task performance and visual fatigue. One with a thin film layer under the physical screen called “Eye Care blue light filter” and two digital software apps for restricting blue light at 60 and 80% respectively. The purpose of the Eye Care blue light filter is to maintain screen brightness and present good color contrast while filtering blue light. The software-based filters reduce the power intensity of light wavelengths which in turn makes the brightness lower while the Eye Care filter is supposed to shift the wavelengths themselves so that the blue light is actually slightly closer to standard green light wavelengths. For example, blue light wavelengths typically peak at about 455nm but with the Eye Care filter, it was closer to 480 nm.

They measured the visual acuity and color deficiency of participants using the Ishihara test and a basic visual acuity test before the test to ensure participants were representative of the average population. During the experiment, they had participants on smartphones play a “Find the Difference Game” in which two images with minor differences (different colors, missing object, etc) and watch 40 minutes of video while recording CFF, the performance of the game, and subjective questionnaires both at the beginning and end of each. CFF also referred to as the persistence of vision decreases in sensitivity as eye fatigue increases. The study found no significant differences with regard to fatigue for both objective and subjective tests. Instead, the primary factor for fatigue was the duration of the testing. The longer the testing went on the more fatigue was seemingly produced likely caused by a sustained use of the eye muscles and less blinking Results did however find notably better task performance results for those using the Eye Care filter likely due to differences in contrast and brightness which helped to identify differences in the “Find the Difference” game easier. This study provides a good basis for further research to be conducted on the differences between digital and physical blue light filtering methodologies.

Another study by Tu *et al* (2021) studied the different effects of visual fatigue on two smart displays, where one screen was a standard LCD and the other a blue-shifted LCD. The study had 10 participants who were asked to use a smartphone for two hours continuously in a dark room and had their visual fatigue measured using EEG, questionnaires, and ocular parameters such as CFF and TBUT. The figure below shows the SPD difference between the two displays.

The results showed that the use of a smartphone for two hours led to a significant increase in visual fatigue, as evidenced by results showing that the visual fatigue decreased when using a low-blue light display, reflected by subjective questionnaires, ocular results, and electroencephalograph signals.

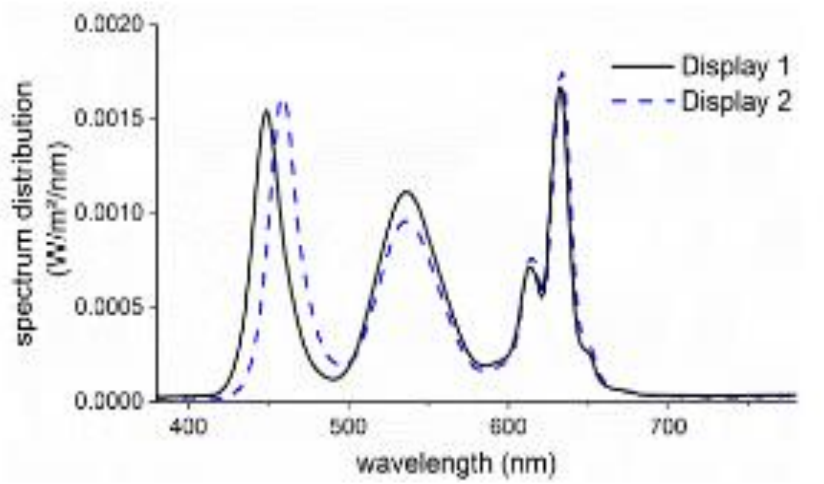


Figure 2.2 SPD of Regular LCD vs SPD of Blue Light Shifted LCD.

Source: Tu *et al.,* 2021

They also noted that the effects of blue light on visual fatigue were more significant in individuals who were younger and had better visual acuity. Below is a graph detailing the results of the subjective questionnaire.

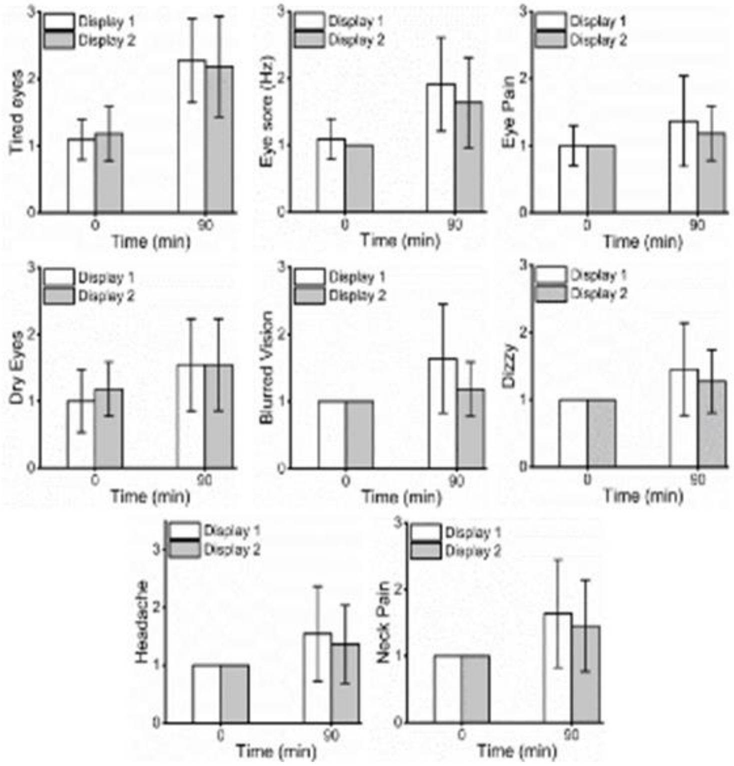


Figure 2.3 Subjective Visual Fatigue Survey Results.

