ORIGINAL ARTICLE

Comparing the Effect of Blue-light Lenses and Built-in Blue Light Filtering Software in Electronic Devices on Accommodation Accuracy During Digital Reading in the Dark

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ABSTRACT

Introduction: Blue light from electronics are linked to several visual problems including blurry vision, eyestrain, dry eye, macular degeneration, and cataracts. Lenses and software that are designed to block out blue light have been recommended for digital reading, but their visual impact remains debatable. This study aims to investigate the effect of blue-blocking ophthalmic lens (BBOL) and built-in blue light filtering software (BIBLFS) on digital reading in the dark on accommodation accuracy. **Methods:** This cross-sectional study design was approved by the UiTM ethics committee. Fifteen young adults were recruited using convenience sampling. The accommodation response of 1-min direct digital reading (DDR) from an iPad at 40 cm in a dark room was measured using Grand Seiko WAM-5500. The digital reading in the dark was repeated with BBOL and with BIBLFS. There was a 5-min dark adaptation in between each testing condition. The spectral transmittance was analysed using Retinal Index (RI) and Circadian Index (CI).**Results:** The comparison of accommodation response in three testing conditions (DDR – BBOL – BIBLFS) revealed no significant difference ($F = 1.735$, $p > 0.05$). However, our RI and CI analysis revealed that BBOL and BIBLFS displayed different protective effects against spectral emission from the electronic display compared to the standard illuminate test. **Conclusion:** The effects of BBOL and BIBLFS on accommodation response was negligible in short-term digital reading in the dark. However, the long-term accumulative effects on the accommodation system after prolonged usage requires further investigation.
Malaysian Journal of Medicine and Health Sciences (2022) 18(8):291-798. doi:10-268.47836/mjmhs18.8.37

Keywords: Blue light, Accommodation, Digital reading, Retinal index, Circadian index

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INTRODUCTION

In this digital information age, electronic displays seem to dominate both day and night (1). Electronics usage patterns are similar across most societies and remain relatively high regardless of age (2). The change in lifestyle from outdoor to indoor, and extension of working hours into the night-time has increased overall exposure to artificial blue light sources (3, 4). Users spend at least three hours a day watching smartphone displays, particularly at night before going to sleep (5). Portable electronic devices such as iPads emit high amounts of blue light ranging from 446 to 484 nm for working distances of 20 or 30 cm, which is extremely close to that of ultra-violet rays and produces a large amount of energy (6, 7). The use of electronic display devices in the dark could have a significant impact on the users' eyes (8). Furthermore, blue light emitted by electronics has been associated with melatonin secretion that is linked to attention, reaction time, mood, and sleeping pattern (3). Expose blue light at night give the person took longer to fall asleep. Blue light reduced melatonin secretion give later timing of the circadian clock, and reduced next-morning alertness (9). Other than that, shorter wavelength been known to cause photoreceptor cell and retinal pigment epithelial cell (RPE) damage (10). There was a peak of blue spectral more on tablets and smartphones on 450 nm, and luminance on a smartphone is the highest (1020 cd/m^2, then tablet (660 cd/m2), then the computer (436 cd/m^2) (7).

Two pathways are affected by blue or short wavelength light, which include non-visual and visual effects. Non-visual effects refer to a complex of effect of light ranging from cell division and hormone production to aspects of basic physiology and changes in behaviour, none of which depend on image processing (11). Visual effects involve various factors such as light intensity, physical activity, viewing distance, and variations in eye focusing (accommodative) requirements (12). Visual stress, symptoms of visual fatigue, and somatic disorders have been linked to workers exposed to lights generated by electronic devices (13). Not only that, visual complaints are higher among workers with prolonged near vision tasks involving electronic displays compared to those without (14). Generally, the causes of symptoms associated with near work could be categorized into two factors: external symptom factors and internal symptom factors (15). External symptom factors such as burning, irritation, tearing, and dryness are commonly related to dry eyes (16). Internal symptom factors (e.g., aches, strains, and headaches located behind the eyes) are linked to accommodative and/or binocular vision stress (15). The impact of near work on accommodation as well as its impact on accommodation (15) and refractive error development (17) is indisputable. In addition, lighting, viewing distance, and posture are among some of the contributing factors (18).

