Received: 2 December 2021 | Accepted: 24 March 2022 | Published online: 11 April 2022

DOI: 10.1111/opo.12988

OPO THE COLLEGE OF OPTOMETRISTS

ORIGINAL ARTICLE

Effects of mild- and moderate-intensity illumination on short-term axial length and choroidal thickness changes in young adults

Ranjay Chakraborty[1,2] | **Konogan Baranton**[3] | **Daniel Spiegel**[4] | **Pascale Lacan**[3] | **Matthias Guillon**[3] | **Coralie Barrau**[3] | **Thierry Villette**[3]

[1]College of Nursing and Health Sciences, Optometry and Vision Science, Flinders University, Adelaide, South Australia, Australia

[2]Caring Futures Institute, Flinders University, Adelaide, South Australia, Australia

[3]Center Innovation & Technologies Europe, Essilor International SAS, Charenton-le-Pont, France

[4]Essilor Asia Pacific Pte Ltd., Singapore City, Singapore

Correspondence
Ranjay Chakraborty, College of Nursing and Health Sciences, Optometry and Vision Science, Flinders University, Adelaide, South Australia, Australia.
Email: ranjay.chakraborty@flinders.edu.au

Funding information
Essilor International, Grant/Award Number: 611.43241

Abstract

Purpose: Previous studies have shown that time spent outdoors is protective against myopia development in children. In this study, we examined the effects of 500 and 1000 lux of illumination to the eye on axial length (AL) and choroidal thickness (CT) changes in young adults.

Methods: Fifteen participants (mean age, 21.60 years [2.16]) with a mean refraction of −0.34 D (0.37) were exposed to 500 and 1000 lux of illumination for 120 min in a dark room on two different days, using a pair of light-emitting glasses. Ocular measurements were repeated on an additional day in darkness (~5 lux). Ocular biometrics and CT were measured and analysed in the right eye before the light exposure (0 min), after 30, 60 and 120 min of exposure and 30 min after light offset to measure recovery using the Lenstar biometer and the Cirrus optical coherence tomographer, respectively.

Results: Exposure to 500 and 1000 lux of illumination resulted in a significant reduction in AL at 30, 60 and 120 min compared to darkness (AL change at 120 min: darkness, +0.020 mm [0.004]; 500 lux, −0.006 mm [0.004]; 1000 lux, −0.013 mm [0.004]; $p < 0.001$). Exposure to 500 and 1000 lux caused a significant overall thickening of the subfoveal choroid compared to darkness (CT change across 120 min: darkness, −0.010 mm [0.007]; 500 lux, +0.006 mm [0.005]; 1000 lux, +0.009 mm [0.003], $p = 0.02$). Ocular changes were not significantly different between the two illumination levels ($p > 0.05$) and returned to baseline within 30 min of light offset.

Conclusions: Exposure to mild- or moderate-intensity illumination on the eye can induce a significant short-term reduction in AL and an increase in CT in young adults. Future studies on larger cohorts with varying light intensities are needed to better understand the effects of ocular illumination on AL changes in humans.

KEYWORDS
axial length, choroidal thickness, illumination, myopia

The work was performed at College of Nursing and Health Sciences, Optometry and Vision Science, Flinders University, Adelaide, Australia.

Aspects of the manuscript were presented at the Association for Research in Vision and Ophthalmology (ARVO) meeting in May 2021

INTRODUCTION

Myopia is the most common refractive disorder, and is more frequent in economically developed, urban regions of the world.[1] The prevalence of myopia is increasing worldwide, affecting around 30% of the population globally and with 50% of the world's population estimated to be myopic by 2050.[1,2] Highly myopic eyes have higher risk of developing sight threatening complications such as retinal detachment, retinal degenerations, glaucoma and cataract.[3,4] Clinical trials over the past decade have identified a number of optical and pharmacological interventions that could effectively slow down the rate of myopia progression in children, with the intent of reducing risk of myopia-associated complications in adulthood (see recent reviews).[5–7] On the other hand, time spent outdoors has been shown to reduce the onset of myopia in children.[8–10]

Animal studies indicate that the intensity of ambient light can influence ocular growth. For instance, rearing young chickens under normal diurnal bright light of 10,000 lux maintains a hyperopic state compared to when reared under normal indoor light levels of 500 lux.[11] Bright light exposure also inhibits the development of form-deprivation myopia (FDM) in chicks,[12,13] rhesus monkeys,[14] tree shrews[15] and mice.[16] In chicks, there is a significant negative correlation between the log light intensity and the development of FDM. Bright lighting also significantly reduces the rate of ocular compensation for lens induced myopia (LIM) in chicks[17] and guinea pigs,[18] but not in monkeys.[19] The effects of elevated light levels on eye growth are believed to be primarily mediated by increased retinal dopamine release,[20,21] but also changes in chromatic cues, pupil responses, circadian rhythms, changes in local retinal luminance and depth of focus.[12,13,15,22–24]

In addition to the intensity, changes in the timing of ambient light can also influence normal eye growth and lead to the development of refractive errors, as shown in animal models.[25,26] Alterations in natural ambient lighting through constant darkness[25] or exposing the eye to bright light at night time[26] can disrupt natural diurnal rhythms in axial length (AL) and choroidal thickness, resulting in refractive errors. The AL of the human eye exhibits natural diurnal rhythms and is typically longest at midday and shortest at night.[27,28] Similarly, a number of studies have confirmed diurnal variations in choroidal thickness, with the choroid being thickest during the night and thinnest during the day.[27,29,30] Choroidal rhythms are generally in antiphase to AL rhythms (i.e., the peaks of the two rhythms are about 12 h apart).[27] A recent study found that the amplitude of diurnal AL variations was negatively associated with the time exposed to bright light and positively associated with longitudinal AL changes measured over 12 months.[31] Given the inverse association between the changes in AL and choroidal thickness, the choroid may play an important role in the regulation of human eye growth.

Key points

- Short-term exposure to mild- or moderate-intensity illumination using light-emitting glasses can induce a significant reduction in axial length in young subjects.
- The changes in axial length in response to light were negatively associated with changes in choroidal thickness.
- The ocular changes to short-term light exposure were transient, and their effect on longer-term eye growth are unknown and require further research.

Several cross-sectional and longitudinal studies from different geographical locations and ethnic groups have reported that time spent outdoors is protective against the development of myopia in children.[8,10,32–37] These findings are further supported by clinical trials showing that an additional 40[38]–80[9] min of outdoor activity per day significantly reduces myopia onset and progression in school children. Greater daily exposure to moderate and high intensity outdoor light results in lesser axial eye growth in children.[38,39] In a study of Australian school children aged 10–15 years, Read et al.[38] found that a 1 log unit increase in average daily light exposure was associated with ~0.12 mm/year less eye growth (approximately 0.3–0.4 D slower myopia progression). Another randomised control trial in grade 1 Taiwanese school children found that outdoor activities with strong sunlight exposure (≥10,000 lux) may not be necessary to protect against myopia, and the same effects can be achieved by longer periods of more moderate light intensity (1000–5000 lux).[40] Together, these studies show that both the intensity and duration of daily light exposure are important in modulating the rate of myopia onset and progression in children.