Source: Tu *et al.*, 2021

They found in general that the blue-shifted LCD induced the least visual fatigue, with a shift of the blue light peak toward a longer wavelength reducing S-cone and ipRGC illuminances. OLEDs, with a large spectral component in medium and long wavelengths, caused the most visual fatigue. Objective parameters like CFF, TBUT, and EEG were more sensitive to display spectrum changes than subjective symptoms. The study proposed a visual fatigue evaluation model, emphasizing the importance of display spectrum in reducing visual fatigue. They suggest that younger individuals may be more susceptible to the effects of blue light due to their more active retina and more sensitive visual system. Additionally, the results indicate that the effects of blue light on visual fatigue were more significant when the participants used their smartphones in a dark room. The researchers suggest that the contrast between the bright smartphone screen and the darkroom may have increased the impact of blue light on visual function. The blue light-shifted display was recommended for reducing visual fatigue.

2.3 Computer Screen Blue Light Effects

In a study by Lin *et al* (2017), they investigated whether the utilization of short-wavelength-blocking eyeglasses could mitigate visual fatigue and decrease symptoms associated with visual discomfort in individuals engaged in computer tasks. The study involved 3 groups of participants. The no-block group wore eyeglasses with clear lenses, the low-blocking group wore eyeglasses with lenses that partially blocked short-wavelength light, and the high-blocking group wore eyeglasses with lenses that substantially blocked short-wavelength light. Below is a figure that shows the transmission % of blue light between the three groups.

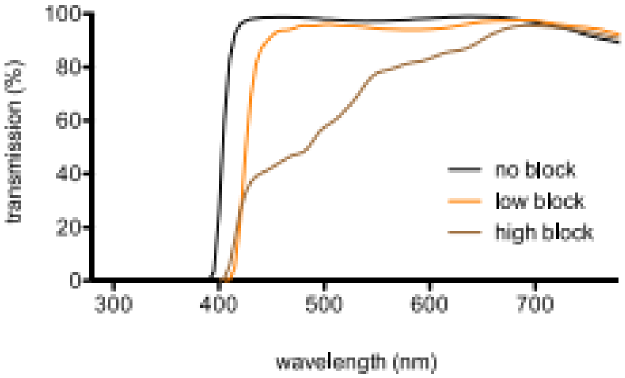


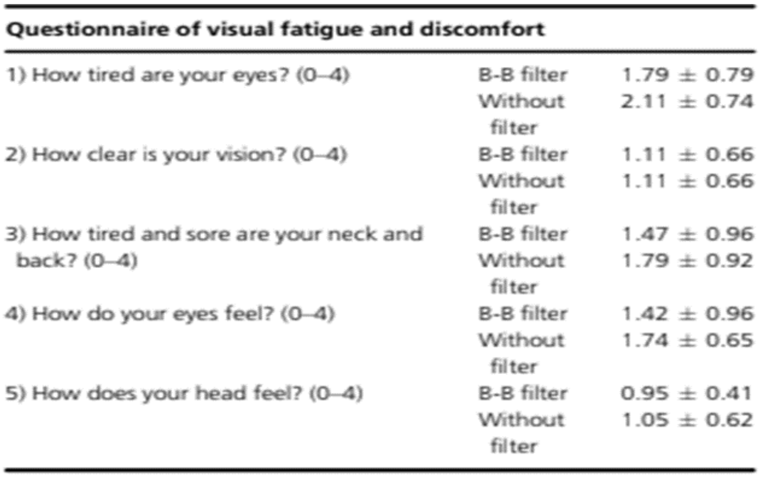
Figure 2.4 Wavelength Transmission Amongst Research Groups.

Source: Lin *et al*, 2017

All participants were instructed to perform a 2-hour computer task while wearing their assigned eyeglasses. The researchers assessed eye fatigue using critical flicker fusion frequency (CFF), a quantitative measure of eye fatigue. They also administered a 15-item questionnaire to evaluate symptoms of eye strain both before and after the computer task. The findings of the study indicated subjects in the high-blocking group showed a significantly more positive change in CFF after the computer task compared to those in the no-block and low-blocking groups. This positive change in CFF suggested reduced eye fatigue in the high-blocking group (Lin et al., 2017). Random assignment to the high-blocking group, but not the low-blocking group, was a predictor of a more positive change in CFF following the computer task. This suggests that high-blocking eyeglasses were effective in reducing eye fatigue. Subjects wearing high-blocking eyeglasses reported significantly fewer symptoms of pain around or inside the eye, less heaviness in the eyes, and less itchiness following the computer task compared to subjects not wearing high-blocking lenses. This supports the idea that such eyeglasses can alleviate specific symptoms associated with eye strain. The study's results strongly support the hypothesis that short-wavelength light-blocking eyeglasses can effectively reduce eye strain experienced during computer use. This conclusion is based on both quantitative physiological measurements (CFF) and subjective self-reports of symptoms typically associated with eye strain.

