Ocular Tolerance of Contemporary Electronic Display Devices

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ABSTRACT: Electronic displays have become an integral part of life in the developed world since the revolution of mobile computing a decade ago. With the release of multiple consumer-grade virtual reality (VR) and augmented reality (AR) products in the past 2 years utilizing head-mounted displays (HMDs), as well as the development of low-cost, smartphone-based HMDs, the ability to intimately interact with electronic screens is greater than ever. VR/AR HMDs also place the display at much closer ocular proximity than traditional electronic devices while also isolating the user from the ambient environment to create a "closed" system between the user's eyes and the display. Whether the increased interaction with these devices places the user's retina at higher risk of damage is currently unclear. Herein, the authors review the discovery of photochemical damage of the retina from visible light as well as summarize relevant clinical and preclinical data regarding the influence of modern display devices on retinal health. Multiple preclinical studies have been performed with modern light-emitting diode technology demonstrating damage to the retina at modest exposure levels, particularly from blue-light wavelengths. Unfortunately, high-quality in-human studies are lacking, and the small clinical investigations performed to date have failed to keep pace with the rapid evolutions in display technology. Clinical investigations assessing the effect of HMDs on human retinal function are also yet to be performed. From the available data, modern consumer electronic displays do not appear to pose any acute risk to vision with average use; however, future studies with well-defined clinical outcomes and illuminance metrics are needed to better understand the long-term risks of cumulative exposure to electronic displays in general and with "closed" VR/AR HMDs in particular.

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INTRODUCTION

Consumers of contemporary electronic devices have increased interactive exposure to electronic computer displays today more than ever before in the form of smartphones, handheld computer tablets, laptop and desktop computers, and televisions (Table 1). These devices are ubiquitous in practically every aspect of our daily lives in the developed world. Computer display technology has undergone a revolution in recent years with the advent and adoption of new display modalities, such as light-emitting diode (LED) and active-matrix light-emitting diode (AMOLED) type displays that are often integrated into the aforementioned devices. These new display technologies have provided for miniaturization and portability of computing displays. Although most of these innovations have resulted in the computer display terminal remaining still at essentially "arm's-length" from the user's eyes, new advances in virtual reality (VR) systems have brought those displays much closer — within the range of 3 mm to 12 mm.[1-3] Indeed, VR head-mounted displays (HMDs) represent the cutting edge of such technologies, made possible by significant progress in electronic miniaturization, computer graphics, and said display technology. VR HMDs are goggle-like devices that position display(s) directly in front of the user's eyes to simulate a three-