Based on these findings, some recent clinical trials[41] and clinical studies[42] have looked at the effects of elevated light levels on myopia. A randomised controlled trial by Hua et al.[41] found that modified lighting systems producing an average illuminance of 300 lux on the desks and 500 lux on the blackboard significantly reduced the onset and progression of myopia in Chinese schoolchildren, aged 6–14 years. In another study, light exposure of 1000 lux before sleep for five consecutive nights was found to significantly reduce the subfoveal choroidal thickness (SFCT) in healthy young men.[42] In this study, we exposed the young adult participants to 500 and 1000 lux of illumination using a pair of custom-made, light-emitting glasses (Figure 1) and measured their effects on axial length (AL), choroidal thickness and other ocular biometric parameters.

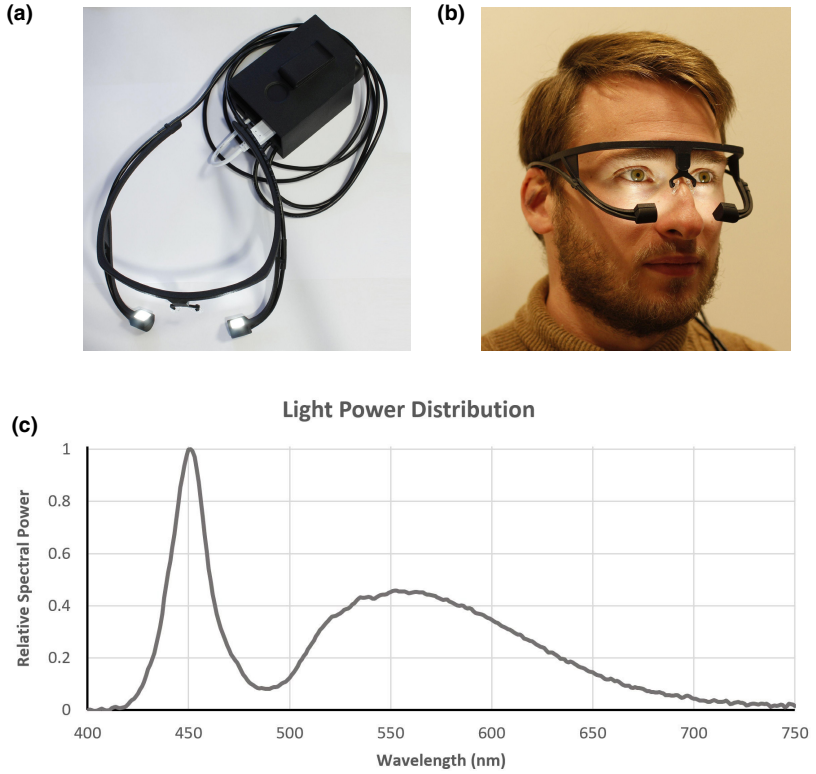

FIGURE 1 Light-emitting glasses. (a) 3D printed light-emitting glasses with wired supply box for power. (b) a subject wearing light-emitting glasses. (c) Spectral composition of the white light used in the experiment

MATERIALS AND METHODS

Participants

Fifteen young, healthy participants (male = 5, female = 10) between the ages of 18 and 25 years (mean age [SD], 21.60 years [2.16]) were recruited to examine the effects of mild-and-moderate-intensity illumination on AL and other ocular biometrics. Prior to participation, all subjects underwent a comprehensive eye examination to assess their refractive status and ocular health. Refraction was measured undilated using a Zeiss i. Profiler plus autorefractor (ZEISS Vision Care, zeiss.com/vision-care). Subjects were a combination of emmetropes and low myopes with a mean spherical equivalent refraction (SER) of −0.30 D (0.39) and −0.34 D (0.37) for the right and left eyes (range, 0.00 to −1.00 D), respectively. All subjects had normal visual acuity of 0.00 logMAR or better, and astigmatic refractive error of less than 1.00 DC. No participants had ocular pathology or a history of any major eye or refractive surgery.

The study was approved by the Southern Adelaide Local Health Network (SALHN, ID: 94.19) ethics committee, and all participants provided written informed consent prior to their participation. All subjects were treated in accordance with the Declaration of Helsinki.

Methods

To investigate the effects of mild-and-moderate intensity illumination on the eye, a series of ocular measurements were performed across three measurement days. On the first day, all measurements were performed in darkness in the absence of any light stimulus (~ 5 lux) to compare the effects of light exposure with 'no light'. On two other days, all participants were subjected to 500 lux (152 μW/cm^2) and 1000 lux (284 μW/cm^2) of illumination in a dark room, and the ocular effects of light exposure were examined over a period of 120 min. The light intensity and duration were chosen based on previous studies showing 60–120 min of outdoor light exposure of ≥1000 lux being protective against myopia in children.[38,43]

On each day, measurements were performed in both eyes before the light onset (0 min), after 30, 60 and 120 min of light exposure and 30 min after light offset to examine recovery from any light induced ocular changes. To avoid any undue influence of diurnal variations on ocular measurements,[27,30] all measurements were collected between 09:00 and 12:00 across all measurement days. All 3 days of measurements were completed within a period of 10 days for all participants. The order of the two lighting conditions were randomised to control for the systematic bias.

Participants' eyes were exposed to diffuse white light using a pair of custom-made, light-emitting glasses that looked similar to commercial light therapy glasses

(Re-timer glasses, Figure 1a).[44] These portable, lightweight glasses were 3D printed and made of Nylon 12 polymer[45] (not intended for vision correction) and were worn like spectacles on the face (Figure 1b). Spectral composition of the white light is shown in Figure 1c.

In the light-emitting glasses, light is emitted through two multi-colour LED emitters covered with white diffusers (LZ7, LuxiGen™, Osram Sylvania, osram.us), one in each eye, located at the lower portion of the plastic frame ~4 cm in front of the eye. The L27 flat lens emitter contains seven different colours of LEDs closely packed in a low thermal resistance package with an integrated glass window. The glasses were powered by a wired supply box including a USB powerbank and the illumination levels were remotely controlled by a Java-based (V2) Android smartphone application that was connected to the device via Bluetooth.

For calibration, light glasses were put onto a mannequin face and the fibre optic of a spectrophotometer (AvaSpec-ULS2048L, Avantes, avantes.com) was inserted through the pupillary aperture of the mannequin. Illuminance and irradiance levels were measured in lux and $\mu W/cm^2$, respectively, at the pupil plane. A pair of calibrated light glasses was further tested by Laboratoire national de métrologie et d'essais (LNE), a French certification laboratory, to ensure that light levels met the safety standards to be used in human subjects.

