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Article

Blue Light of the Digital Era: A Comparative Study of Devices

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Abstract: The prevalence of digital devices in modern society has raised concerns about the potential negative effects of blue light emissions on eye health and biological rhythms. Research into blue light emissions from digital devices and their potential impact on eye health emphasizes the importance of understanding and quantifying the extent and scope of blue light emissions produced by commonly used screens (smartphones, tablets and computers). This comparative study specifically evaluates three popular Apple devices: iPhone 12 mini®, iPad Pro 12.9® and MacBook Pro®. The devices' spectral power was measured using a spectroradiometer while displaying text and a game at different brightness levels. The study also examines the effectiveness of blue-blocking lenses from well-known brands. The research highlights the importance of quantifying blue light emissions and understanding their potential impact on eye health. By doing so, appropriate measures can be developed to mitigate adverse effects on ocular structures. Above all, this research provides valuable information about the risks associated with exposure to blue light, showing that all tested devices have blue wavelength peaks between 445 nm and 455 nm. By recognizing and addressing the potential negative impacts of blue light, the risks of eye health problems can be reduced and ensure more responsible and conscious use of digital devices.

Keywords: blue light; blue-blocking lens; computer; digital devices emission; ocular health smartphone; tablet

1. Introduction

Growing evidence suggests that the use of blue light-emitting digital devices can interfere with human tissue at the level of biological ocular structures [1,2]. We all have some knowledge about the effects of UV exposure, the variety of sunscreens to protect our skin and sunglasses to protect our eyes. But most ultraviolet light is absorbed by the structures in front of the eye (cornea and lens) and most does not pass through to the retina. This is a key difference between UV light and blue light - blue light passes through the sensitive tissues of the human eye [3].

Publications on blue light emitted by digital devices state that the risk of blue light from these digital and similar devices with prolonged exposure is below safe viewing limits, therefore blue light should not cause acute harm [4]. However chronic exposure over a lifetime can have a cumulative, long-term degenerative impact, which should continue to be discussed [5]. New data and new devices should be update.

Brightness, color, pattern and time of exposure to light can interfere and alter cellular functions. Most current devices are frequently used at night for many hours and can negatively affect users' sleep and eyes [6–9].

Not all wavelengths corresponding to different colors have the same effect on human eyes. There is evidence showing the probability of greater impact of light with a wavelength up to 495 nm, where many older devices have been shown to have peaks, specifically at these wavelengths [10].

Digital devices have replaced paper and other non-digital formats and have also changed traditional low-intensity and reflected lighting. However, these new ways of viewing have very different light ranges, naturally with biological effects on users. This problem is significant when we observe that, across Europe, 51% of all devices are desktops, followed by smartphones with 46% and the use of mobile data in Europe has increased by 569% since 2016 [11].

Digital devices with Internet access still have several possibilities of use, such as access to browsers, online games, social networks or digital books, with evidence in the performance of several of these tasks, alternately, at the same time.

Until the end of the 20th century, most light measurement studies quantified light stimuli in Lux, the photopic illuminance unit. The most frequent resource was the luxmeter, due to its easy access and because it is a very popular device to measure lighting and photography. However, this measurement method was not sufficient to provide complete data [12]. This experimental work arises with the need to measure, register and update data referring to the daily use of digital devices, quantifying their illuminance and irradiance values.

2. Objectives

Considering background references [1–10], this new experimental work proposes the light measurement, or more precisely, obtaining the spectral profile of three contemporary devices that are widely used daily. In particular, it was decided to include three categories of devices: a tablet, a smartphone and a laptop computer. Comparative tests were carried out between the three devices' categories using a text and a game display.

The visible blue light hazard was defined by the CIE/IEC (62778:2014). Known as human photopic photoreceptor responses, namely, S cones (λ=420 nm), M cones (λ=530 nm) and L cones (λ=560 nm), the danger of exposure to blue light occurs in the 420 nm which corresponds to the maximum absorption of A2E. This isomer (A2E: λ_{max}=338 nm), is the unique constituent of retinal pigment epithelial cells [13]. The exposure would cause changes in the retinal pigment epithelium and the death of photoreceptor cells [14].

With the objective of obtaining data to analyze the risk factors, the spectral profile of each category in the automatic adjustment was analyzed. Later, we analyzed the same sources with blue light blocking lenses from Carl Zeiss, Shamir, Hoya and Novacel. Knowing the response peak for each of the five photopigments in the human eye [15], the purpose of this experimental work was to provide reliable reference data for each device, comparing them with each other and extrapolating these data for eventual complementary studies.