Another study by Redondo *et al* (2020) aimed to investigate the effects of blue light-blocking filters on the dynamics of the accommodative response and perceived visual discomfort in healthy young adults during a 30-minute reading task with computers. Accommodative dynamics is the ability of the eye's lens to change its shape and focal length to focus on objects at varying distances. This dynamic adjustment is necessary for clear vision at different distances, and it's controlled by the ciliary muscles within the eye and is relevant as a mechanism of visual fatigue. The study involved 19 participants who read from a computer screen with or without a blue light filter on separate days. The researchers assessed several factors, including the accommodative response, pupil dynamics, reading speed, and perceived levels of visual discomfort. They measured these factors at different time intervals during the reading task.

They found the use of blue light filters did not significantly affect the lag or variability of accommodation. Visual discomfort and fatigue, as assessed through a questionnaire, did not show significant differences between the blue light filter and non-filter conditions. Reading speed improved when using the blue light filter, with an increase of 16.5 words per minute. Below is a figure that shows blue light’s perceived effect on visual fatigue.



Questionnaire of visual fatigue and discomfort		
1) How tired are your eyes? (0–4)	B-B filter	1.79 ± 0.79
	Without filter	2.11 ± 0.74
2) How clear is your vision? (0–4)	B-B filter	1.11 ± 0.66
	Without filter	1.11 ± 0.66
3) How tired and sore are your neck and back? (0–4)	B-B filter	1.47 ± 0.96
	Without filter	1.79 ± 0.92
4) How do your eyes feel? (0–4)	B-B filter	1.42 ± 0.96
	Without filter	1.74 ± 0.65
5) How does your head feel? (0–4)	B-B filter	0.95 ± 0.41
	Without filter	1.05 ± 0.62

Figure 2.5 Questionnaire of visual fatigue and discomfort.

Source: Redondo *et al*, 2020

Ultimately the study found that while the testing done with blue light filter performed better on average it was not statistically significant for relieving fatigue. They concluded that the results did not find strong evidence supporting the use of blue light filters to alleviate visual discomfort or improve accommodative dynamics in healthy young adults using electronic devices. However, it did suggest that blue light filters could enhance productivity via reading speed. The study emphasizes the need for further research to establish a stronger link between blue light filters and the reduction of visual discomfort.

Another study by Hong-Ming Cheng *et al* (2014) investigated the effects of blue light filters on tear production and relief from Computer Vision Syndrome (CVS)-related symptoms in patients with prior dry eye symptoms compared to those without. Schirmer's test was used heavily throughout this study which is a diagnostic test used to measure the quantity of tears a person's eyes produce. It is primarily employed to assess tear production and diagnose conditions related to dry eyes or keratoconjunctivitis sicca. It works by using “Schirmer strips” which are thin, sterile paper strips that are typically marked with a scale in millimeters. They are gently inserted into the lower eyelid. The results are measured by looking at how far tears traveled. The longer the tears traveled along the strips, the more tears were produced during the test. Conversely, shorter wetting lengths may indicate reduced tear production, which could be associated with dry eye syndrome.

In the study dry eye participants with a baseline Schirmer's test measuring less than 10mm and a control group with normal Schirmer's test values participated in the study. The subjects had no other eye diseases and were tested for standard visual acuity. They sequentially wore blue light filter glasses of low, medium, and high densities for one week each. Schirmer's test and a questionnaire of graded ocular complaints were administered at the end of each week. Both normal and dry eye groups showed a tendency toward increasing Schirmer's test values with higher filter densities, although this change was not statistically significant in either group. Ocular complaint scores increased steadily in both groups with increasing filter densities. Dry eye patients reported significantly more comfortable and relaxed computer work with all filter densities, while this response was statistically insignificant in the normal group.

The study found that wearing blue light-blocking filters did not significantly affect tear production in either the normal or dry eye groups. However, the dry eye patients reported a clear improvement in CVS-related complaints. They suggest that perceived improvement in ocular comfort may result from reduced blue light irradiation, possibly decreasing irritation to nerve endings in desiccated corneas, and conclude that blue light filters may be helpful in improving the comfort of computer users with dry eyes.

2.4 Analysis of Literature Review

In summary, these studies and reviews offer valuable insights into the effects of blue light on the human eye and vision. While they provide evidence for the impact of blue light on visual fatigue and other eye-related factors, there are still questions and variations in findings that warrant further research. The use of blue light filters, both physical and software-based, shows potential benefits, with many of the studies showing positive impacts on fatigue and productivity across various factors and testing methods .The long-term effects of digital blue light exposure remain an area of ongoing investigation and of course, a definitive mechanism of action for how blue light may be causing this visual fatigue and or damage are still important questions to be answered. A meta-analysis table of the previously discussed literature is shown on Table 2.1 on the next page.

Table 2.1 Meta-Analysis of Recent Studies On The Blue Light Effects of Smartphone And Computer Displays