There are two major types of light entering the eyes - the room light and the light emitted from the electronic devices. Luminance distribution in the field of view has been claimed to be one of the causal factors to have a significant influence on visual fatigue and visual functions (19). The surrounding luminance was reported to have a significant impact on the accommodation amplitude (13). However, there were mix results to support significant difference in accommodation response reported for handheld electronic devices of different display sizes (iPad versus iPhone) (19, 20). Task performance varied between digital text and non-digital texts due to the light emitted from the electronic visual display (22). Light exposure from electronic devices is a fraction of that emitted by the sun. Naturally, anterior structures of the adult human eye including the cornea and lens are very effective at blocking UV rays from reaching the light-sensitive retina at the back of the eyeball. However, due to the number of times people focus on electronic devices and the proximity of their displays to the user's face, there are concerns about the possibility of long-term effects of blue light on eye health. Blue light has been linked to the risk of digital eye strain (DES) (23). Lenses and software that are designed to block out blue light have been recommended for digital reading (24). Built in software programs have been incorporated in mobile electronic devices to decrease the amount of blue light on the device display (25). Blue-blocking ophthalmic lenses have been prescribed to treat electronic device-related symptoms to improve working performance (26). However, the scientific evidence of both intervention on accommodation accuracy remains inconclusive. Thus, this study aimed to investigate the effects of blue-blocking ophthalmic lens and built-in light filtering software of digital reading in the dark on accommodation accuracy.

MATERIALS AND METHODS

Information on digital text

Short stories were compiled as reading material. It was presented as black text on a white background with a contrast ratio of more than 80%, measured by luminance meter (LS-100, Konica- Minolta, Tokyo, Japan). The font type was Bookman Old Style and the letter size was equivalent to N8 (2 mm x 2 mm for the capital letter and 1.3 mm x 1.5 mm for lowercase). The reading text was presented on an iPad Air (Model, MD794ZP/A) with a display size of 240 mm x 169 mm. The display of the iPad Air was built with a resolution of 2048-by-1536 at 264 pixels per inch (ppi) in Light Emitting Diode (LED)-backlit multi-Touch display with In-Plane Switching (IPS) technology. Pixel density was higher than the traditional Apple display.

Subject selection and grouping criteria

Our cross-sectional experimental study design adhered to the tenets of the Declaration of Helsinki. The ethical approval was obtained from UiTM [600-IRMI(5/1/6) REC/5/17]. A priori power analysis using the GPower 3.1 software (Heinrich Heine University Dusseldorf, https://www.psyhologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower.html) was performed to calculate the minimum required sample size (27). We assumed a medium effect size of 0.54, (28) alpha of 0.05, and power of 0.96, which projected a required sample size of 18 subjects. From 18 subjects recruited, three of them did not complete the experiments. Written informed consent from 15 young adults (mean age of 28 ± 2 years) was gained prior to participation. Young adults were recruited to minimize the effects of ocular media transmittance particularly in the blue region, as it might influence the spectral distribution on contrast sensitivity (29). The selection criteria included no known ocular disease, anisometropia <1.00D difference in spherical equivalents between the eyes, less than -0.50 DC of astigmatism and best corrected visual acuity of 6/6 or better using the Bailey-Lovie acuity chart. The spherical component was refined (in 0.25 D increments) with the best sphere and binocular balancing. Endpoint criteria of maximum plus sphere and minimum minus cylinder power consistent with best visual acuity were used. The subjects were equally divided into three groups, which were an emmetropic group, stable myopic group, and progressive myopic group, with five subjects in each group. Subjects with refractive powers between +0.25 D to Plano were classified under emmetropes. Subjects with refractive powers between -0.50 D to -2.75 D were classified under myopes. Myopes were further sub-categorized into stable myopia and progressing myopia. Previous studies found that adult progressing myopes had greater lags of accommodation than stable myopes at near work (30,31). Based on our subjective refraction and history taking, stable myopes were defined as those who had been wearing the same prescription, for at least the last 2 years, within a range of ±0.25 dioptres (D) in spherical equivalent. The progressive myopes classification were defined whose had the increment in refractive power of -0.5 D or more within the past one year (32).