On the day of the experiment, participants reported to the laboratory around 09:00. Before the baseline measurement, participants undertook a period of 10 min of binocular distance viewing (sitting and watching a television at 4 m) in darkness to wash out any residual effects of previous visual activities,[46,47] as described previously.[48] The 50×30 cm television placed at 4 m corresponded to a field of view of 7.15×4.30 degrees. After the baseline measurement, participants wore the light-emitting glasses and continued to watch television in the dark room for the remainder of the experiment. The television was set for low brightness and greyscaled (all colour channels were muted) to avoid any influence of different narrowband wavelengths on AL and choroidal thickness changes, as reported recently.[49] At each session, participants were asked to remove the glasses immediately prior to the measurements. After 120 min, the light-emitting glasses were turned off and participants watched television for an additional 30 min for recovery measurements. On day 1 with no light stimulus, participants just watched television in darkness without glasses. Participants were given small snacks during the study but were not allowed to take any bathroom breaks during the experiment. Because hydration levels can affect AL,[50] subjects were asked to refrain from hot or cold beverages before the experiment and restrict their water consumption during the study. Five subjects with myopia (average SER, −0.77±0.18 D) were corrected with contact lenses (Proclear® 1 Day CL, CooperVision, coopervision.co.uk) for distance vision. The CLs were introduced immediately after the baseline session and were removed at each subsequent measurement session for ocular measurements. During the measurement procedure, the lenses were kept safely in a CL case with solution and were gently placed back onto the eye after the measurement.

An optical biometer (Lenstar LS 900; Haag-Streit AG, haag-streit.com) was used to obtain measurements of AL and other ocular biometric parameters. AL was measured from the anterior corneal apex to the retinal pigment epithelium (RPE). The instrument is highly repeatable (reported intra-and inter-session repeatability for AL is 0.013 and 0.006 mm, respectively) and comparable with other validated instruments.[51,52] Considering the mean intra-session SD of 13 μm for AL measurements, it was determined that a sample size of 16 participants would provide 80% power to detect a minimum significant change of 10 μm in AL in response to light, at an alpha level of 0.05.

The following ocular biometric measures were collected: corneal curvature (CC), central corneal thickness (CCT), anterior chamber depth (ACD), lens thickness (LT), vitreous chamber depth (VCD) and AL.[27] The first five measurements of each biometric parameter at each session were recoded for analysis. Only those measurements that were deemed inaccurate by the instrument were discarded. The Cirrus HD spectral domain optical coherence tomographer (OCT) was used for choroidal thickness measurements (Cirrus HD-OCT 5000, Zeiss, zeiss.com). Three horizontal 6 mm, HD 5-line raster scans were taken at each measurement session using the enhanced depth imaging (EDI) mode, as described elsewhere.[53] The spacing between the lines was kept at 0 mm to allow for multiple B-scans to be collected from the same retinal location. This instrument has an axial resolution of 5 μm and transverse resolution of 15 μm in the tissue.

Data analysis

Following data collection, all three OCT scans from each participant were exported for detailed analysis using custom written software. The software performed automatic segmentation of chorio-retinal images for the calculation of choroidal thickness.[54] Choroidal thickness was defined as the distance from the RPE to the inner boundary of the choroid/scleral interface. Automatic segmentations were checked for accuracy, and if required, were manually adjusted for any segmentation errors by an independent examiner who was not involved in data collection or the final analysis. The order of participants, the three lighting conditions and the order of measurement sessions were randomised for blinding (by RC). The blinded OCT files were then given to the independent examiner for analysis.

Choroidal thickness could not be calculated for one participant due to extreme pupillary miosis and eye movements during measurements. Sixteen scans from the remaining 14 participants with a signal-to-noise ratio <6 were excluded from the analysis due to poor visibility of the choroid/scleral interface. Choroidal thickness in a range of different zones was then calculated based on this automatic segmentation, including the SFCT, and the parafoveal choroidal thickness (PFCT) for both nasal and temporal regions, within a series of width zones located at 0.5, 1.0 and 2.0 mm from the foveal centre, as described previously (Figure 2).[48]

Because both eyes were exposed to the same lighting conditions at the same time, only the right eye data has been presented. AL and choroidal thickness data from the left eye are shown in Figure S1. The average of all biometric parameters for each subject at each measurement session was calculated. For each measurement day, data at each time point was normalised to its baseline to calculate the "change across time" for all ocular variables. Changes in AL, choroidal thickness (both SFCT and PFCT) and ocular biometrics across each illumination condition were analysed with repeated-measures, two-way analysis of variance (ANOVA) and Holm-Sidak post-hoc tests for statistical significance, using the two within-subjects factors ("time" and "illumination"). To examine the baseline differences between the nasal and temporal regions of the parafoveal choroid, the repeated-measures ANOVA was used with parafoveal eccentricity (0.5, 1.0 and 2.0 mm from the fovea) and region (nasal or temporal) as the two within-subjects factors. To investigate the association between the changes in AL and choroidal thickness, a linear regression analysis was performed using the least-squares approach. To provide an assessment of the within-session measurement variability for each of the measured ocular parameters, we analysed data from each subject to calculate the mean within-subject standard deviation (SD) and coefficient of variation of the repeated measurements for each variable.[27] Statistical analyses were performed using commercial software (SigmaStat 3.5, Systat Software, sigmaplot.co.uk). A p-value of <0.05 was considered to be statistically significant. All data are expressed as mean (SEM).

RESULTS

Within-session measurement repeatability

Table 1 shows the within-subject SD and coefficient of variation for the repeated measures collected at each measurement session across the three measurement days to illustrate the overall within-subject variability in the measurements. The within-session variability was small for AL (mean coefficient of variation of 0.03% across the three measurement days), but greater for the SFCT (mean coefficient of variation, 4.01%) and PFCT (mean coefficient of variation, 4.20%, Table 1).

Axial length

The change in AL across the three measurement days is shown in Figure 3a and Table 2. Exposure to 500 and 1000 lux of illumination on days 2 and 3 caused a significant reduction in AL compared to day 1 in darkness (two-way repeated measures ANOVA time by illumination interaction $F[8209] = 8.449$, $p < 0.001$, Figure 3a). While exposure to darkness caused a gradual increase in AL at 30, 60 and 120 min, both 500 and 1000 lux of illumination led to small reductions in AL at all time points (Holm-Sidak multiple comparisons, $p < 0.05$, Figure 3a). The AL changes associated with 1000 lux were stronger than for 500 lux (mean change at 120 min, −0.013 mm [0.004] vs. −0.006 mm [0.004] mm for 1000 and 500 lux, respectively), but these differences were not statistically significant between the two illumination levels (Holm-Sidak multiple comparisons, $p > 0.05$). The decrease in AL with mild- and moderate-intensity illumination were transient and returned back to baseline 30 min after light offset for either illumination condition, but not for darkness (Figure 3a).