As mentioned before, we set out to measure the irradiance and spectral profiles of three of the most popular and contemporary devices to compare their emissions. Some of the frequent uses of these devices are reading or playing a game. We measure and compare the light output of the same screens with the game and with the text.

Since the devices have screen lighting conditions, we tried to test the real effect of these adjustments on the spectral profile using two strategies:

1. Acquisition of emission from light-emitting screens, in automatic mode (without manually interfering in the brightness or intensity settings of the devices).
2. Using the same methodology, lenses from the brands Carl Zeiss, Shamir, Hoya and Novacel were placed on the device-optic fiber interface, all currently available with blue blocking.

3. Materials and Methods

Three categories of the most popular brand of devices in 2022 (iPad Pro®, iPhone 12 mini®, Macbook Pro®) were chosen, according to ICD [16,17]. The data for each device were obtained from the manufacturer's technical specifications and the light measurements were acquired at a distance from the source as close as possible, starting from zero. The characteristics of the devices can be consulted in Table 1.

Table 1. Digital devices characteristics.

	Macbook Pro 13* (2019)	iPad Pro* (A2378)	iPhone 12 mini* (A2399)

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Diagonal (inch/cm)	13.3/33.8	12.9/32.8	5.4/13.7
Technology	OLED IPS (In-plane switching)		
Pixels by inch	227	264	476

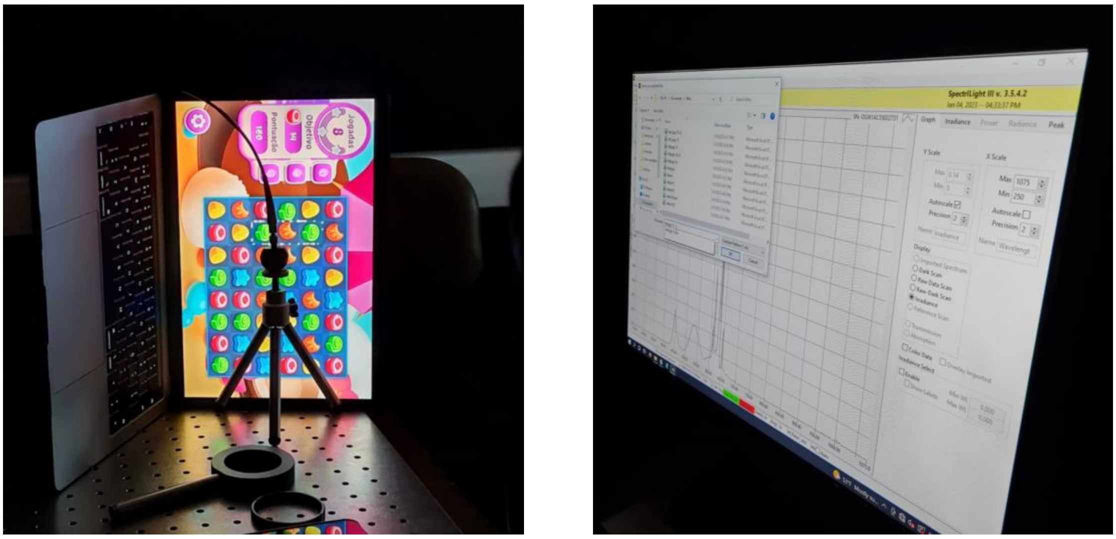
* Macbook Pro, iPad Pro and iPhone 12 mini are registered trademarks of Apple Inc.

Any of the selected devices can be used at night in an unlit, completely darkened room. For this reason, the first measurements were carried out in a room without lighting and the brightness levels were not adjusted, leaving all devices with the configuration in automatic mode. For each device, the illuminance and irradiance were measured with the respective exact spectral power distribution (SPD) with the calibrated spectroradiometer (SpectraLight III, ILT 950, International Light Technologies, Inc., Peabody, USA). The setup and measurement output are shown in Figure 1.

Regarding the first strategy mentioned in section 2, the measurements used similar images on all devices, both for the text (Figure 2) and for the popular game (Figure 3), while the illuminance and irradiance measurements were recorded with the spectroradiometer.

In the second strategy, we tested blue-blocking lenses, all with the same refractive index (n=1.5), with a neutral refractive power (P=00.00D) and with the following commercial names: Blue Guard® (Carl Zeiss), Blue Zero® (Shamir), Blue Control® (Hoya) and Blue Clear® (Novacel). Each lens was placed between the device tested and the spectroradiometer, and the first strategy measurements were repeated using the same protocol, but at this time with blue light blocking lenses between the different sources and the spectroradiometer.