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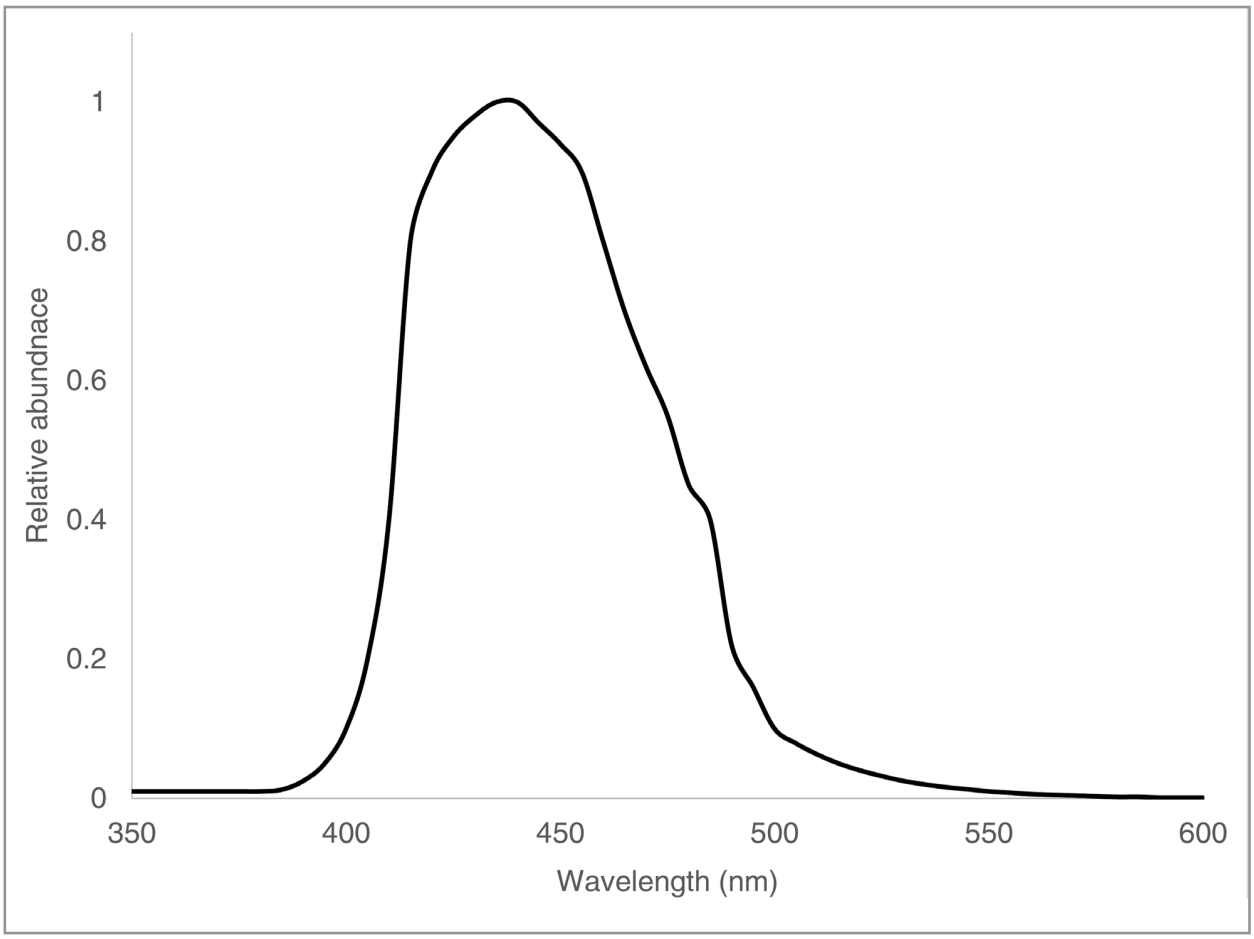

Figure 1. Blue light hazard function describes the relative risk of retinal toxicity based on wavelength of visible light. The retina is most sensitive to photochemical damage when exposed to wavelengths between 430 nm and 470 nm.

dimensional visual environment, with each eye receiving an independent video image. Augmented reality (AR) HMDs operate similarly by blending virtual elements captured by video camera of the real world (collectively referred to as "VR/AR" hereafter) with data tags, geolocation data, and additional information from computing databases that can enhance the traditional visual information received from the camera alone.

GROWTH OF VR/AR AND USE IN MEDICINE

The industry for VR/AR HMDs has seen huge growth in the past several years since the arrival of the newest generation of affordable devices for the typical home consumer, including the Oculus Rift (Oculus, Menlo Park, CA), which many have come to closely associate with VR technology itself (Note: Although generally avoided, in the present review, we use the brand names of exemplar consumer electronic devices and manufacturer names to provide clarity for the reader). Oculus Rift was purchased by Facebook (Menlo Park, CA) for $3 billion in 2014,[4] whereas other companies began to develop their own devices such as the Gear VR (Samsung, Seoul, South Korea), Vive (HTC, New Taipei City, Taiwan), PlayStation VR (Sony, Minato, Tokyo, Japan), and HoloLens (Microsoft, Redmond, WA), among many others. It is predicted that VR will grow from a billion-dollar industry in 2016[5] to between $80 billion and $150 billion within the next 10 years.[6] It is important to note that most VR HMDs available today only officially launched to consumers in the past year, reflecting both their novelty and unexplored potential.