Visual demand and measurements

Viewing distance for the reading materials was set at 40 cm, which was relatively close to the reported distance of 36.2 cm as the typical mean reading working distance for smartphones (33). The iPad was positioned on the rod attached to the auto-refractor, parallel to the subject's visual axis to ensure that the viewing distance remained constant throughout the measurements. The accommodation demand for the digital reading task was 2.5 D. An accommodation response record of 2.5 D indicated perfect accuracy in accommodation. Any accommodation response measurement of less than 2.5 D was considered as accommodation lag (indicated by a minus sign). Any accommodation response measurement of more than 2.5 D was considered as accommodation lead (indicated by a plus sign). The open field auto-refractor Grand Seiko WAM 5500 was used to measure the accommodation response, connected with WCS-1 software via an RS-232 cable for Hi-Speed (continuous recording) mode, which allowed for refractive data collection at a temporal resolution of 50 Hz. Sixty seconds were allocated to measure the monocular accommodative responses of the right eye to avoid any fatigue and stress in accommodation system after the subjects expose to the reading materials. Subjects have been read the text less for 3 minutes to familiarise the reading condition.

Spectral transmittance analysis

The spectral transmittance was analysed using two indices, Retinal Index (RI) and Circadian Index (CI) (34). Retinal Index (RI) measured possible hazardous visual effects on the retina when exposed to a predefined wavelength range and is mathematically expressed as Equation (1):

$$RI = \frac{\sum_{300nm}^{780nm} T(\lambda) \times I(\lambda) \times B(\lambda) \times \Delta\lambda}{\sum_{300nm}^{780nm} I(\lambda) \times B(\lambda) \times \Delta\lambda}$$

where T(λ) - the intensity ratio of transmitted light to the incident light in the visible spectrum (380 nm – 780 nm), I(λ) - the source illuminant, and B(λ) - the blue light hazard function as defined by International Commission on Non-Ionizing Radiation Protection (ICNIRP) (35). A score of RI = 1 indicated that the retina has no protection from the blue light, while RI = 0 denoted that the retina has total protection from the exposure.

Next, the Circadian Index gauged the circadian cycle protection against the disruptive effects of blue light. It is defined as Equation (2):

$$CI = \frac{\sum_{300nm}^{780nm} T(\lambda) \times I(\lambda) \times M(\lambda) \times \Delta\lambda}{\sum_{300nm}^{780nm} I(\lambda) \times M(\lambda) \times \Delta\lambda}$$

where M(λ) - circadian efficiency function (spectral weightage of the blue light exposure disruption towards the circadian cycle); CI = 1 - no non-visual photoreceptor protection from the blue light exposure; CI = 0 - total non-visual photoreceptor protection from the blue light exposure. (11)

To estimate the protective ability of the built-in mode provided in the iPad, the transmittance of the Night Shift mode, defined as TNS(λ), the ratio between the illuminant measured from the Night Shift mode, and the illuminant when the mode is turned off was determined. The parameter T(λ) from Equations (1) and (2) was replaced with TNS(λ) to quantify the visual and non-visual impact of the built-in blue light filtering software. The corresponding RINS and CINS are mathematically expressed as Equation (3) and Equation (4) respectively:

$$RI_{NS} = \frac{\sum_{300nm}^{780nm} T_{NS}(\lambda) \times I(\lambda) \times B(\lambda) \times \Delta\lambda}{\sum_{300nm}^{780nm} I(\lambda) \times B(\lambda) \times \Delta\lambda}$$

$$CI_{NS} = \frac{\sum_{300nm}^{780nm} T_{NS}(\lambda) \times I(\lambda) \times M(\lambda) \times \Delta\lambda}{\sum_{300nm}^{780nm} I(\lambda) \times M(\lambda) \times \Delta\lambda}$$

Experiment protocols

Subjects were required to complete all the experiment conditions. Each subject first underwent experiment DDR (direct digital reading) before being randomly assigned to 2 additional experiments: experiment BBOL (digital reading through the blue-blocking ophthalmic lens) & experiment BIBLFS (digital reading with built-in blue light filtering software). Subjects were randomly selected using a random number generator. For numbers 1-10, examiners employed a random number generator to ensure that odd numbers indicated a BBOL and even numbers indicated an BIBLFS. The lighting information of the darkroom (7 m length x 3 m width x 3 m height) was measured using CL-500a illuminance spectrophotometer from Konica Minolta Japan at the corneal plane, i.e., perpendicular to the iPad. The spectral data for each testing condition is summarized in Table I. Subjects were dark adapted for 5 minutes in the darkroom in between each testing condition to minimize the residual visual effects (36).