Author	n	Screen type	Technology tested	Visual task	Testing Used	Factors Measured	Results
Shi *et al* (2021)	10	Smart phone	LCD, OLED and LCD with physical filter overlay	90-min video watching task	CFF machine, questionnaire, Snellen test, sodium fluorescein dye, EEG	CFF, perceived eye fatigue, visual acuity, tear breakup, brain activity	The blue light filter has significant positive fatigue effect
Chiu & Liu (2019)	36	Smart phone	Software 60 and 80% filters, and physical filter overlay	Smartphone game for 40 min	CFF machine, game scores, questionnaire	CFF, game performance, perceived eye fatigue	The blue light filter had no significant effect on fatigue but did help productivity
Tu *et al* (2021)	10	Smart phone	LCD and LCD with physical filter	Video clips of a documentary 30 min	CFF, TBUT, EEG, questionnaires	CFF, Tear break up, brain activity, perceived eye fatigue	The blue light filter has significant positive fatigue effect
Lin *et al* (2017)	36	Computer	Filter eyeglasses, no filter	2 hours to view videos or to engage in games	CFF machine, questionnaire	CFF, perceived eye fatigue	The blue light filter has significant positive fatigue effect for across all factors
Redondo *et al* (2020)	19	Computer	Physical filter overlay, no filter overlay	Read 30-min passages	Autorefractometer, questionnaire	Accommodative dynamics, pupil size, reading speed and perceived eye fatigue	The blue light filter had no significant effect on fatigue but did help productivity
Cheng *et al* (2014)	40	Computer	Low, medium, high density filter eyeglasses	Each filter was worn for one week for two hours of daily computer work	Schirmer's test, questionnaire	Tear production, perceived discomfort feedback	The blue light filters had no significant effect on objective measurements but did improve dry eye patients perceived comfort

The meta-analysis table summarizes findings from various studies assessing the effects of blue light exposure from smartphones and computers on factors such as visual fatigue, productivity, and eye health. Notably, studies by Tu *et al*. 2021, and Lin *et al*. 2017 involving smartphones and computers, respectively, found that blue light filters, both physical and software-based, had a significant positive effect on reducing visual fatigue. Chiu & Liu (2019) reported that while smartphone blue light filters had no significant impact on fatigue, they did enhance productivity. Redondo *et al*. (2020) observed that computer blue light filters did not significantly affect fatigue but positively influenced productivity. Cheng et al. 2014 noted that blue light filters had no significant impact on objective measures but improved the perceived comfort of individuals with dry eyes. The results underscore the varying effects of blue light filters, emphasizing the need for nuanced considerations in optimizing digital workstations for user comfort and health.

Many of these studies have several limitations, including small sample sizes, lack of access to specialized equipment, and the lack of reliable in vivo research on humans and obviously long-term effects research given how new much of the technology is. There was also inconsistency amongst certain areas of these studies, which should be studied further and compared cumulatively to yield a higher level of repeatability and consensus. There are also several variables to control for research like this including ambient light, screen type/size, viewing distance, screen angle/curvature, time of day during testing, and prior visual acuity/health issues. The most important factor to consider for blue light's effects on visual health would be the long-term effect since the potential photochemical damage likely occurs over time in small increments that eventually accumulate to something like macular degeneration similar to how most musculoskeletal diseases are caused by long term accumulated trauma rather than any individual event.

CHAPTER 3

A PILOT STUDY ON BLUE LIGHT EFFECTS ON FATIGUE/PRODUCTIVITY

3.1 Method of Experiment

The pilot study was conducted with six participants of good visual health all of whom were college students in their twenties. They each played two computer games. Similar games were used in previous studies (Chiu & Liu, 2019) that are easy to play but induce strong metal and visual efforts. Game #1 was “Spot the Difference Game” which shows two similar pictures side by side with minor changes found within an image and its text.

ROUND 1: 01:49 Help! ROUND SCORE: 540 GAME SCORE: 0

BEYOND THE NUMBERS BLS
U.S. BUREAU OF LABOR STATISTICS
FEBRUARY 2013 • VOLUME 2/ NUMBER 5
PRICES AND SPENDING

Expenditures of urban and rural households in 2011

Author: William Hawk, Consumer Expenditure Program

The United States is a nation of great diversity. Large houses and big red barns are found on the open farmlands of the Midwest while apartments and coffee shops occupy the corners of busy city streets. The varying landscapes shape the lives, customs, and spending habits of Americans. Using data from the Bureau of Labor Statistics Consumer Expenditure Survey (CE), this **BEYOND** THE **NUMBERS** article examines demographic characteristics and spending habits of urban and rural households in the United States in 2011. In total, approximately 92 percent of households were urban and 8 percent were rural.[1] The following data highlight important differences between consumer expenditures by rural and urban households in 2011:

- Urban households spent $7,808 (18 percent) more than rural households.
- Urban households received $15,779 (32 percent) more in yearly income than rural households.[2]

Related articles

More BLS articles and information related to consumer expenditures are available online at the following links:

- “Consumer expenditures in different-sized cities,” *Monthly Labor Review*, **http://www.bls.gov/mlr/1989/12/art6full.pdf**.
- Consumer Expenditure Survey: Geography, **http://www.bls.gov/cex/csxgeography.htm**.
- “Expenditures of urban and rural consumers, 1972-73 to 1985,” *Monthly Labor Review*, **http://www.bls.gov/opub/mlr/1988/03/rpt1full.pdf**.