Choroidal thickness

As shown in Figure 3b, exposure to 500 lux (mean change across 120 min, +0.006 mm [0.005]) and 1000 lux (+0.009 mm [0.003]) of controlled illumination for 2 h resulted in a significant overall thickening of the subfoveal choroid compared to darkness on day 1 (−0.010 mm [0.007], two-way repeated measures ANOVA main effect

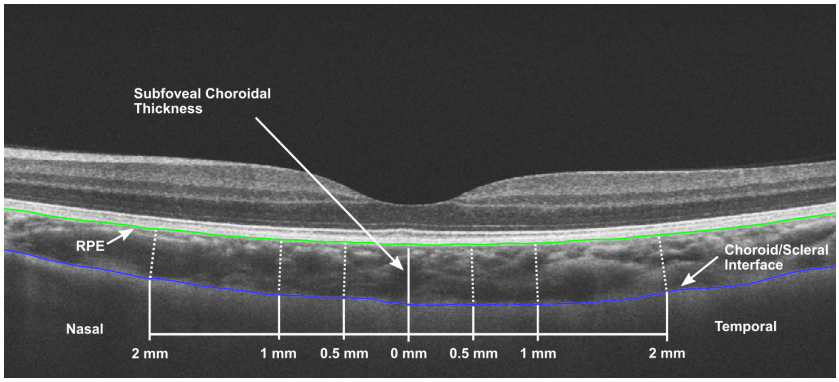

FIGURE 2 Example of an optical coherence tomographer (OCT) image from one measurement session, showing choroidal thickness (the distance from the retinal pigment epithelium or RPE to the inner boundary of the choroidal/scleral interface) measurements in a range of different zones based upon automatic segmentation of each scan. This includes the subfoveal choroidal thickness, and the parafoveal choroidal thickness for both nasal and temporal regions, within a series of width zones located at 0.5, 1.0, and 2.0 mm from the foveal centre

TABLE 1 Overview of the mean within-subject variability for the repeated measures collected at each measurement session across the three measurement days for axial length (AL), central corneal thickness (CCT), anterior chamber depth (ACD), lens thickness (LT), vitreous chamber depth (VCD), subfoveal choroidal thickness (SFCT) and parafoveal choroidal thickness (PFCT, averaged across the nasal and temporal regions)

Measured variables	Mean within-session standard deviation	Mean coefficient of variation
AL (mm)	0.010	0.03%
CCT (mm)	0.002	0.44%
ACD (mm)	0.017	0.58%
LT (mm)	0.026	0.69%
VCD (mm)	0.028	0.77%
SFCT (mm)	0.016	4.01%
PFCT 0.5 mm from foveal centre (mm)	0.015	4.12%
PFCT 1.0 mm from foveal centre (mm)	0.016	4.11%
PFCT 2.0 mm from foveal centre (mm)	0.018	4.38%

of illumination F [2, 189] = 5.039, p = 0.02). However, there was no significant time by illumination interaction in the subfoveal choroid (p = 0.11). The SFCT changes returned toward baseline levels after 30 min of light offset for both illumination conditions, but not for darkness (Figure 3b).

Linear regression analysis revealed a significant negative association between the changes in AL and SFCT (slope = −0.48; r^2 = 0.12, p < 0.01, Figure 4).

Table S1 shows the changes in the parafoveal choroid (both nasal and temporal regions at 0.5, 1.0 and 2.0 mm peripheral eccentricities) across the three measurement days. The choroid was found to be significantly thinner in the more peripheral locations on either side of the fovea (average thickness of all baseline sessions across the 3 days: nasal choroid: 0.5 mm, 0.390 mm [0.013]; 1.0 mm, 0.374 mm [0.013]; 2.0 mm, 0.307 mm [0.010]; temporal choroid: 0.5 mm, 0.399 mm [0.013]; 1.0 mm, 0.391 mm [0.012]; 2.0 mm, 0.350 mm [0.008], two-way repeated measures ANOVA main effect of eccentricity F [2, 245] = 18.543, p < 0.001). Except for a significant change in the nasal choroid 1.0 mm away from the fovea (two-way repeated measures main effect of time, p = 0.03), none of the other PFCT parameters showed any significant or consistent change under any illumination condition (all p > 0.05, Table S1).

Other ocular biometric parameters

Effects of the two illumination levels on other ocular parameters are shown in Table 2. There was a small but significant thinning of the cornea with time on each measurement day (mean change in CCT at 120 min relative to baseline: darkness, −0.001 mm [0.001]; 500 lux, −0.002 mm [0.001]; 1000 lux, −0.001 mm [0.001], two-way repeated measures ANOVA main effect of time F [4, 209] = 5.295, p = 0.001). However, these CCT changes were not significantly different between the three illumination conditions (p = 0.11).

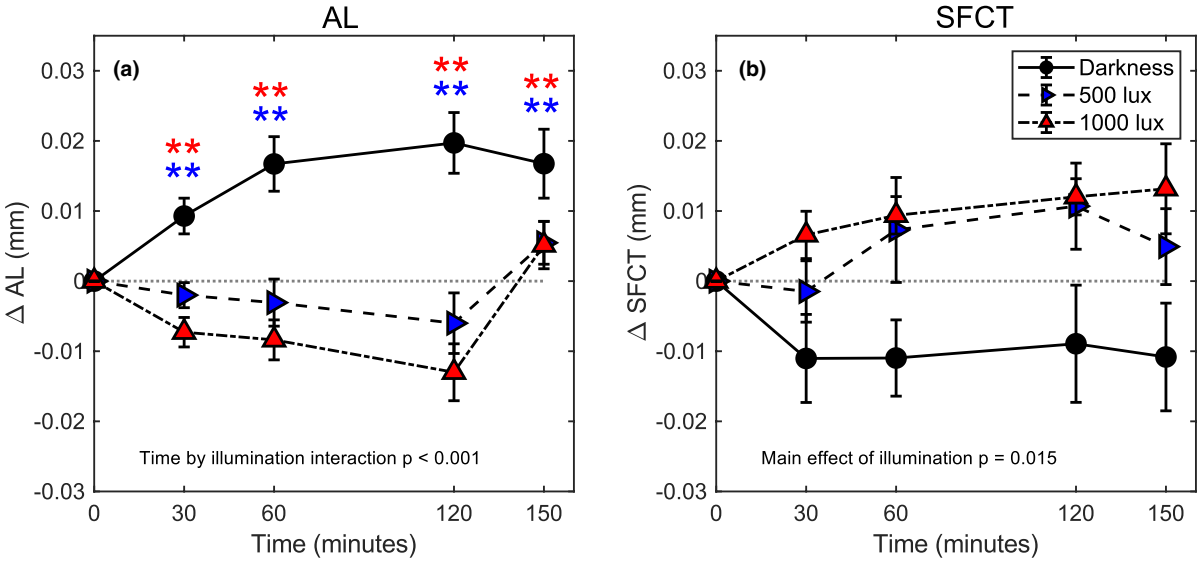

FIGURE 3 Axial length (AL) (a) and subfoveal choroidal thickness (SFCT) (b) changes to mild- and moderate-intensity illumination. (a) Exposure to 500 (blue triangles) and 1000 (red triangles) lux of illumination caused a significant reduction in AL compared to day 1 in darkness (black circles) (two-way repeated measures ANOVA time by illumination interaction F [8209] = 8.449, p < 0.001). (b) Exposure to 500 and 1000 lux resulted in a significant overall thickening of the subfoveal choroid compared to darkness (two-way repeated measures ANOVA main effect of illumination F [2, 189] = 5.039, p = 0.02). Red asterisks and blue asterisks indicate that ocular changes in darkness were significantly different from 500 lux and 1000 lux of illumination, respectively