Table I Summary of the lighting information for the three experiments

Lighting information	Experiment DDR	Experiment BBOL	Experiment BIBLFS
Room illuminance (lux)	5	5	5
Display:			
Maximum luminance (cd/m^2)	299	282	220
Minimum luminance (cd/m^2)	8	8	6
Contrast (%)	95	95	95
Chromaticity coordinate (x, y)	0.37, 0.44	0.37, 0.44	0.43, 0.46
Dominance wavelength (nm)	566	574	566
Peak wavelength (nm)	539	606	539

Experiment DDR:
Each subject was instructed to perform digital reading binocularly using an iPad Air at 40 cm in a dark room without switching on any room lights. Additionally, the subjects were instructed to perform silent reading at least 3 min. To familiarize subjects on how to move the text on the display using their fingers, demonstration and practice were allowed prior to measurements. The concentration of subjects was closely monitored both subjectively via verbal reminders and objectively through fixation observation. The examiner ensured that the reading was engaged by the subject before the accommodation responses were recorded for a duration of 60 seconds.

Experiment BBOL:
The testing procedure was the same as Experiment DDR except for a pair of blue-blocking ophthalmic lenses to be worn by subjects while performing the digital text reading. The blue-blocking ophthalmic lens used in this study was a plano ophthalmic lens fitted on a trial frame. Kodak Total Blue Lenses were used (KodakLens 2018 Signet Armorlite, Inc.). The lens was enhanced with advanced UV filtering features as indicated by the manufacturer. It was embedded with digital device protection from High-Energy Visible (HEV) Blue Light, which was associated with eyestrain, eye fatigue and disruption in normal sleeping patterns and colour renders (37). The lens that responded to the blue light was characterized using two indices, Retinal Index (RI) and Circadian Index (CI).

Experiment BIBLFS:
The testing condition was the same as Experiment DDR except for built-in blue filtering software in the iPad which had to be turned on while the subject performed the digital text reading. There was a special feature in the iPad known as Night Shift mode. The colour temperature of the screen display could be fine-tuned at night or in conditions with low illumination. The application was initiated by the manufacturer by changing the spectral from pure white to warmer white light (8) with the purpose of "making the display easier on the eyes" by automatic adjustment of the display. Protective ability of the built-in mode provided in the iPad was reported using RINS and CINS.

In the normality test, there was normal distribution on data assessed by Shapiro-Wilk's test of normality ($p > 0.05$). Data were analysed by describing the maximum and minimum accommodation responses (D) for each experiment and comparing the accommodation response for reading condition experiment groups (within subject) and refractive error groups (between subject) using two-way mixed ANOVA (IBM SPSS Statistics Version 25). Then, the RI, CI, RINS and CINS were quantified using Spectral Transmittance Analysis.

RESULT

From the two-way mixed ANOVA, there was no statistically significant interaction between the refractive error and reading condition on accommodation response changes $F(2.753, 16.519) = 1.735$, $p = 0.201$, partial $\eta^2 = 0.224$, $\varepsilon = 0.688$. The main effect of testing reading condition (DDR-BBOL-BIBLFS) showed not statistically significant difference in mean accommodation response changes at the different reading condition, $F(1.377, 16.519) = 0.645$, $p = 0.481$, partial $\eta^2 = 0.051$, $\varepsilon = 0.688$. The main effect of refractive error groups showed that there was no statistically significant difference in mean accommodation response changes between refractive groups $F(2, 12) = 1.267$, $p = 0.317$, partial $\eta^2 = 0.174$. The difference between accommodation stimulus and accommodation response under three viewing conditions was insignificant for all three refractive groups, with $p > 0.05$ (Table II). The maximum and minimum values of the accommodation differences were +0.25 D and -0.49 D; +0.79 D and -0.85 D; -0.14 D and -0.80 D for the emmetropic group, stable myopic group, and progressive myopic group, respectively (Fig. 1).