U.S. BUREAU OF LABOR STATISTICS | FEBRUARY 2013 1 www.bls.gov

BEYOND THE NUMBERS BLS
LABOR STATISTICS
FEBRUARY 2013 • VOLUME 2/ NUMBER 5
PRICES AND SPENDING

Expenditures of rural and urban households in 2011

Author: William Hawk, Consumer Expenditure Program

The United States is a nation of great diversity. Large houses and big red barns are found on the open farmlands of the Midwest while apartments and coffee shops occupy the corners of busy city streets. The varying landscapes shape the lives, customs, and spending habits of Americans. Using data from the Bureau of Labor Statistics Consumer Expenditure Survey (CE), this Beyond the Numbers article examines demographic characteristics and spending habits of urban and rural households in the United States in 2011. In total, approximately 92 percent of households were urban and 8 percent were rural.[1] The following data highlight important differences between consumer expenditures by rural and urban households in 2011:

- Urban households spent $7,808 (18 percent) more than rural households.
- Urban households received $15,779 (32 percent) more in yearly income than rural households.[2]

Related articles

More BLS articles and information related to consumer expenditures are available online at the following links:

- “Consumer expenditures in different-sized cities,” *Monthly Labor Review*, **http://www.bls.gov/mlr/1989/12/art6full.pdf**.
- Consumer Expenditure Survey: Geography, **http://www.bls.gov/cex/csxgeography.htm**.
- “Expenditures of urban and rural consumers, *Monthly Labor Review Monthly Labor Review* 1972-73 to 1985,” dsa Consumer Expenditure Survey: Geography,

U.S. BUREAU OF LABOR STATISTICS | FEBRUARY 2013 1 www.bls.gov

Figure 3.1 BLS “Spot the difference game” Sample.

Source: Bureau of Labor Statistics, 2023

There are several sets of different pictures and texts with the same difficulty level that changed randomly for each trail. The participants played a different “spot the difference” game in each of the experimental trials. Each round has a built-in score that helps to measure accuracy and productivity. The participants were instructed to attempt for the highest possible score. However, the score was not used for the measurement of the effect of blue light   The game can be found on the Bureau of Labor Statistics (2023).

Game #2 was reading a “pseudo-text” comprised of 800 randomized characters presented on the screen which contained a known number of the letter “A”.

KGfvdUNogxvv4QqLoFZQ
mpcLOmcvw1yirCqLgFFI
CixpnBmC1f9unRUAuhS1
kW3Gr03rJTCnYwamLSxD
C3luCj1c1UEYg4maSiiq
wHhtEVNTcDQzW9mf91Jn
gXDT2DTHaBhziABBapMa
5W0Em1C2zIYeCyIFsECs
DrgQSsr4iFyciP39Ax5s
byJCpUp71VuTqiyDWFwc
k0485DtSe6aAy1cAJ7QW
RUemLjKpdEAhWIFhSOdx
s2YhZa0o4sJu1GdACFTT
EY1ecqVWb76OIVyehRf7
HApVOkiZYQU1Mq6LdIB8
bMXMoG5y3TNEt1iPRkLz
JkvCGLwGTIEpvEIqyhXI
BYjDkSQFyb72fghk5fJr
QWYnMq1o9TUUvks4UHcF
r4TUNFf894eAqx104anC
KGfvdUNogxvv4QqLoFZQ
mpcLOmcvw1yirCqLgFFI
CixpnBmC1f9unRUAuhS1
kW3Gr03rJTCnYwamLSxD
C3luCj1c1UEYg4maSiiq
wHhtEVNTcDQzW9mf91Jn
gXDT2DTHaBhziABBapMa
5W0Em1C2zIYeCyIFsECs
DrgQSsr4iFyciP39Ax5s
byJCpUp71VuTqiyDWFwc
k0485DtSe6aAy1cAJ7QW
RUemLjKpdEAhWIFhSOdx
s2YhZa0o4sJu1GdACFTT
EY1ecqVWb76OIVyehRf7
HApVOkiZYQU1Mq6LdIB8
bMXMoG5y3TNEt1iPRkLz
JkvCGLwGTIEpvEIqyhXI
BYjDkSQFyb72fghk5fJr
QWYnMq1o9TUUvks4UHcF
r4TUNFf894eAqx104anC

Figure 3.2 Sample random collection of character presented in the Pseudo-text game.

The participant's task was to find these A's. A timer was used to track how fast the task was completed and the participants were instructed to complete the takes as fast as they can.

In the study, participants played the game three times. One for the standard screen with no filter, one for a standard screen with 90% blue light filtering eyeglasses, and one for a digital blue light filter software set to the 90% filter (Microsoft Night Light). Microsoft Night Light is a feature built into Windows OS that reduces the amount of blue light emitted by a computer screen by adjusting the color temperature to reduce the power intensity of blue light waves. The eyeglasses use specialized lens materials that absorb or block a certain amount of blue light, in this pilot study a pair from Zenni Optical Blokz line was used.

A questionnaire was prepared based on a previous study (Kim *et al*, 2017) and included questions on perceived symptoms of tired eyes, sore eyes, aching eyes, dry eyes, eye glowing, ghosting, blurred vision, and headache. Participants rated each symptom on a 10-point scale with one meaning no symptoms and ten being extreme. Before starting the experimental session, a questionnaire was issued to record the baseline eye fatigue ratings, and then after each experimental trial, it was given again to measure the change in eye fatigue ratings.

Controlled parameters for this experiment included the Strix ROG laptop computer with a screen size of 18 inches which was set to the same resolution (1080p) for every test run. The participant sat on an adjustable-height office chair and the laptop was placed on an adjustable-height table. The table and the chair height were adjusted to the preference of the participant. The viewing distance was controlled for the recommended 12-32”, and color calibration of the laptop screen was done before each participant was tested and the brightness was set to 100%. The ambient light conditions were also measured and kept consistent at 470 lux with the aid of a lux meter from Urceri. The order of the experimental trials was randomized. Participants practiced both games before the experimental trails, to negate any learning curve effect. Participants were also given adequate rest of five minutes in between tests to avoid the effects of cumulative fatigue. Overall testing took about 90 minutes to complete for each participant.