TABLE 2 Summary of mean change (SEM) in axial length (AL), central corneal thickness (CCT), corneal curvature (CC), anterior chamber depth (ACD), lens thickness (LT), vitreous chamber depth (VCD) and subfoveal choroidal thickness (SFCT) at 120 min of light exposure and after 30 min of light offset (recovery measured at 150 min) for each of the three measurement days (day 1 darkness, day 2, 500 lux and day 3, 1000 lux illumination), along with *p*-values from repeated measures ANOVA illustrating the effects of illumination, time and illumination by time interaction

Measured variables	Measurement day	Mean change at 120 min of light exposure (SEM) (mm)	Mean change after 30 min of light offset (recovery measured at 150 min) (SEM) (mm)	*p* value (illumination)	*p* value (time)	*p* value (illumination by time interaction)
AL	Day 1 (darkness)	+0.020 (0.004)	+0.017 (0.005)	**<0.001***	**0.001***	**<0.001***
	Day 2 (500 lux)	−0.006 (0.004)	+0.005 (0.003)			
	Day 3 (1000 lux)	−0.013 (0.004)	+0.005 (0.003)			
CCT	Day 1 (darkness)	−0.001 (0.001)	−0.001 (0.001)	0.11	**0.001***	0.20
	Day 2 (500 lux)	−0.002 (0.001)	−0.003 (0.001)			
	Day 3 (1000 lux)	−0.001 (0.001)	−0.001 (0.001)			
CC[a]	Day 1 (darkness)	+0.010 (0.019)	+0.065 (0.042)	0.74	0.54	0.11
	Day 2 (500 lux)	+0.045 (0.029)	+0.003 (0.025)			
	Day 3 (1000 lux)	+0.022 (0.030)	−0.033 (0.039)			
ACD	Day 1 (darkness)	+0.016 (0.005)	+0.017 (0.008)	**0.05***	0.94	0.30
	Day 2 (500 lux)	−0.007 (0.007)	−0.002 (0.013)			
	Day 3 (1000 lux)	−0.015 (0.007)	−0.004 (0.006)			
LT	Day 1 (darkness)	+0.012 (0.005)	+0.011 (0.009)	0.72	0.50	0.98
	Day 2 (500 lux)	−0.004 (0.010)	−0.004 (0.016)			
	Day 3 (1000 lux)	+0.006 (0.012)	−0.004 (0.012)			
VCD	Day 1 (darkness)	−0.012 (0.006)	−0.013 (0.011)	0.49	0.55	0.85
	Day 2 (500 lux)	+0.005 (0.009)	+0.013 (0.007)			
	Day 3 (1000 lux)	−0.005 (0.012)	+0.011 (0.008)			
SFCT	Day 1 (darkness)	−0.009 (0.008)	−0.011 (0.008)	**0.02***	0.30	0.11
	Day 2 (500 lux)	+0.011 (0.006)	+0.005 (0.005)			
	Day 3 (1000 lux)	+0.012 (0.003)	+0.013 (0.006)			

Note: Significant *p* values ($p < 0.05$) are highlighted in bold*.

[a]The change in CC is shown in dioptres (D).

The introduction of mild-and-moderate-intensity illumination on day 2 (mean change across 120 min with 500 lux, −0.004 mm [0.005]) and day 3 (1000 lux, −0.010 mm [0.006]) led to a significant shallowing of the ACD compared to day 1 (darkness, +0.013 mm [0.006], two-way repeated measures ANOVA main effect of illumination F [2, 194] = 3.422, $p = 0.05$]). There were no significant changes in any of the other biometric parameters with different illumination levels (Table 2).

DISCUSSION

In this study, we found that exposure to 500 and 1000 lux of direct illumination to the eye for 2 h resulted in a significant reduction in AL and overall thickening of the subfoveal choroid in young adult participants compared to darkness. The ocular changes were transient in nature and returned toward baseline levels within 30 min of light offset.

Exposure to high intensity bright light significantly slows the rate of ocular elongation and inhibits the development of FDM in animal models.[12–14] Several large-scale longitudinal studies have found that greater daily exposure to moderate and high intensity outdoor light results in less axial eye growth in children and offers significant protection against myopia.[38,39,55] Studies generally agree that approximately 2 h or more of natural outdoor exposure of ≥1000 lux each day is required to provide protection against myopia development in children.[38,56] In this study, we exposed the participants to mild and moderate intensity illumination levels using custom-made, light-emitting glasses and found that 2 h of controlled light exposure to the eye resulted in a significant reduction in AL.

In our study, the changes in AL with 1000 lux were not significantly different from 500 lux. This suggests that higher intensity thresholds (such as 2000 or 5000 lux) may be required to see a clear dose-dependent relationship between light intensity and short-term AL changes in human eyes. Previously, a significant correlation was observed between log light intensity and the development of FDM in chicks, with a lesser myopic refraction and shorter axial length associated with increasing light intensities.[13] Future

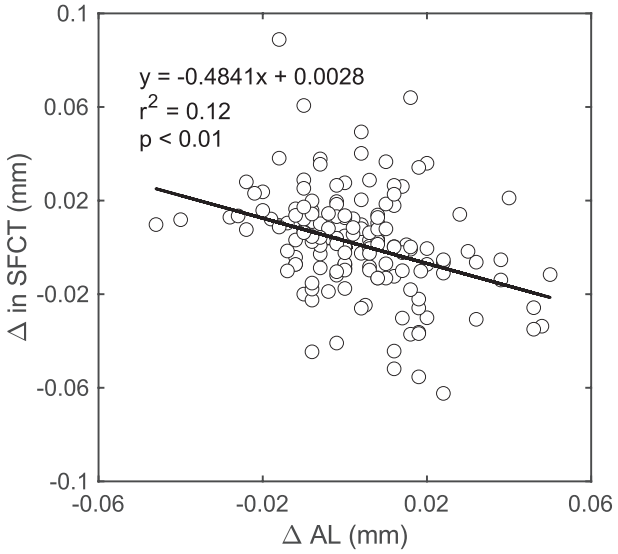

FIGURE 4 Linear regression analysis showing a significant negative association between the changes in axial length (AL) and subfoveal choroidal thickness (SFCT)

studies on larger cohorts and with varying light intensities are needed to understand better the effects of ocular illumination on AL changes in humans.