Advances in VR/AR capability and commercial availability have spurred great interest in VR/AR's potential uses in various fields, beginning with gaming and extending to education, medicine, and even medical education. For example, it was determined that a VR HMD like Oculus Rift could be worn by patients in order to emulate tasks for effective clini-

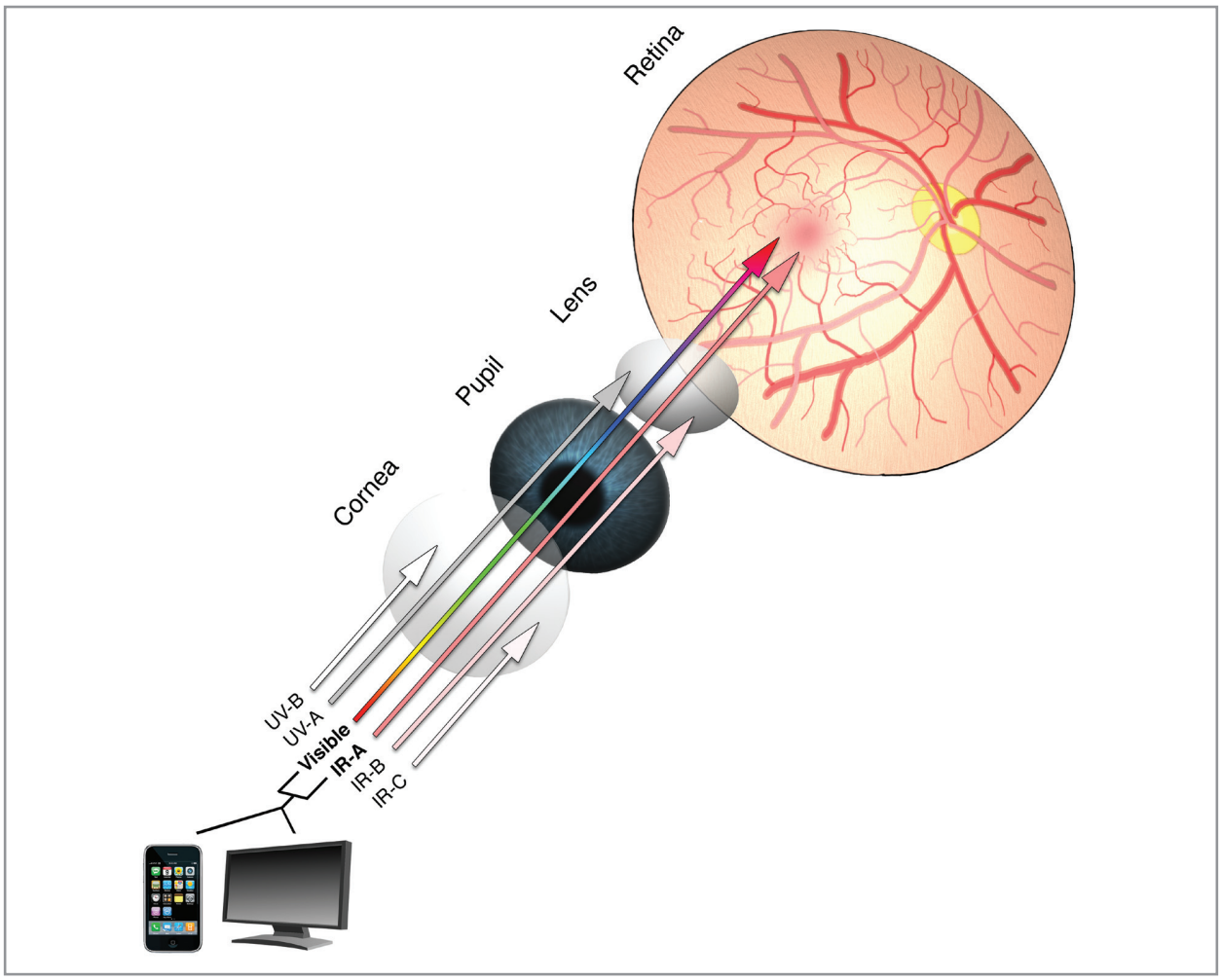

Figure 2. Light irradiation and ocular anatomy. Wavelengths produced by consumer electronics (visible and infrared [IR]-A) are transmitted through the anterior segment to the retina, whereas ultraviolet and longer IR bands are absorbed by the cornea and crystalline lens.

cal diagnosis of Parkinson's disease,[7] and that VR HMDs provided standardized visual testing conditions for reliable and reproducible evaluation of visual and neurologic disorders.[8] The use of VR HMDs in medical training has become a burgeoning field of research, with a number of recent studies highlighting how AR and VR could be used in enhancing residency training, simulation, and providing real-time intraoperative information across a variety of surgical subspecialties.[9-13]