3.2 Results

The baseline ratings of eye fatigue levels of participants were recorded before they started the experimental trials. These baseline ratings were subtracted from the post-test eye fatigue ratings for each subject to obtain the change in eye fatigue ratings from the visual tasks with no filter, with a physical filter, and with a digital filter. The results from the pilot testing found changes in four symptoms: tired eyes, sore eyes, dry eyes, and blurred vision. The average ratings are provided in Figures 3.3 and 3.4.

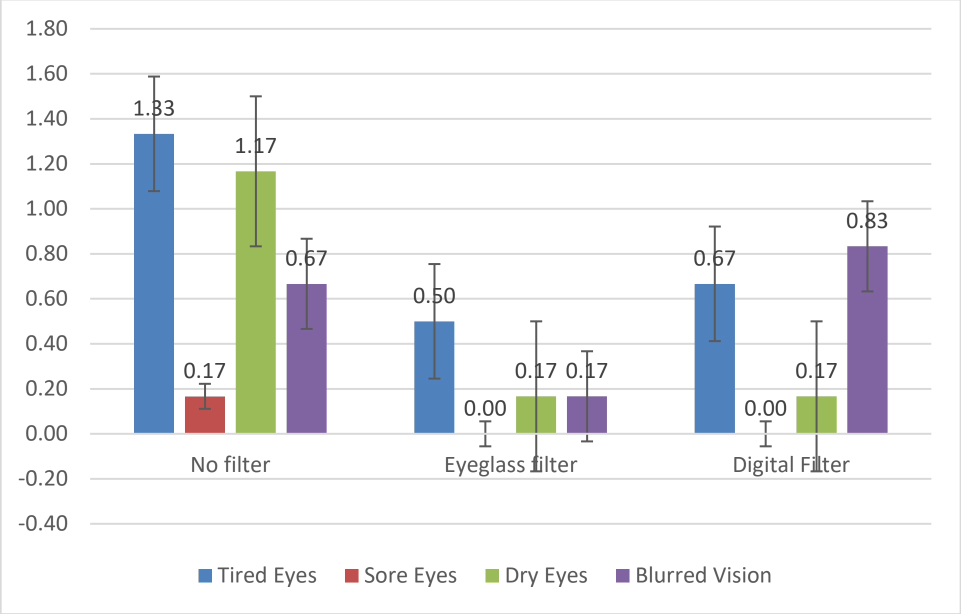


Figure 3.3. The average change in symptom ratings after playing the “Spot the Difference” game.

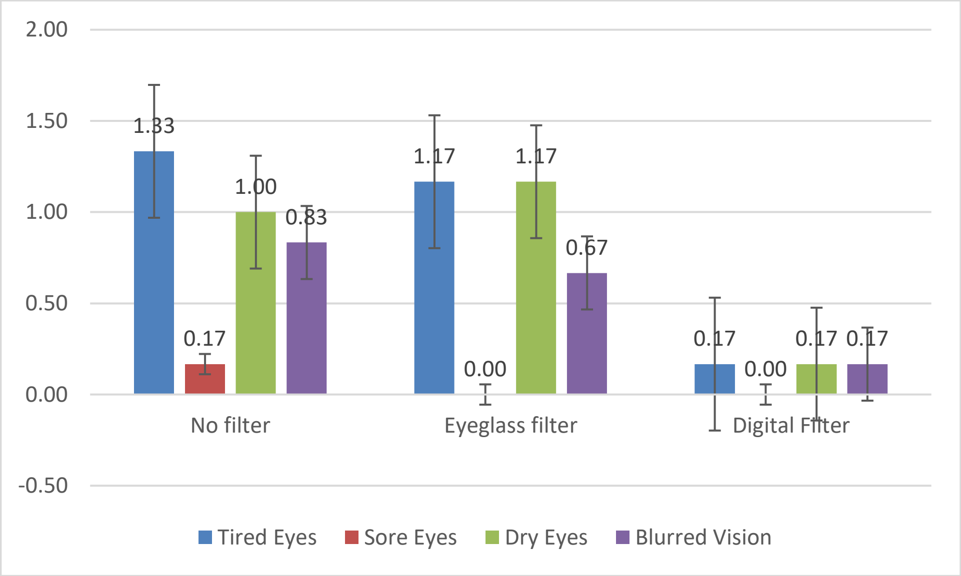


Figure 3.4. The average change in symptom ratings after playing the “Pseudo-text” game.

The fatigue ratings of symptoms were small, with most not changing much, however, average symptom ratings for tired eyes and dry eyes saw an increase of up to 1.33 and 1.17, respectively. The results showed that both types of filters produced lower ratings of eye fatigue symptoms as compared to no-filter trails. For Spot the Difference game, the physical filter performed better with lesser eye fatigue symptom ratings than the no-filter. As opposed to that, in the Pseudo-text game, the digital filter caused lesser symptom ratings. Overall, the no-filter tests induced the most perceived fatiguing ratings, with the digital and physical filters showing improvement for some symptoms.