The evaluated lenses' manufacturers advertise the blocking of potentially harmful light, blue violet light, up to around 40%. They have little disagreement each other on what percentages of blue light should be transmitted. By absorbing the percentage of blue from 400 nm to 455 nm, lenses maintain high transparency above 455 nm and manufacturers refer to this important factor related to the circadian rhythm. [18–21]



(a) (b)

Figure 1. (a) Image of the measurement setup with spectroradiometer (SpectrlLight III, ILT 950) suported by a tripod in front of the screen of a laptop, and the support used for the tested blocking lens (on botton); (b) example of the output of the spectroradiometer.

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Figure 2. Text presented on all devices.

Figure 3. Game image presented on all devices.

4. Results

Figures 4 and 5 show the emission spectrum of the 3 categories of devices, comparing them with each other. All devices showed very similar enhanced short wavelength blue peaks when displaying the same text (445 nm – 455 nm). The spectral profile of the game Candy Crush® was also very similar; the text emissions, however, showed greater intensity.

The first strategy measurements were repeated using the same protocol, but at this time with blue light blocking lenses between the different sources and the spectroradiometer. All blue blocking tested lenses have reduced short-wavelength light emissions for the smartphone category (Figure 6), for the tablet category (Figure 7) and for the computer category (Figure 8).

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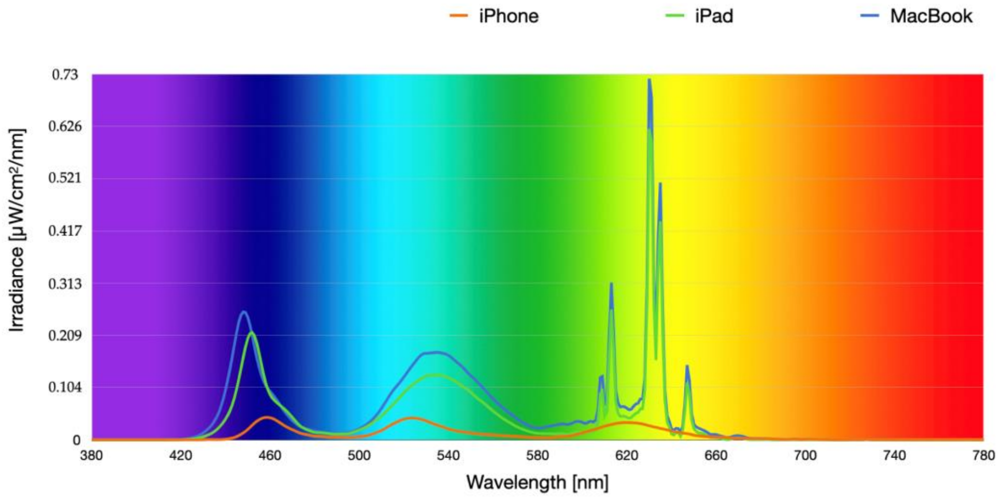

Figure 4. Comparison of the spectral profile between devices with a text display.

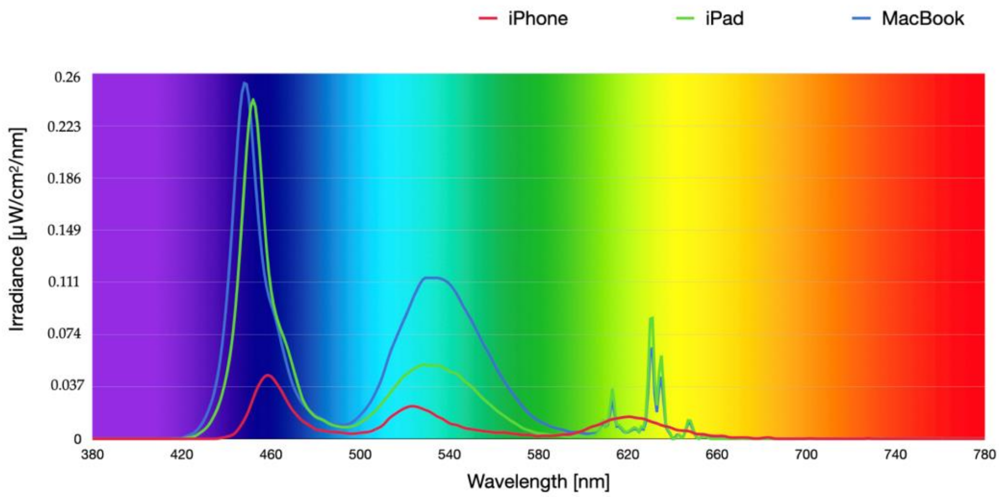

Figure 5. Comparison of spectral profile between devices with game display (Candy Crush*). *Candy Crush is a registered trademark of King Digital Entertainment Plc.