Choroidal thickness was also influenced significantly by mild-and-moderate intensity illumination. Exposure to 500 and 1000 lux of illumination for 2 h resulted in a significant overall thickening of the subfoveal choroid (Figure 3b). The SFCT changes were not significantly different between the two illumination levels. Consistent with our findings, a recent study found that a one-week period of increased light exposure delivered through the use of light therapy glasses for 30 min each morning (506 lux of 500 nm blue-green light) resulted in a small but statistically significant increase in choroidal thickness in young adults.[57] In addition, the Role of Outdoor Activity in Myopia study revealed that children habitually exposed to greater amounts of daily outdoor light exhibited greater choroidal thickening over an 18-month period.[58] Furthermore, increased light exposure has also been shown to result in an increase in choroidal thickness in chicks.[59] Similar to several previous reports,[27,48,53] the present study found that the SFCT changes were negatively associated with the changes in AL. Interestingly, one investigation found that light exposure of 1000 lux for five consecutive nights (4 h each night) before sleep caused choroidal thinning in healthy young men.[42] The SFCT changes found in that study[42] could be attributed to several factors, including the total duration of light exposure (20 h across five nights vs. 2 h in the present study) or the effects of diurnal variations in choroidal thickness (light exposure given at night when the choroid is naturally thinner vs daytime here).[27] Finally, in the current study, the choroid was thickest in the subfoveal region, and thinner in the parafoveal regions on either side of the fovea (temporal thickness > nasal thickness).[60,61] However, the effects of elevated light levels were largely confined to the subfoveal region, and the PFCT only exhibited small and insignificant changes with light treatment. This may be due to the greater within-session variability in the PFCT data (mean coefficient of variation, 4.20%). Alternatively, it may reflect limited diffusion of light in the parafoveal regions due to pupillary construction and/or relatively poor sensitivity of the parafoveal choroidal regions in processing mild- and moderate-intensity light levels. Whether these small increases in choroidal thickness with the use of light-emitting glasses could influence short-term diurnal variations in AL and choroidal thickness, and eventually longer-term axial eye growth in humans,[31] warrants further research.

Interestingly, in contrast to the present study, a recent investigation by Lou and Ostrin[49] found a small increase in AL and reduction in choroidal thickness following 60 min of exposure to 100 μW/cm^2 broadband white light. These changes reflected normal diurnal rhythms of the eye under typical indoor lighting. In comparison, the irradiance or energy of 1000 lux of illumination used in our study was almost 3× greater (284 μW/cm^2) and so the ocular changes clearly reflected the effect of light exposure (and not diurnal rhythms). However, 500 lux of illumination, which is also a typical indoor light level,[62] was closer to the illumination levels used by Lou and Ostrin. Despite low illuminance, the ocular changes with 500 lux in this study may not represent the normal diurnal changes in the eye. Firstly, the irradiance of white light at the corneal plane was 1.5× higher (152 μW/cm^2) compared to the 100 μW/cm^2 used by Lou and Ostin.[49] Secondly, because light levels vary significantly depending on the position of the source and viewing direction,[63] wall-mounted LED panels in Lou and Ostrin study (with light reflecting from walls and other surfaces in the laboratory) can produce a very different ocular effect compared to direct light from a closer distance via light-emitting glasses. With regards to indoor lighting, the illuminance levels can vary significantly at different locations.[62] Therefore, despite being under 500 lux indoors, the eye may not constantly receive the same illuminance at all times, which is different to a close and continuous exposure of 500 lux for 2 h. Thirdly, the spectral composition of white light used in the current study (Figure 1c) was slightly different from Lou and Ostrin, and had relatively less energy in the higher wavelength region. Given the evidence of small increases in AL and choroidal thinning under red light in humans,[49] it is possible that reduced energy in the red spectrum can induce small reductions in AL and choroidal thickening.

On day 1, there was a gradual increase in AL and reduction in SFCT in darkness. Similarly, a recent study found that 60 min of darkness resulted in a small increase in AL and decreased choroidal thickness in young humans.[49] Studies have also reported an increase in axial eye growth and choroidal thinning in young chicks,[25] and ocular elongation and myopia in tree shrews[64] reared in darkness. In chicks, these changes were thought to be mediated by the absence of visual feedback related to the effective refractive state of the eye in darkness.[25]

We found that these light-induced changes in AL and choroidal thickness were significant, but transient, as the changes almost returned to baseline after 30 min of light offset. Although recovery from light induced changes has not been documented previously in human subjects, studies have shown that young human eyes recover quickly from other optical stimuli (such as induced defocus).[65,66] Whether ocular changes quickly revert back to normal for higher intensity illumination levels and/or longer durations of light exposure (>2 h) warrants further research.

With regard to other biometric parameters, we observed a significant shallowing of the ACD with light exposure. Surprisingly, we did not see any significant change in VCD (the primary individual biometric contributor of axial length),[67] which was probably due to high intrasession variability in LT and VCD data owing to a poor signal from the posterior lens surface in Lenstar, as reported previously.[27]

Although we reported some significant findings, our study also had limitations. Firstly, it was done on a relatively small sample size comprising young adults, so the results may not represent the effects of mild- and moderate-intensity illumination on AL and other ocular parameters in different age groups. Secondly, we had only a small number of myopes in the study (n = 5, mean SER of less than −1.00 D). Future studies should examine the effects of moderate and high intensity illumination on AL and ocular biometric changes in younger populations with high and progressive myopia.

In conclusion, our results show that 2 h of mild- or moderate-intensity illumination to the eye can induce a significant *short-term* reduction in AL and an overall thickening of the choroid in young adult subjects. These changes were not significantly different between the two illumination levels (500 and 1000 lux) used in this study. Future investigations should use higher intensity illumination levels to better understand the effects of ocular illumination on short-term AL changes in human eyes.

ACKNOWLEDGEMENT

This project was supported by funding from Essilor International (Project code: 611.43241).

CONFLICT OF INTEREST

Co-authors KB, DS, PL, MG, CB and TV are all employees of Essilor.

AUTHOR CONTRIBUTIONS

Ranjay Chakraborty: Conceptualization (lead); formal analysis (lead); funding acquisition (lead); investigation (lead); methodology (lead); project administration (lead); resources (lead); supervision (lead); writing – original draft (lead). **Konogan Baranton:** Data curation (supporting); investigation (supporting); project administration (supporting); software (lead); writing – review and editing (supporting). **Daniel Spiegel:** Data curation (supporting); formal analysis (supporting); investigation (supporting); project administration (supporting); writing – review and editing (supporting). **Pascale Lacan:** Methodology (supporting); project administration (supporting); resources (supporting); supervision (supporting); writing – review and editing (supporting). **Matthias Guillon:** Project administration (supporting); software (supporting); writing – review and editing (supporting). **Coralie Barrau:** Conceptualization (supporting); funding acquisition (supporting); project administration (supporting); writing – review and editing (supporting). **Thierry Villette:** Project administration (supporting); supervision (supporting); writing – review and editing (supporting).