Table 3.1 Comparison of Fatigue Ratings with No Filter, Eyeglass Filter, And Digital Filter Responses

	Spot the Difference game			Pseudo Text game		
Tired eye	No filter Mean (sd)	Eyeglass filter Mean (sd)	Digital filter Mean (sd)	No filter Mean (sd)	Eyeglass filter Mean (sd)	Digital filter Mean (sd)
	1.33 (1.51)	0.50 (0.84)	0.67 (1.21)	1.33 (0.82)	1.17 (1.47)	0.17 (2.23)
	P-value from no-filter	**0.02**	**0.01**		0.31	**0.03**
	P-value between the two filters	0.18			**0.02**	
Dry eye	No filter Mean (sd)	Eyeglass filter Mean (sd)	Digital filter Mean (sd)	No filter Mean (sd)	Eyeglass filter Mean (sd)	Digital filter Mean (sd)
	1.17 (0.75)	0.17 (0.41)	0.17 (0.41)	1.00 (1.10)	1.17 (1.72)	0.17 (0.75)
	P-value from no-filter	**0.04**	**0.01**		0.42	**0.05**
	P-value between the two filters	0.50			0.09	

Note: Significant difference (*P*-values <0.05) in means by paired *t*-test with is bolded

A paired t-test revealed a statistically significant reduction in mean symptom ratings for “Tired Eye” and “Dry Eye” when blue light filters were used (Table 3.1). The use of a digital filter reduced tired eye and dry eye symptoms significantly (p-value < 0.05) for both the Spot the Difference game and the Pseudo-text game. The eyeglass filter reduced tired eye and dry eye symptoms significantly (p-value < 0.05) for the Spot the Difference game, however, the reduction was not significant for the Pseudo text game. When comparing the effects of two types of filters, digital filter produced significantly (p-value < 0.05) reduced tired eye symptom ratings only for the Pseudo-Text game.

3.3 Comparison of Pilot Study

The results from the pilot study suggest a statistically significant improvement for those using blue light filter technologies which is in line with much of the current literature. While the literature review offered a comprehensive exploration of existing knowledge and trends, the pilot study provided a more focused investigation into the immediate effects of blue light exposure during a specific task and analyzed the differences between several filter technologies. The pilot study certainly helps to reinforce the potential implementation of blue light blocking technologies in the workplace.

The combination of both approaches contributes to a more nuanced and practical understanding of the potential implications of artificial blue light exposure, further emphasizing the need for ongoing research to bridge existing gaps and inform comprehensive guidelines for optimizing digital workstations through the potential implementation of blue light filtering technology.

CHAPTER 4

CONCLUSION

In conclusion, this study aimed to investigate the effects of artificial blue light exposure on health, productivity, and visual fatigue in the context of digital display workstations. The literature review and meta-analysis explored existing studies, methodologies, and findings related to blue light exposure and its potential consequences. The pilot study, involving six participants, compared software-based filters to physical filters, revealing nuanced changes in symptoms. Overall, the findings suggest that physical and software-based blue light filters may positively impact reducing visual fatigue and improving task performance, particularly for individuals with dry eyes.

For workplace modifications, recommendations include implementing blue light filters, especially those shifting the blue light peak toward longer wavelengths, to reduce visual fatigue. The choice of display technology, such as OLED versus LCD screens, can also impact visual fatigue. Various factors like ambient light, screen type, viewing distance, and individual health issues should be considered. While blue light filters show promise in alleviating visual discomfort, ongoing research is necessary to establish a comprehensive understanding of the impact of blue light on visual health, especially in the long term.

Concerns about potential photochemical damage from prolonged blue light exposure, as raised in studies like that of Tu et al. (2021), underscore the need for ongoing research to establish guidelines and safeguards. Given the widespread use of digital devices and the cumulative effects of blue light exposure, addressing concerns about photochemical damage is crucial for individuals immersed in digital environments. In summary, while the literature review and pilot study provide valuable insights, further research is needed to address the complexities of blue light exposure and its potential long-term impact on eye health, productivity, and overall well-being. The urgency to optimize digital workstations to mitigate risks associated with artificial blue light exposure adds significance to the broader conversation about digital environment safety.

REFERENCES

Bangor, Aaron. “Display Technology and Ambient Illumination Influences on Visual ...” *VTechWorks*, 2000, vtechworks.lib.vt.edu/bitstream/handle/10919/26376/vfatigue.pdf.

Bullough, John D. “The Blue-Light Hazard: A Review.” *Journal of the Illuminating Engineering Society*, vol. 29, no. 2, 2000, pp. 6–14, https://doi.org/10.1080/00994480.2000.10748312.

Cheng, Hong-Ming, et al. *Does Blue Light Filter Improve Computer Vision Syndrome in Patients with Dry Eye?* , Life Science Journal, 2014, www.lifesciencesite.com/lsj/life1106/094_A00291life110614_612_615.pdf.

Chiu, Hsiao-Ping, and Chien-Hsiou Liu. “The effects of three blue light filter conditions for smartphones on visual fatigue and visual performance.” *Human Factors and Ergonomics in Manufacturing & Service Industries*, vol. 30, no. 1, 2019, pp. 83–90, https://doi.org/10.1002/hfm.20824.

Demers, Cedric, and Adriana Wiszniewska. “TV Size to Distance Calculator and Science.” *RTINGS.com*, 12 Mar. 2021, https://www.rtings.com/tv/reviews/by-size/size-to-distance-relationship#the

Der-Song Lee, Ya-Hsien Ko, I-Hsuan Shen, Chih-Yu Chao, Effect of light source, ambient illumination, character size and interline spacing on visual performance and visual fatigue with electronic paper displays, Displays, (2019) https://doi.org/10.1016/j.displa.2010.09.001.

EEG and fNIRS for the detection of sleep-deprivation-induced fatigue and Its inhibition

Eyesafe. “What Is Blue Light From Digital Devices? Is It Harmful for Eyes?” Eyesafe, 31 Jan. 2023, eyesafe.com/bluelight.