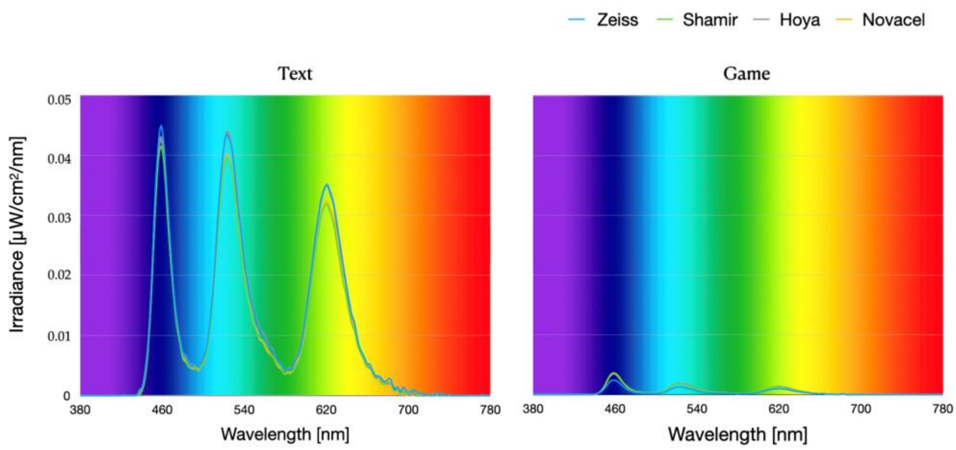

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Figure 6. iPhone 12 mini spectral profile with the blue blocking lens for both text and game displays.

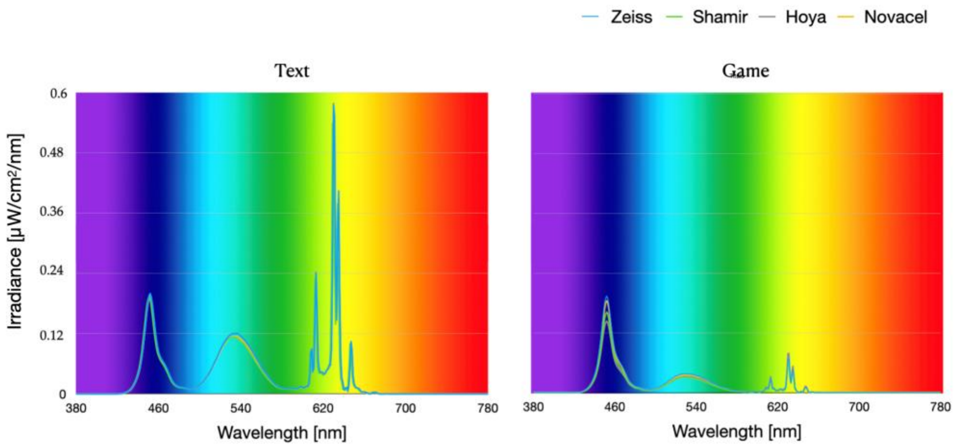

Figure 7. iPad Pro spectral profile with blue blocking lens.

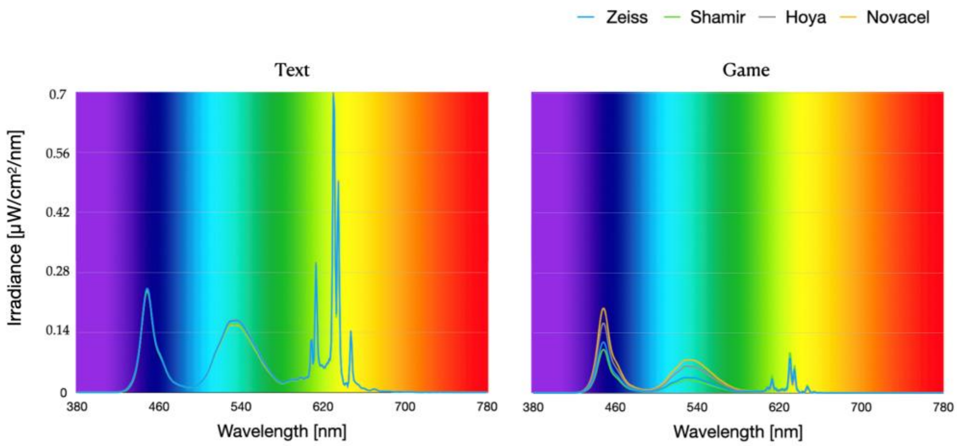

Figure 8. Macbook Pro spectral profile with blue blocking lens for both text and game displays.