LIGHT EFFECT OF VR/AR HMDS AND OTHER COMMONLY USED CONSUMER ELECTRONIC DISPLAY DEVICES

Damage to the retina caused by light is a well-established phenomenon, first critically analyzed by Noell et al. in 1966.[14] Although the mechanisms and consequences of light toxicity have since been further elucidated, there exists a dearth of information in how current display technologies, including smartphones and VR/AR HMDs, can affect the health of our eyes. Manufacturers do not regularly publish detailed specifications regarding light produced by devices. Instead, said information can be found through third-party companies like DisplayMate, which performs extensive technical evaluations of the newest smartphone devices and the display technologies used within. In the scope of this review, this information has proven useful in that types of displays used in smartphones are analogous and sometimes equivalent to those used in VR/AR HMDs.[15] It is the purpose of this review to summarize how retinal light toxicity can occur and to identify how these mechanisms presented in the current literature may correlate with how the light produced by novel display modalities can affect the retina.

TABLE 1

Approximate Spectral Peaks of Common Consumer Electronic Displays

Device Category	Example (Release Year)	Display Type	Approximate Spectral Peaks (nm)	Maximum Luminance (cd/m^2)
Television	Mitsubishi 1772ie (1999)	CRT	450, 530, 630*	176
	Samsung UN65JS9500 (2015)	LCD	455, 530, 640	419
	Sony PFM-42V1 (2003)	Plasma	450, 545, 625*	212
	LG 65EG9600 (2015)	OLED	460, 550, 610	433
Computer Display	Acer AL1712 (2009)	LCD	490, 545, 610*	300
	Microsoft Surface Pro 4 (2015)	LCD	460, 540, 610	436
Smart Phone	Apple iPhone 7 (2016)	LCD	450, 530, 630	705
	Samsung Galaxy S8 (2017)	OLED	460, 525, 630	1020
	HTC One (2013)	LCD	450, 530, 610	491
Tablet	Apple iPad Pro (2015)	LCD	450, 530, 630	511
	Galaxy Tab S 10.5 (2014)	OLED	465, 530, 620	518
	Galaxy Note 3 (2013)	OLED	460, 525, 615	660
	Kindle Fire HDX 7 (2013)	LCD	450, 550, 610	494
Smart Watch	Apple Watch (2015)	OLED	N/A	482
	Samsung Gear 2 (2014)	AMOLED	N/A	415
HMD	Oculus Rift (2016)^	OLED	N/A	N/A
	HTC Vive (2016)	OLED	N/A	N/A
	Playstation VR (2016)	OLED	N/A	N/A

Although all the spectral peaks for each of the listed displays fall within the visible light spectrum, all of these devices contain a spectral peak that is very near the violet / indigo / blue portion of the visible spectrum (380 nm to 500 nm).

** indicates data shown from Reference No. 66. All other data found from corresponding device webpage on DisplayMate.[68]*

^Of note, display in Oculus Rift Development Kit 2 (2014) is the same as that of Samsung Galaxy Note 3.[15]

N/A = no publically available measurements; HMD = head-mounted display; LCD = liquid-crystal display; CRT = cathode ray tube; LED = light-emitting diode; OLED = organic light-emitting diode; AMOLED = active-matrix light-emitting diode

BRIEF REVIEW OF LIGHT TOXICITY

There are already a multitude of excellent reviews of retinal light toxicity existing in the literature, including those by Lanum[16] in 1978, Wu et al.[17] in 2006, Youssef et al.[18] in 2011, and Contín et al.[19] in 2016. We will focus briefly on the major findings of selected landmark studies and identify important points.

It is important to note that the specific biochemical pathways by which retinal cells sustain damage upon exposure to light (eg, apoptosis, oxidative stress, and inflammation), although not contained within the scope of this review, are still being actively researched and delineated.[20-32]

Beginning with the seminal work performed by Noell et al. in 1966, the mechanisms and consequences of light damage to the retina have been studied extensively (Table 2). Noell et al. first discovered the "surprising effect" of continuous exposure of low-intensity fluorescent light on the retina of albino rats that was reported to cause irreversible damage to the photoreceptor cell layer and retinal pigment epithelium (RPE) on light microscopy.[14] In this study, rats were exposed to 2,040 foot-lamberts of light (converted to 6,989 cd/m^2) at an intensity of approximately 1,200 lux to 2,500 lux. It was thus hypothesized that light at an intensity lower than that which causes thermal or mechanical injury actually results in photochemical damage to the retina. Subsequently, Kuwabara and Gorn exposed albino rats to continuous light at 750 foot-candles (converted to 8,072 lux or 2,569 cd/m^2) and saw that initial reversible damage to the outer segments of photoreceptor cells progressed to irreversible damage to photoreceptor cells after 1 week on electron microscopy.[33] O'Steen et al.[34] and Shear et al.[35] found similar results using prolonged