The spectral transmittance analysis was calculated based on two illuminant sources – standard illuminant D65 and spectral emission of an LED display (34). The calculated RI and CI using standard illuminant D65 for BBOL were 0.81 and 0.89, respectively. Replacing

Table II Summary of the accommodation measurements in relation to 3 testing conditions for 3 refractive groups

Refractive groups	Mean and standard deviation of the difference between accommodation response and accommodation stimulus in Dioptres (D)			
	Experiment DDR	Experiment BBOL	Experiment BIBLFS	
Emmetropia	-0.13 ± 0.25	-0.12 ± 0.22	-0.21 ± 0.34	Statistical Test Between Subject Refractive Group
Stable myopia	-0.15 ± 0.62	-0.42 ± 0.26	-0.35 ± 0.39	
Progressive myopia	-0.51 ± 0.18	-0.40 ± 0.23	-0.43 ± 0.18	F = 1.267, $p > 0.05$
	Statistical Test Within Subject Reading Condition F = 0.645, $p > 0.05$			

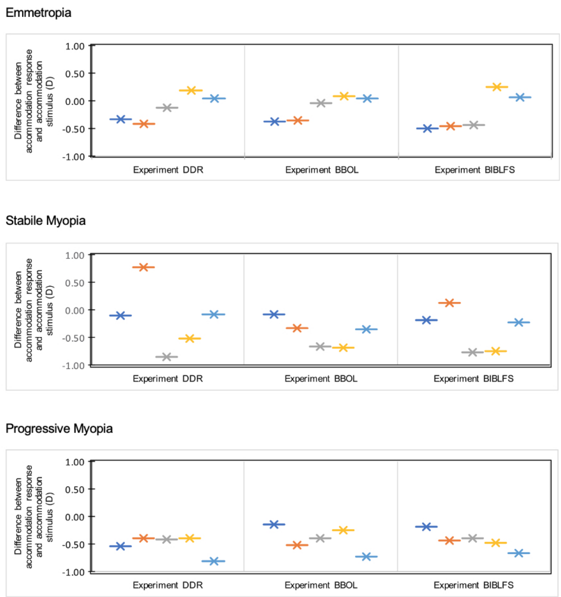

Fig. 1 Comparison of the differences between accommodation response and accommodation stimulus in relation to 3 testing conditions for 3 refractive groups (emmetropia; stabile myopia; progressive myopia). [Notes: The same scale was used in Y-axis to plot all three diagrams. A plus sign indicates the lead of accommodation. A minus sign indicates the lag of accommodation. Each colour indicates one individual.] Experiment DDR: Direct digital reading, Experiment BBOL: Digital reading through blue-blocking ophthalmic lens. Experiment BIBLFS: Digital reading with built-in blue light filtering software.

the source illuminant with the LED display resulted in the RI and CI of 0.95. These results indicated that the lens provided more protective effect against standard illuminant compared to the spectral emission of an LED display. Conversely, RI_{NS} and CI_{NS} of the Night Shift mode with the source illuminant of the LED display were found to be 0.44 and 0.53, respectively. Lower scores for both RI_{NS} and CI_{NS} suggested better protection from blue light with the built-in Night Shift mode equipped in the iPad.