Blue blocking lenses selectively reduce light at short wavelengths transmission, but do not interfere with medium and long wavelengths transmission, and this selective blocking can reduce the contrast of some objects.

The generation to which the tested lenses belong was designed to limit exposure to harmful blue light and it showed to be effective in doing so. However, its use may have some undesirable effects such as changes in color perception [22] and reduced contrast [23].

Finally, the irradiance for each of the five photopigments of the human eye, is presented according to the values of the International Commission on Illumination (CIE), for the two measurements: the text and the game (Figure 6). The spectral distribution for each human retinal photoreceptor, its irradiance and illuminance, the spectral peaks in the several emitting devices can be easily quantified and compared, for the two proposed display conditions (Figures 9 and 10).

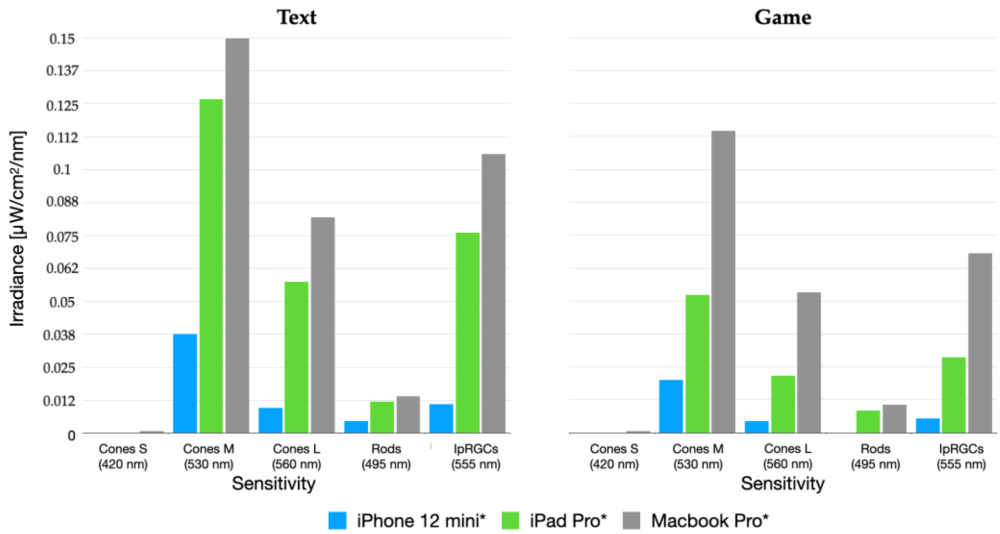

Figure 9. Measured spectral devices distribution for human retinal photoreceptors for both text and game displays.

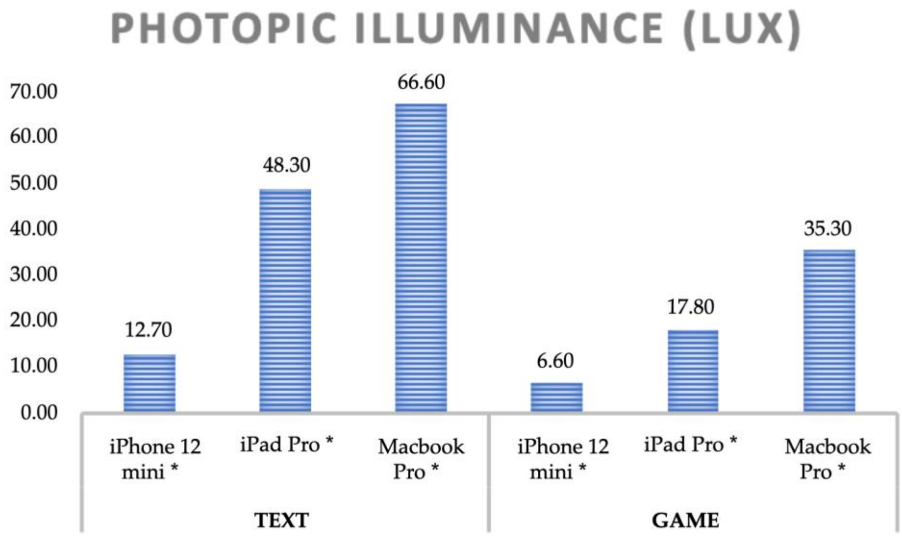

Figure 10. Photopic illuminance of digital devices with text and game display. *Macbook Pro, iPad Pro and iPhone 12 mini are registered trademarks of Apple Inc. ** Candy Crush is a registered trademark of King Digital Entertainment Plc.

Melanopsin, the structural photopigment of ipRGC cells, is more closely related to non-image photoreceptor opsins than to rod and cone opsins [24]. Melanopsin phototransduction depends on irradiance, a fundamental light response of ipRGCs, even at low light levels, requiring only 1 lux or less to suppress melatonin in humans [25].