TABLE 2

Characteristics of Foundational Studies Performed in Albino Rats That Identified Retinal Damage After Visible Light Exposure

Study	Light Source	Light Intensity	Intensity Equivalent	Exposure Length	Retinal Layer Damaged
Noell (1966)	Fluorescent light (white and monochromatic)	2,040 foot-lamberts (6,989 cd/m^2, 1,200-2,500 lux)	Overcast day	2 hours to 20 hours	Photoreceptors and retinal pigment epithelium
Kuwabara (1968)	Fluorescent light	750 foot-candles (8,072 lux)	Clear, sunny day	1 hour to 1 month*	Photoreceptors
O'steen (1972)	Fluorescent light	70 foot-candles (753 lux)	Bright office/Lit TV studio	4 months to 6 months	Photoreceptors, plus anatomical derangements of ganglion cells and retinal vasculature
Shear (1972)	Fluorescent light	70 foot-candles (753 lux)	Bright office/Lit TV studio	6 hours to 18 hours	Outer layer of photoreceptors and retinal pigment epithelium

**Irreversible changes in photoreceptors apparent after 1 week of exposure.*

exposure to low-intensity light at 70 foot-candles (753 lux). They determined that when rats were exposed to light for longer durations of 4 to 6 months as opposed to cyclic light, there were further changes to the bipolar cell layer and retinal microvasculature. Cumulatively, these findings established that the extent of retinal damage varied with the intensity and exposure duration of light. They also suggested that there was a threshold at which retinal damage may occur. Later studies by Lawwill, Ham et al., and Griess and Blankenstein explored the boundaries of such a threshold by comparing photic intermittent exposures to single exposures.[36-39] Each study was able to identify a threshold, but results varied due to varying methodological conditions.

Although light intensity and exposure duration are clear risk factors for retinal damage, the wide variance of these factors used in these early studies suggests the methodological shortcomings of discussing exact thresholds. Studies, including recent ones, use different light sources with differing intensity, duration, and patterns of exposure on a wide range of test animals like rats, mice, and Rhesus monkeys. Furthermore, few studies utilize human subjects, limiting our understanding of how light relates to human retinal disease. This problem also manifests itself later in our discussion regarding the potential light toxicity caused by newer lighting and display technologies.

BLUE LIGHT HAZARD

The work of Anderson et al,[40] Ham et al,[37] and Williams and Howell[41] confirmed the hypotheses posited by earlier works, which suggested that retinal light toxicity was largely a function of wavelength. In fact, all three studies showed that photochemical damage was caused by light in the lower part of the visible spectrum and that the retina was most sensitive to blue light. The cornea and crystalline lens absorb essentially all ultraviolet and long-wavelength infrared (IR) bands but visible and short-wavelength IR light, wavelengths produced by consumer electronic displays, are transmitted unimpeded to the retina (Figure 2).[18] The mechanism by which visible light causes photochemical damage to the retina still remains controversial. Previous studies, including those cited above, speculated that light damage was mediated by rhodopsin or some other pigment. In 2000, Grimm et al. showed that genetically altered mice without a key retinal pigment epithelium (RPE) protein (*RPE65*) lacked rhodopsin and did not experience photoreceptor cell apoptosis on exposure to intense white fluorescent light, confirming rhodopsin to be the primary mediator of light damage in photoreceptor cells.[21] Boulton et al.[42] and Różanowska et al.[23] demonstrated that the particular sensitivity of the retina to blue light was also mediated by lipofuscin in the RPE. Lipofuscin are lipid-protein pigment granules that aggregate in cells as they age, becom-

ing apparent in the RPE of humans by the age of 10 and ultimately making up 19% of RPE cytoplasmic volume by 80 years of age.[17,42] As lipofuscin ages, it becomes more susceptible to blue light.[23] This phenomenon may help to explain the incidence of age-related macular degeneration (AMD) in elderly people, as observed by Taylor et al., who found that patients with AMD had significantly higher exposure to blue light than controls.[43] Further epidemiological studies have suggested a similar correlation between blue light and AMD, although a clear link is still difficult to establish due to the logistical problems associated with accurately determining lifetime light exposure in a given population.[17]