DISCUSSION

Accommodation and spectral

The effects of the blue-blocking ophthalmic lenses and built-in blue light filtering software on difference of accommodation response and stimulus were negligible under short-term dark reading. While engaging in dark reading, humans usually adjust the low proportion of the luminous display to minimize the ratio between the display and surroundings, and hence reduce discomfort from the glare (23). This low illuminance and sustained near demand has been linked to visual fatigue and difficulty of falling asleep due to alertness activation by the 446 to 484 nm wavelength (6). Manipulation of short wavelength might alter cone contrast linked to hyperopic and myopic defocus (38). However, our black and white text might counter-balance the spectral distribution to give more accurate accommodation response compared to the narrow band wavelength (39). When the luminance of display was reduced in the testing condition, pupil dilation might increase the longitudinal chromatic aberration (LCA) (40). The effect of short wavelength could be diminished by the effect of LCA on accommodation accuracy. Another possible explanation for our insignificant findings might be due to our subject selection. The accommodation system of our asymptomatic subjects might be more robust towards spectral variation as indicated in accommodation system of non-visual stress subjects in previous study (41). The chromaticity vergence of the test target showed high inter-subject variability in accommodation response, which indicated that accommodation function was not an infallible cue (42). However, the effects of continuous accommodation response for those who displayed visual stress tendencies could behave differently with and without the spectral changes (41). Furthermore, minimal effects on accommodation response were reported in a comparison study between 90% and 60% contrast (43). The luminance contrast of approximately 95% in our study for all three testing conditions might be one of the explanations of the similar accommodation accuracy between the three conditions.

One interesting finding in our study revealed that the RI and CI findings did not seem to support the usual claims about the protective effect of BBOL towards possible hazardous visual effects on the retina from the iPad screen. Nevertheless, the BIBLFS seemed to provide more protection than BBOL for the direct dark reading. Our findings supported the protective element of blue-light hazards (44) under the standard illuminant D65, but the protective element from electronic display illuminant source remained uncertain. The role of blue-blocked ophthalmic lens in glare reduction, visual fatigue reduction and improved sleep patterns might not benefit users of electronics. Built in software embedded in a smartphone or tablet for night reading with slight yellowish shade (Red-Green-Blue values of 255, 255 and 230) was preferred compared to the pure white to reach the optimal display colour for night-time users (45).

Accommodation and refractive status

Our emmetropic subjects demonstrated relatively stable accommodation. The difference between accommodation response and accommodation stimulus was within 0.50 D for both lead and lag direction. The accommodation ranges of stable myopic subjects appeared to be slightly stretched but still fell within 1.00 D for both directions. The progressive myopic subjects consistently showed accommodation lag in all three testing conditions but remained below 1.00 D. Theoretically, performing visually demanding near tasks for prolonged duration might induce stress on the accommodation system (46). Continuous overloaded parasympathetic system might adapt to the demanding environment by re-adjusting the visual system such as ciliary muscle tension that could lead to excessive axial length growth (47). Accommodation stimulus-response curve for stable myopic eyes has been reported to be quite similar to the ideal curve of emmetropic eyes (30). Progressive myopia has been usually linked to lag in accommodation. Additionally, lag has been associated with hyperopic chronic defocus that might lead to myopia (32). Persistence of lag in accommodation led to the formation of hyperopic defocus that might act as a catalyser for ocular growth in a myopic-environment aetiology. Animal studies have also advocated similar explanations in which each of reared chicken eyes with small dioptric hyperopic defocuses induced myopia by the axial elongation (48). Lag in accommodation formed hyperopic blur that might act as a driving force for ocular growth linked to myopia (49).

Limitations

The open field auto-refractor has been widely used in accommodation studies in humans. However, there was a possibility that the spectral power distribution from the fixation target could have been altered when it was transmitted through the silver mirror of the autorefractor as part of the built-in optical configuration of the instrument when the subject was reading through the autorefractometer. The experimental set up might vary from the ocular status during real electronic reading in dark conditions.

CONCLUSION

The impact of blue-blocking ophthalmic lens & built-in blue light filtering software on accommodation was negligible on short-term digital reading in the dark. However, our findings on short-term immediate effects might not reflect the long-term accumulative effects on the accommodation system under prolonged usage. Based on RI and CI analysis, the blue-blocking ophthalmic lens might be inadequate to block shorter wavelengths from the electronic display. The built-in blue light filtering software might be a better option for digital reading in the dark. Further investigation into the long-term accumulative effects on the accommodation system under prolonged usage is necessary to re-examine this short-term immediate effect.

ACKNOWLEDGEMENTS

Financial support by the Ministry of Higher Education Malaysia: Prototype Research Grant Scheme [600-IRMI/PRGS 5/3 (012/2019)].

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