The efficiency of melanopsin is comparable to that of rod and cone opsins. However, melanopsin photoreception is much less sensitive than that of rods or cones [26]. This stimulus combination causes circadian and neurophysiological responses into non-image forming responses to light [27,28].

Physiological responses to light signal are defined by the melanopsin-driven phototransduction mechanism of ipRGC and rods and cones. Each of these light detection mechanisms has a distinct spectral sensitivity. Rhodopsin is the rod photopigment with peak sensitivity (λ_{max}) at 495 nm in all mammalian species. Cones have distinct spectra. The cyanolable, S-cone opsin, has sensitive peaks to wavelengths up to 420 nm, the M cones contain chlorolabe, with a peak sensitivity of 530 nm and the L cones a red-sensitive opsin (erythrolable), with a maximum peak 560 nm [29].

Blue light range is between 380 nm and 495 nm and can be essentially divided into two ranges: blue-violet light (380 nm - 455 nm) and turquoise light (455 nm - 495 nm). Turquoise blue light helps maintain and regulate memory, cognition, humor and hormonal balance and synchronize our biological rhythms (the circadian cycle), but blue-violet light can pose a potential risk to the eyes of digital device users [30]. Thus, the spectral profiles of blue light were measured in the different categories of digital devices with the presentation of the text and the game (Figure 11).

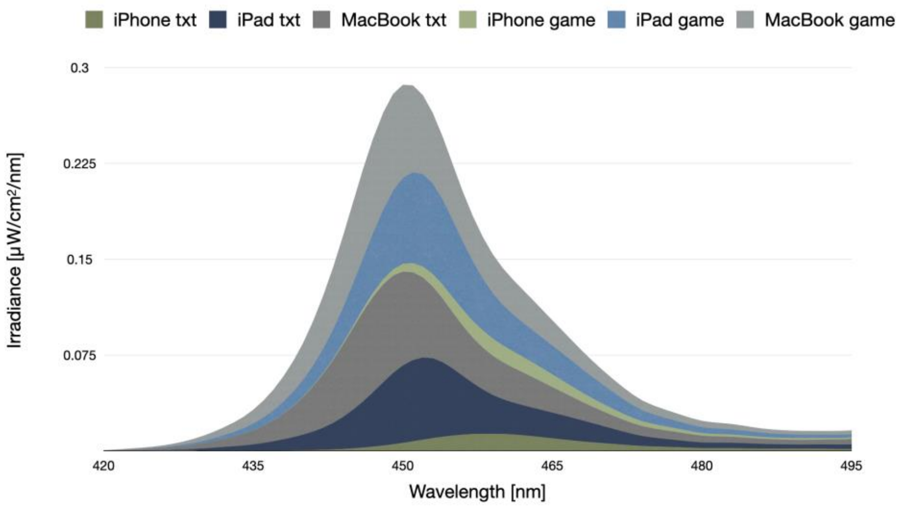

Figure 11. Spectral blue light profile comparing text and game screen across three categories of digital devices.

To provide data on the impact and negative risks for ocular and visual health and the environment, the International Commission on Non-Ionizing Radiation Protection (ICNIRP), affirms the absence of risks in the use of LED devices that form RG0 (no risk) and RG1 (low risk) [31]. However, consecutive and cumulative exposure to digital devices can lead to potential long-term sequelae, raising a question: could exposure even with low irradiance, but during daily periods, throughout life, be harmful to ocular health?

5. Analysis

We can see the spectral emission data obtained from the three categories of devices in Figure 9. It shows that they all have peaks, in the blue wavelength, very similar for the text and for the game display (445 nm – 455 nm). However, the spectral profile in the text display revealed greater intensity than in the game display. The tested ophthalmic lenses slightly reduced blue wavelength light emissions. In the text, the emission peaks in the blue range, at 450 nm, went from 0.03 µW/cm²/nm on the iPhone®, from 0.22 µW/cm²/nm on the iPad Pro® and from 0.21 µW/cm²/nm on the Macbook Pro® to an average value of all tested lenses of 0.02 µW/cm²/nm, 0.19 µW/cm²/nm and 0.20 µW/cm²/nm, respectively. On the game display, the emission peaks in the blue range, at 450 nm, went from 0.02 µW/cm²/nm on the iphone®, from 0.23 µW/cm²/nm on the iPad Pro® and from 0.24 on the Macbook Pro®, to an average of all tested lenses of 0.015 µW/cm²/nm, 0.15 µW/cm²/nm and 0.13 µW/cm²/nm, respectively (Figures 3–8).