LEDS AND NEWER TECHNOLOGY DISPLAYS

The proliferation of artificial light sources, consisting of more sophisticated lighting technology, has made the blue light hazard[44] particularly important in a contemporary discussion of retinal light toxicity (Table 1, Figure 1). It is known that LEDs, which have become a primary domestic light source in recent years due to their energy efficiency and high luminance, have a significant blue-light component in their illumination spectra.[45] LED-produced blue light was shown to cause photoreceptor cell death in vitro through increased reactive oxygen species production.[46] A number of animal studies focused on the effects of LEDs have also shown that retinal damage might possibly occur at lighting levels resembling a domestic setting.[47-49] A similar issue as previous studies on retinal light toxicity reveals itself in these studies in that the precise lighting conditions are either not stated or not standardized. For example, Peng et al.[47] does not describe the luminance of the LED light, nor the housing of the tested animals, while Shang et al.[48] described their attempts to achieve a "common domestic luminance level of 750 lux." There have been efforts made by some regulatory agencies such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) to establish exposure limit values for light,[50] but Jaadane et al. showed that LED-caused retinal damage occurs at light levels far below those set by the ICNIRP, suggesting that current regulations require reevaluation.[49]

LED-induced retinal damage is still an active area of study, but the rapid arrival of newer display technologies and the ever-evolving ways that humans interact with displays indicate that new avenues of research are required. A review of the literature published in the last 10 years revealed only two case reports and two studies that focused specifically on retinal damage caused by light emitted from contemporary smartphones.[32,51,52] The case reports described two patients who experienced transient monocular vision loss after viewing a smartphone screen with the other eye covered, which the authors hypothesized was attributable to differential bleaching of photopigment.[51] A 2016 study by O'Hagan et al. determined that the light produced by smartphones, tablets , and computers was not "a cause for concern for public health,"[52] but based this determination using the same ICNIRP criteria rejected by Jaadane et al.[49] The more recent study by Lin et al. showed that chronic exposure to short-wavelength blue LED light at low luminance mimicking chronic smartphone usage did, in fact, cause retinal damage.[32] However, the work by Lin et al. is limited in that although many current television and computer displays are comprised of LEDs, most current smartphones use organic LED (OLED) technology (Table 1).[53] In addition, most current generation VR HMDs use OLED displays. OLEDs emit light from organic electroluminescent material and are potentially superior to LEDs in terms of luminance and contrast.[54] Relative to LEDs, OLEDs have not been studied at all with respect to their effects on the retina.

Both display-makers and third parties have begun to recognize the theoretical risks associated with use of modern displays and are starting to offer methods to reduce the amount of blue-light produced by these products. For example, Flux Software produces f.lux, software that adjusts color temperature on desktop and mobile devices with the intent of reducing eye strain and interference with sleep patterns attributed to blue-light exposure.[55] Apple (Cupertino, CA) has also added the "Night Shift" option in a recent software update for its mobile products that functions similarly.[56] DisplayMate has validated the display spectral changes in Apple devices — namely a reduction in blue output with concomitant rise in red wavelengths-with the use of "Night Shift."[57]

VR/AR HMDS

The lack of rigorous medical research on new lighting and display technologies extends to VR/AR HMDs. A review of literature published in the last 10 years indicates that current research on the adverse effects of VR HMDs is focused on VR-induced symptoms and effects, such as cybersickness.[58,59] There is a burgeoning interest in investigating the visual effects of these devices in the pediatric and adolescent populations. This population is of particular interest due to the increased prevalence of myopia and recognition of smartphone use as a risk factor.[60] Several small studies have identified user discomfort unique to VR HMD use and transient changes in refractive error, but no long-term effects on vision were noted.[61-63]

These studies are limited, however, by one-time, short-term device exposures (< 2 hours) that likely do not correlate with average use. Also, effects unique to the retina attributable to VR/AR HMD use have not yet been investigated in any population.