Fadzil, N. F., & Othman, S. A. (2021). Interrelation between Qai’lullah, Blue Light Exposure and Neurocognitive Performances: A Short Review. Journal of Quality and Scientific Research, 5(1), 1-6. Retrieved from

from Smartphone on Visual Fatigue. Sustainable Development and Technology, https://sid.onlinelibrary.wiley.com/doi/abs/10.1002/sdtp.14396

https://publisher.uthm.edu.my/ojs/index.php/jqsr/article/download/9104/30

Iskander, J., Hossny, M., & Nahavandi, S. (2018). A review on ocular biomechanic models for assessing visual fatigue in virtual reality. IEEE Access, 6, 19345-19361. J. E. Sheedy (2007) The physiology of eyestrain, Journal of Modern Optics, 54:9, 1333-1341, DOI: 10.1080/09500340600855460

K. Sakamoto, S. Aoyama, S. Asahara, K. Yamashita and A. Okada, "Evaluation of viewing distance vs. TV size on visual fatigue in a home viewing environment," 2009 Digest of Technical Papers International Conference on Consumer Electronics, Las Vegas, NV, USA, 2009, pp. 1-2, doi: 10.1109/ICCE.2009.5012190.

Kim, Dong Ju, et al. “Visual fatigue induced by viewing a tablet computer with a high-resolution display.” Korean Journal of Ophthalmology, vol. 31, no. 5, 2017, p. 388, https://doi.org/10.3341/kjo.2016.0095.-science-behind-our-tv-size-and-distance-calculator.

Kyung, G., & Park, S. (2021). Curved Versus Flat Monitors: Interactive Effects of Display Curvature Radius and Display Size on Visual Search Performance and Visual Fatigue. Human Factors, 63(7), 1182–1195. https://doi.org/10.1177/0018720820922717

Lim, K, Li, X, Tu, Y. Effect of moving pictures on visual task performance and fatigue using 4K OLED and LCD TVs. *J Soc Inf Display*. 2020; 28: 177–183. https://doi.org/10.1002/jsid.841

Lin, Jonathan B., et al. “Short-wavelength light-blocking eyeglasses attenuate symptoms of eye fatigue.” Investigative Opthalmology &amp; Visual Science, vol. 58, no. 1, 2017, p. 442, https://doi.org/10.1167/iovs.16-20663.

Megaw, E. D. (1995). “The definition and measurement of visual fatigue.” In J. R. Wilson and E. N. Corlett (Eds.). Evaluation of Human Work: Second Edition (pp. 840-863). London: Taylor and Francis, Ltd.

Munsamy, A. J., Moodley, M., Khan, Z., Govender, K., Nkwanyana, M., Cele, S., & Radebe, M. (2022). Evidence on the effects of digital blue light on the eye: A scoping review. African Vision and Eye Health, 81(1), 9. https://doi.org/10.4102/aveh.v81i1.685.

PN Youssef, N Sheibani and DM Albert, “Retinal light toxicity.” *Eye*, vol. 25, no. 1, 2011, pp. 1–14, https://doi.org/10.1038/eye.2011.149.

Redondo, Beatriz, et al. “Effects of a blue-blocking screen filter on accommodative accuracy and visual discomfort.” Ophthalmic and Physiological Optics, vol. 40, no. 6, 2020, pp. 790–800, https://doi.org/10.1111/opo.12738.

Rehman I, Mahabadi N, Ali T. Anatomy, Head and Neck, Eye Ciliary Muscles. [Updated 2022 Aug 8]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2023 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK482132/

Sánchez López de Nava A, Somani AN, Salini B. Physiology, Vision. [Updated `Publishing; 2023 Jan-. https://www.ncbi.nlm.nih.gov/books/NBK538493/

Shi, Yunyang, Yan Tu, Lili Wang, Yin Zhang, Yuning Zhang, et al. “Spectral influence of the normal LCD, blue-shifted LCD, and OLED smartphone displays on visual fatigue: A comparative study.” *Displays*, vol. 69, 2021, p. 102066, https://doi.org/10.1016/j.displa.2021.102066.

Shoaib, Z., Akbar, A., Kim, E., Kamran, M. A., Kim, J. H., & Jeong, M. (2023). Utilizing

Tu, Y., Shi, Y., Wang, L., Zhang, Y., & Yang, Y. (2021). Invited Paper: Influence of Blue Light using colored light stimulation. Scientific Reports, 13(1), 1-12.

U.S. Bureau of Labor Statistics, 2023, “BLS, Classroom Games & Quizzes Spot the Difference.” www.bls.gov/k12/games/spot-the-difference/. Accessed 15 Nov. 2023.

Wong, Nikita A., and Hamed Bahmani. “A review of the current state of research on artificial blue light safety as it applies to digital devices.” *Heliyon*, vol. 8, no. 8, 2022, https://doi.org/10.1016/j.heliyon.2022.e10282.

Yang Chaopu, Fang Wenqing, Tang Jiancheng, Yang Fan, Liu Yanfeng, and Li Chun, "Change of blue light hazard and circadian effect of LED backlight displayer with color temperature and age," Opt. Express 26, 27021-27032 (2018)

Zhi-Chun Zhao, Ying Zhou, Gang Tan,/et al. Research progress about the effect and prevention of blue light on eyes. Int J Ophthalmol 2018;11(12):1999-2003 https://doi.org/10.18240/ijo.2018.12.20.