Background evidence are divided regarding the effectiveness of blue light blocking lenses. While some say that ophthalmic lenses can be a resource and have been shown to effectively attenuate blue light exposure, impacting circadian rhythm and photoreceptor function [32], others state they find no evidence to support the use of blue light blocking lenses, to improve visual performance, sleep

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quality, alleviate eye strain, or maintain macular health [29]. However, we can state that lenses have been shown to effectively attenuate the spectral emission of blue light, although this selective blocking of light may have consequences for visual function and color perception. Therefore, blue light blocking lenses may have advantages despite altering the images appearance during use. They also decrease digital devices' lighting, causing changes on the images display on the screen, but reducing the intensity of blue light. Tested lenses are not expected to cause significant changes in daytime conditions but may slightly affect performance in conditions where the overall luminance is considerably lower.

It is necessary to consider the blue light saturation in ocular structures and extrapolate from research results. To date, modeling studies have provided information on possible long-term effects of repeated exposure to artificial blue light, but further experimental research will be needed to add knowledge in this area.

In our opinion it would be of the utmost importance for research to establish a standard approach in measuring and recording the light sources characteristics. The potential long-term effects of artificial blue light exposure will be better understood with a quantification of light exposure and consequent indexes of ocular health, circadian function and other metrics of interest. We believe the impact of blue light on ocular structures is not an isolated phenomenon and a multidisciplinary approach can contribute to improve research on the safety of artificial blue light and digital devices.

The prolonged exposure to blue light implications and the quick pace of technological developments can affect many physiological processes with numerous implications beyond the digital device safety. Therefore, good practices are recommended in using digital devices rich in blue light, such as moderate use or interruption of use at night.

As the contribution of light, peaking at 555 nm (non-visual) becomes clearer, it is also important to understand how changing the spectral composition of light can affect its therapeutic effects. New insights into artificial blue light may support safer and more effective light therapy and prevention practices. The effort to understand and study the safety of artificial blue light, its potential risks, but also the benefits must be encouraged.

6. Discussion

Three current devices were tested in the tablet, smartphone and laptop categories. The effects of reading stimuli and, above all, games on registered digital devices show significant differences between the spectral profile of the text and the game tested, both in terms of irradiance and illuminance values.

The evaluated blue light blocking lenses effectively reduced the emission of enriched light with a wavelength at around 450 nm. The reduction of the spectrum emitted in the Blue Light Hazard (BLH) ranges is in accordance with what was announced by the manufacturers of the tested ophthalmic lenses. The BLH highlights the risks of blue radiation for each wavelength between 390 nm to 500 nm. Based on in vitro and in vivo studies, it calculates the risk of damage from wavelengths along the blue radiation spectrum. However, according to the CIE International Commission on Illumination, BLH is not based on common artificial light sources such as LEDs or digital devices and is not particularly relevant for lenses that block blue radiation or for determining eye hazards from radiation, digital or artificial blue.

Digital devices' producers presented new models of digital devices with a frequency that far exceeds the time taken to carry out experimental work and publish new research. This fact compromises the current studies that evaluate the hardware right at the time of publication. Despite these limitations, the tendency of new devices enhances the definition of screens, increasing brightness and contrast in daytime use. These daytime characteristics are the same as nighttime use, which can interfere with sleep quality and with some ocular structures. Human retina is adapted for both photopic and color vision due to the fovea. This area of the retina has a high density of photoreceptors, the cones. It is on the fovea that the light, coming from digital equipment, focus after passing through the optical means, namely the cornea and the lens, as shown in Figure 12.

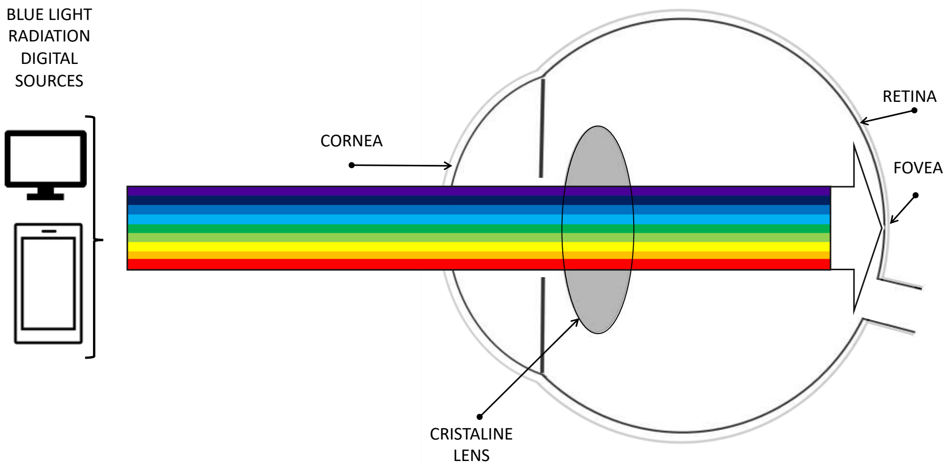

Figure 12. Digital devices short-wavelength blue-violet light emitted, passing through the cornea and crystalline lens, reaching the fovea in the retina.