It may be possible to extrapolate how VR/AR HMDs might affect the health of our eyes through analogous technologies such as smartphones and other light-producing devices, but they themselves are lacking in research. It is anticipated that with the growth of VR/AR in popularity and usefulness, there will be more investigation on its potential harmful effects. We speculate that VR/AR HMDs may actually prove useful in studying these effects because they can provide a quasi-standardized lighting environment when worn on different subjects' heads.

There does not appear to be a consensus operational definition for discussing retinal light toxicity caused by electronic display devices, which creates a major problem when attempting to even discuss the issue. This may be attributable to the rate at which display technologies are progressing or to the fact that studying the ophthalmologic significance of new display technologies requires some understanding of technological engineering. Furthermore, most of our current understanding of how light affects the retina is through studies of ambient or lamp-produced light, whereas studies involving actual displays are lacking. Many of the pitfalls in discussing retinal light toxicity mentioned earlier in the review also remain true for current studies. In the future, it may prove easier to examine the harmful effects of VR/AR HMDs and other display technologies due to the increasingly widespread availability of less invasive diagnostic tools such as spectral-domain optical coherence tomography (OCT), which has been shown to detect changes to the retina due to light toxicity.[64,65]

Implementing these tools to assess retinal health may become critical as display technology continues to rapidly evolve. For example, virtual retinal displays (VRDs), HMDs that directly project images upon the retina, have recently come to the consumer market.[66] Though early work with these displays suggest they are safe in short-term use,[67] it is unclear if directly illuminating the retina in this manner over a prolonged period of time is acceptable. Using modern retinal imaging technology may help elucidate microscopic changes in areas directly illuminated by VRDs to better understand any risks posed by these devices.

FUTURE DIRECTIONS AND CONCLUSIONS

Given the ubiquity of electronic displays in modern life and the lack of data directly implicating these displays as the source of major visual deficits, it is our opinion that these devices are unlikely to pose any significant acute or subacute risk to the user's retina. The prevalence of smartphones, tablets, and now, VR/AR HMDs continues to increase our exposure to emitted light to ever higher levels, though. One consumer report estimated the average American spent 7.4 hours per day in front of electronic screens in 2014, with two-thirds of that time devoted to mobile computing devices.[68] These findings raise concern that a threshold for acute damage may exist or, more concerning, long-term, chronic changes that may potentially be already occurring under current usage patterns.

Although it may be desirable to attempt to create exposure nomograms using these average exposure times and reported device luminance, the actual radiometric exposure to the retina is likely to vary significantly based on both the particular device used and user behavior. It is clear from Table 1 that the maximum luminance varies depending on the screen technology and display manufacturer. The spectral data for a particular device must also be weighted using the blue light hazard function (Figure 1) to calculate the amount of blue-light produced.[52] Whether the user is leaving the device constantly at a desired brightness level or allowing built-in auto-brightness adjustments to vary luminance based on ambient lighting also confounds any sweeping estimates. A user's preferential viewing distance and pupil diameter can also affect the quantity of light illuminating the retina.

Legitimate concerns have already been raised regarding distraction, attentiveness, and possible ocular surface disease related to the use of these devices, and the more profound and potentially irreversible type of chronic, photic damage on the retina has yet to be elucidated. Designing high-quality studies to answer this question is complicated by the prevalence of displays and will likely make finding a similar, nonexposed population control difficult. Comparisons may only be possible between different quantity users and/or device-type users.

VR/AR HMDs present both a further challenge and an opportunity. The proximity of VR/AR HMDs to the users face significantly reduces the distance between screen and retina compared to conventional displays while also removing the ability to temporarily divert gaze from the screen. Whether this sort of engagement is more detrimental to a user's vision is currently unknown and should be more robustly characterized before this technology becomes more widely adopted. The closed VR/AR HMD system, however, may provide a useful experimental platform to better understand the effect of modern display output on the

retina, in comparison to smartphones where distance, brightness and ocular engagement may vary significantly from user to user. Testing with VR/AR HMDs would allow quantitation of radiometric exposure to help determine safe use guidelines and calculate relative risks associated with device use.

Regardless of the technology studied, more rigorous, standardized studies in human subjects using well-characterized measurements-such as OCT and fundus autofluorescence-along with supplemental visual function and psychometric testing are necessary to better understand the mechanisms through which these displays impact the retina. With this information, improved exposure limits and safety recommendations can be developed.

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