ORCID

Ranjay Chakraborty https://orcid.org/0000-0001-8850-1907

REFERENCES

1. Morgan IG, French AN, Ashby RS, Guo X, Ding X, He M, et al. The epidemics of myopia: aetiology and prevention. *Prog Retin Eye Res*. 2018;62:134–49.
2. Holden BA, Fricke TR, Wilson DA, Jong M, Naidoo KS, Sankaridurg P, et al. Global prevalence of myopia and high myopia and temporal trends from 2000 through 2050. *Ophthalmology*. 2016;123:1036–42.
3. Vongphanit J, Mitchell P, Wang JJ. Prevalence and progression of myopic retinopathy in an older population. *Ophthalmology*. 2002;109:704–11.
4. Saw SM, Gazzard G, Shih-Yen EC, Chua WHJO. Myopia and associated pathological complications. *Ophthalmic Physiol Opt*. 2005;25:381–91.
5. Bullimore MA, Richdale K. Myopia control 2020: where are we and where are we heading? *Ophthalmic Physiol Opt*. 2020;40:254–70.
6. Brennan NA, Toubouti YM, Cheng X, Bullimore MA. Efficacy in myopia control. *Prog Retin Eye Res*. 2021;83:100923. https://doi.org/10.1016/j.preteyeres.2020.100923
7. Huang J, Wen D, Wang Q, McAlinden C, Flitcroft I, Chen H, et al. Efficacy comparison of 16 interventions for myopia control in children: a network meta-analysis. *Ophthalmology*. 2016;123:697–708.
8. Rose KA, Morgan IG, Ip J, Kifley A, Huynh S, Smith W, et al. Outdoor activity reduces the prevalence of myopia in children. *Ophthalmology*. 2008;115:1279–85.
9. Wu PC, Tsai CL, Wu HL, Yang YH, Kuo HK. Outdoor activity during class recess reduces myopia onset and progression in school children. *Ophthalmology*. 2013;120:1080–5.
10. French AN, Ashby RS, Morgan IG, Rose KA. Time outdoors and the prevention of myopia. *Exp Eye Res*. 2013;114:58–68.
11. Cohen Y, Belkin M, Yehezkel O, Solomon AS, Polat U. Dependency between light intensity and refractive development under light-dark cycles. *Exp Eye Res*. 2011;92:40–6.
12. Ashby R, Ohlendorf A, Schaeffel F. The effect of ambient illuminance on the development of deprivation myopia in chicks. *Invest Ophthalmol Vis Sci*. 2009;50:5348–54.
13. Karouta C, Ashby RS. Correlation between light levels and the development of deprivation myopia. *Invest Ophthalmol Vis Sci*. 2015;56:299–309.
14. Smith EL 3rd, Hung LF, Huang J. Protective effects of high ambient lighting on the development of form-deprivation myopia in rhesus monkeys. *Invest Ophthalmol Vis Sci*. 2012;53:421–8.
15. Norton TT, Siegwart JT. Light levels, refractive development, and myopia–a speculative review. *Exp Eye Res*. 2013;114:48–57.
16. Chen S, Zhi Z, Ruan Q, Liu Q, Li F, Wan F, et al. Bright light suppresses form-deprivation myopia development with activation of