These photoreceptor cells of three types, S, M and L cones, respond to short, medium and long wavelengths, with an unique photopigment with absorption peaks at 420, 530 and 560 nm, respectively [33,34]. A 1971 study mentions the spectral sensitivity of ipRGCs cells, non-visual photopic with a photopic peak of 555 nm. This is a pioneer publication with electrophysiological recordings of human RGCs [35].

Although the European Scientific Committee on Health, Environmental and Emerging Risks states that there is no evidence of risk under normal conditions of use, cumulative exposure to digital devices can lead to long-term changes. Daily exposure to blue light throughout life can be harmful. Despite the available information regarding the use of digital devices and its associated risks, it is very difficult to indicate to users the best choices for their health. However, it is evident that recent technological advances in devices have emphasized features that improve their brightness, blue light output, visibility and contrast in daylight conditions. These features that improve usability during the day can have harmful effects when used at night, interfering with the quality of sleep and potentially affecting different ocular structures. The blue light emission by digital devices and their safety in use is still just a hypothesis and, therefore, this topic generates controversy and no consensus in the scientific community.

In order to carry out future research and experimental work in this area of study, it is essential to have consistency in the units to prevent the comparison of experimental conditions. It is agreed that to measure blue light, illuminance has the units of lux, luminance cd/m^2 or irradiance W/m^2, to characterize light sources. Frequently, the details of the light sources are not known in the publications and the respective units cannot be converted.

A faster and more sustainable solution may lie in technological advances and concerns about the irradiance and illuminance of new devices. A better image does not necessarily mean a brighter one.

7. Conclusions

In contemporary life, artificially light is a reality. However, of all available sources, blue light emitting digital devices are the only ones we look at directly and at length. We spend more and more time exposed to these digital devices, professionally and for leisure, and therefore it is relevant trying to understand the impact of blue light on our well-being and visual health. It is generally accepted that low luminance artificial blue light such as in digital devices does not have an acute impact on the eyes, but there is not enough qualitative and quantitative research to conclude how blue light from these devices can effectively affect our eyes in the long run.

This research results quantify the devices emissions and, with the existing data, we can state that blue light levels should not significantly affect ocular health, at least without considering prolonged exposure. However, it is necessary to integrate new data, with new studies, in order to assess the safety of new technological developments and potential risks for the future using these devices in daily life. Efectivelly, this study has the following limitations:

- Only one Apple device per category was tested, leaving devices with the Android operating system, Windows, Symbian OS, Bada, MeeGo, among others, to be tested.
- The contribution of environmental factors was not considered, knowing that the spectral emission of these devices is not the only factor of interaction with ocular structures.
- Some users of these devices (Macbook, iPad and iPhone) can manually adjust the light intensity or invert the colors. Thus, the results are only applicable to users using auto/default lighting settings.
- The exposure time to these sources is another important factor, not considered, in the cellular photoexcitation of human eyes.
- Technological development and the consequent emergence of new devices is faster than the analysis time, data interpretation and eventual publication of new research. It obviously results in technological outdatedness at the time of publication.
- The saturation time of ocular structures for each device and the intensity is not known, but it is an important area for future research.
- Only automatic configuration for each device with a text and a game was tested.

Despite the lack of agreement in literature, we believe that reducing direct exposure to blue light, whether by reducing the number of hours per day or using ophthalmic lenses that block blue light, can be an advantage for all users. Tested and commercially available lenses effectively attenuate blue light exposure, particularly at short wavelengths responsible for interfering with the circadian rhythm and the functional activity of photoreceptors (cones) [22].

As research continues to create new strategies to understand the real influences of artificial blue light, it will be important to consider not only the possible consequences of technological development and evolution on human health, but also new forms of technological performance with benefits for the users' wellbeing.

Author Contributions: Conceptualization, J.M.P.C.; methodology, V.H.; formal analysis, V.H. and J.M.P.C.; investigation, V.H. and J.M.P.C.; writing—original draft preparation, V.H.; writing—review and editing, V.H. and J.M.P.C.; supervision, V.H. and J.M.P.C.; project administration, V.H. and J.M.P.C.; funding acquisition, J.M.P.C. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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