dopamine D1 receptor signaling in the ON pathway in retina. *Invest Ophthalmol Vis Sci*. 2017;58:2306–16.
17. Ashby RS, Schaeffel F. The effect of bright light on lens compensation in chicks. *Invest Ophthalmol Vis Sci*. 2010;51:5247–53.
18. Li W, Lan W, Yang S, Liao Y, Xu Q, Lin L, et al. The effect of spectral property and intensity of light on natural refractive development and compensation to negative lenses in guinea pigs. *Invest Ophthalmol Vis Sci*. 2014;55:6324–32.
19. Smith EL 3rd, Hung L-F, Arumugam B, Huang J. Negative lens–induced myopia in infant monkeys: effects of high ambient lighting. *Invest Ophthalmol Vis Sci*. 2013;54:2959–69.
20. Feldkaemper M, Schaeffel F. An updated view on the role of dopamine in myopia. *Exp Eye Res*. 2013;114:106–19.
21. Zhou X, Pardue MT, Iuvone PM, Qu J. Dopamine signaling and myopia development: what are the key challenges. *Prog Retin Eye Res*. 2017;61:60–71.
22. Ashby R. Animal studies and the mechanism of myopia—protection by light? *Optom Vis Sci*. 2016;93:1052–4.
23. Stone RA, Cohen Y, McGlinn AM, Davison S, Casavant S, Shaffer J, et al. Development of experimental myopia in chicks in a natural environment. *Invest Ophthalmol Vis Sci*. 2016;57:4779–89.
24. Chakraborty R, Ostrin LA, Nickla DL, Iuvone PM, Pardue MT, Stone RA. Circadian rhythms, refractive development, and myopia. *Ophthalmic Physiol Opt*. 2018;38:217–45.
25. Nickla DL, Wildsoet CF, Troilo D. Endogenous rhythms in axial length and choroidal thickness in chicks: implications for ocular growth regulation. *Invest Ophthalmol Vis Sci*. 2001;42:584–8.
26. Nickla DL, Totonelly K. Brief light exposure at night disrupts the circadian rhythms in eye growth and choroidal thickness in chicks. *Exp Eye Res*. 2016;146:189–95.
27. Chakraborty R, Read SA, Collins MJ. Diurnal variations in axial length, choroidal thickness, intraocular pressure, and ocular biometrics. *Invest Ophthalmol Vis Sci*. 2011;52:5121–9.
28. Stone RA, Quinn GE, Francis EL, Ying GS, Flitcroft DI, Parekh P, et al. Diurnal axial length fluctuations in human eyes. *Invest Ophthalmol Vis Sci*. 2004;45:63–70.
29. Tan CS, Ouyang Y, Ruiz H, Sadda SR. Diurnal variation of choroidal thickness in normal, healthy subjects measured by spectral domain optical coherence tomography. *Invest Ophthalmol Vis Sci*. 2012;53:261–6.
30. Burfield HJ, Carkeet A, Ostrin LA. Ocular and systemic diurnal rhythms in emmetropic and myopic adults. *Invest Ophthalmol Vis Sci*. 2019;60:2237–47.
31. Ulaganathan S, Read SA, Collins MJ, Vincent SJ. Daily axial length and choroidal thickness variations in young adults: associations with light exposure and longitudinal axial length and choroid changes. *Exp Eye Res*. 2019;189:107850. https://doi.org/10.1016/j.exer.2019.107850
32. Jones LA, Sinnott LT, Mutti DO, Mitchell GL, Moeschberger ML, Zadnik K. Parental history of myopia, sports and outdoor activities, and future myopia. *Invest Ophthalmol Vis Sci*. 2007;48:3524–32.
33. Guo Y, Liu LJ, Tang P, Lv YY, Feng Y, Xu L, et al. Outdoor activity and myopia progression in 4-year follow-up of Chinese primary school children: the Beijing children eye study. *PLoS One*. 2017;12:e0175921. https://doi.org/10.1371/journal.pone.0175921
34. Guggenheim JA, Northstone K, McMahon G, Ness AR, Deere K, Mattocks C, et al. Time outdoors and physical activity as predictors of incident myopia in childhood: a prospective cohort study. *Invest Ophthalmol Vis Sci*. 2012;53:2856–65.
35. Jacobsen N, Jensen H, Goldschmidt E. Does the level of physical activity in university students influence development and progression of myopia? A 2-year prospective cohort study. *Invest Ophthalmol Vis Sci*. 2008;49:1322–7.
36. Dirani M, Tong L, Gazzard G, Zhang X, Chia A, Young TL, et al. Outdoor activity and myopia in Singapore teenage children. *Br J Ophthalmol*. 2009;93:997–1000.
37. Read SA, Vincent SJ, Tan CS, Ngo C, Collins MJ, Saw SM. Patterns of daily outdoor light exposure in Australian and Singaporean children. *Transl Vis Sci Technol*. 2018;7:8. https://doi.org/10.1167/tvst.7.3.8
38. Read SA, Collins MJ, Vincent SJ. Light exposure and eye growth in childhood. *Invest Ophthalmol Vis Sci*. 2015;56:6779–87.
39. Ostrin LA, Sajjadi A, Benoit JS. Objectively measured light exposure during school and summer in children. *Optom Vis Sci*. 2018;95:332–42.
40. Wu PC, Chen CT, Lin KK, Sun CC, Kuo CN, Huang HM, et al. Myopia prevention and outdoor light intensity in a school-based cluster randomized trial. *Ophthalmology*. 2018;125:1239–50.
41. Hua WJ, Jin JX, Wu XY, Yang JW, Jiang X, Gao GP, et al. Elevated light levels in schools have a protective effect on myopia. *Ophthalmic Physiol Opt*. 2015;35:252–62.
42. Ahn J, Ahn SE, Yang KS, Kim SW, Oh J. Effects of a high level of illumination before sleep at night on chorioretinal thickness and ocular biometry. *Exp Eye Res*. 2017;164:157–67.
43. Lanca C, Teo A, Vivagandan A, Htoon HM, Najjar RP, Spiegel DP, et al. The effects of different outdoor environments, sunglasses and hats on light levels: implications for myopia prevention. *Transl Vis Sci Technol*. 2019;8:7. https://doi.org/10.1167/tvst.8.4.7
44. Bogen S, Legenbauer T, Gest S, Holtmann M. Morning bright light therapy: a helpful tool for reducing comorbid symptoms of affective and behavioral dysregulation in juvenile depressed inpatients? A pilot trial. *Z Kinder Jugendpsychiatr Psychother*. 2017;45:34–41.
45. Mostafa KG, Montemagno C, Qureshi AJJPM. Strength to cost ratio analysis of FDM nylon 12 3D printed parts. *Procedia Manuf*. 2018;26:753–62.
46. Mallen EA, Kashyap P, Hampson KM. Transient axial length change during the accommodation response in young adults. *Invest Ophthalmol Vis Sci*. 2006;47:1251–4.
47. Woodman EC, Read SA, Collins MJ. Axial length and choroidal thickness changes accompanying prolonged accommodation in myopes and emmetropes. *Vis Res*. 2012;72:34–41.
48. Chakraborty R, Read SA, Collins MJ. Monocular myopic defocus and daily changes in axial length and choroidal thickness of human eyes. *Exp Eye Res*. 2012;103:47–54.
49. Lou L, Ostrin LA. Effects of narrowband light on choroidal thickness and the pupil. *Invest Ophthalmol Vis Sci*. 2020;61:ARVO E-Abstract 40.
50. Read SA, Collins MJ. Water drinking influences eye length and IOP in young healthy subjects. *Exp Eye Res*. 2010;91:180–5.
51. Holzer MP, Mamusa M, Auffarth GU. Accuracy of a new partial coherence interferometry analyser for biometric measurements. *Br J Ophthalmol*. 2009;93:807–10.
52. Buckhurst PJ, Wolffsohn JS, Shah S, Naroo SA, Davies LN, Berrow EJ. A new optical low coherence reflectometry device for ocular biometry in cataract patients. *Br J Ophthalmol*. 2009;93:949–53.
53. Moderiano D, Do M, Hobbs S, Lam V, Sarin S, Alonso-Caneiro D, et al. Influence of the time of day on axial length and choroidal thickness changes to hyperopic and myopic defocus in human eyes. *Exp Eye Res*. 2019;182:125–36.
54. Alonso-Caneiro D, Read SA, Collins MJ. Automatic segmentation of choroidal thickness in optical coherence tomography. *Biomed Opt Express*. 2013;4:2795–812.
55. He M, Xiang F, Zeng Y, Mai J, Chen Q, Zhang J, et al. Effect of time spent outdoors at school on the development of myopia among children in China: a randomized clinical trial. *JAMA*. 2015;314:1142–8.
56. Chakraborty R, Read SA, Vincent SJ. Understanding myopia: pathogenesis and mechanisms. In: Ang M, Wong TY, editors. Updates on myopia: a clinical perspective. 1st ed. Singapore: Springer; 2020. p. 65–94.
57. Read SA, Pieterse EC, Alonso-Caneiro D, Bormann R, Hong S, Lo C-H, et al. Daily morning light therapy is associated with an increase in choroidal thickness in healthy young adults. *Sci Rep*. 2018;8:8200. https://doi.org/10.1038/s41598-018-26635-7
58. Read SA. Ocular and environmental factors associated with eye growth in childhood. *Optom Vis Sci*. 2016;93:1031–41.

59. Lan W, Feldkaemper M, Schaeffel F. Bright light induces choroidal thickening in chickens. *Optom Vis Sci*. 2013;90:1199–206.
60. Ikuno Y, Kawaguchi K, Nouchi T, Yasuno Y. Choroidal thickness in healthy Japanese subjects. *Invest Ophthalmol Vis Sci*. 2010;51:2173–6.
61. Manjunath V, Taha M, Fujimoto JG, Duker JS. Choroidal thickness in normal eyes measured using cirrus HD optical coherence tomography. *Am J Ophthalmol*. 2010;150:325–29.e1.
62. Bhandary SK, Dhakal R, Sanghavi V, Verkicharla PK. Ambient light level varies with different locations and environmental conditions: potential to impact myopia. *PLoS One*. 2021;16:e0254027. https://doi.org/10.1371/journal.pone.0254027
63. van Duijnhoven J, Aarts MPJ, Kort HSM. The importance of including position and viewing direction when measuring and assessing the lighting conditions of office workers. *Work*. 2019;64:877–95.
64. Norton TT, Amedo AO, Siegwart JT Jr. Darkness causes myopia in visually experienced tree shrews. *Invest Ophthalmol Vis Sci*. 2006;47:4700–7.
65. Delshad S, Collins MJ, Read SA, Vincent SJ. The time course of the onset and recovery of axial length changes in response to imposed defocus. *Sci Rep*. 2020;10:8322. https://doi.org/10.1038/s41598-020-65151-5
66. Delshad S, Collins MJ, Read SA, Vincent SJ. Effects of brief periods of clear vision on the defocus-mediated changes in axial length and choroidal thickness of human eyes. *Ophthalmic Physiol Opt*. 2021;41:932–40.
67. Xie R, Zhou XT, Lu F, Chen M, Xue A, Chen S, et al. Correlation between myopia and major biometric parameters of the eye: a retrospective clinical study. *Optom Vis Sci*. 2009;86:E503–8.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Chakraborty R, Baranton K, Spiegel D, Lacan P, Guillon M, Barrau C, et al. Effects of mild- and moderate-intensity illumination on short-term axial length and choroidal thickness changes in young adults. *Ophthalmic Physiol Opt*. 2022;42:762–772. https://doi.org/10.1111/opo.12988