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Objectively Measured Light Exposure during School and Summer in Children

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Abstract

Significance—Significant differences in light exposure were observed between school and summer in children, while activity and sleep were similar. Associations between parent and child behaviors suggest a potential mechanism for how myopia is transmitted from parents to children through patterns of environmental exposure, in addition to genetic factors.

Purpose—Objectively measured time outdoors, light exposure, activity and sleep were examined in children during school and summer, and assessed with eye growth. Associations between parent and child behaviors were evaluated.

Methods—Children (aged 7.6 ± 1.8 years, $n = 60$) in Houston, Texas, wore an actigraph device for three 2 week sessions (fall school, spring school, summer) to quantify time outdoors, light exposure, activity, and sleep. Cycloplegic autorefraction (WAM-5500) and axial length (LenStar) were measured at baseline and one year. A subset of parents wore the device during their child's first 2 week session to compare behaviors ($n = 33$).

Results—Children spent 94.4 ± 30.6 minutes per day outdoors in spring, 110.6 ± 45.7 minutes in summer, and 72.2 ± 31.0 minutes in fall, with significant differences between sessions ($P < 0.0001$). Daily activity and sleep duration were similar across sessions ($P = 0.73$ and 0.06 , respectively). Axial growth rate decreased with light exposure, but did not reach significance after adjusting for baseline axial length, age, sex, activity, and parental myopia ($P = 0.073$). Parent and child time outdoors and sleep duration were significantly correlated ($P = 0.0002$ and 0.026 , respectively).

Conclusions—Significant differences in light exposure were observed between school and summer, while activity and sleep were constant throughout the year. Children's behaviors were associated with their parent's behaviors, which may represent a modifiable component to potential environmental influences on eye growth. However, light exposure was not a significant environmental influence on axial growth in this study.

Keywords

myopia; refractive error; axial length; environment; behavior; light exposure; time outdoors

The prevalence of myopia has been increasing and is considered an epidemic in some populations.^{1, 2} Refractive development and eye growth are regulated by a complex interaction between genetic and environmental factors.^{3, 4} Environmental and behavioral factors that have been investigated with respect to myopia include time outdoors,^{5, 6} near work,^{7–9} physical activity,^{6, 10} nutrition,¹¹ and urbanization.¹² Of these, growing evidence suggests that the most important influence is outdoor light exposure, with the majority of studies reporting a protective effect against the development of myopia with increased light exposure.^{5, 13–15}

At birth, humans, as well as many other vertebrate species, have a mismatch between optical power and eye length resulting in refractive error, with a Gaussian distribution centered around low hyperopia.¹⁶ There is a rapid decrease in refractive error over the first 12 months of life, then continuing at a slower rate, so that by 6 years of age, refractive error in the population demonstrates a leptokurtotic distribution centered at low hyperopia.^{17, 18} This process of emmetropization is visually guided and locally regulated within the retina.^{19–21} Myopia tends to have its onset during grade school, and is generally attributed to the eye growing too long axially.²² Myopia, even at mild levels,²³ is associated with an increased risk of retinal detachment,²⁴ cataract, and glaucoma.²⁵ Retinal complications in myopia reflect the retinal stretching²⁶ and thinning²⁷ that accompany excessive axial elongation. Urban areas of East Asian countries have experienced the greatest increase in myopia over the past decade, with the most recent figures showing prevalences exceeding 80–90%.^{2, 28–30} Importantly, the prevalence of high myopia is also rising, with an 8 fold increase in myopia greater than 8 D in the US from 1972 to 2004,¹ and with it, the prevalence of associated pathologies will increase.

Studies utilizing questionnaires have reported associations between parent-reported time spent outdoors and myopia in children^{5, 31–33} and young adults,³⁴ with meta-analysis showing a 2% reduced odds of myopia per additional hour of time spent outdoors per week.³⁵ More recently, wearable light sensors have been utilized to assess the influence of light exposure in children^{14, 36, 37} and adults^{38, 39} on refractive status. Read, et al, found that myopic subjects, ages 10–15 years, experienced significantly lower daily light exposure than similarly aged emmetropic subjects.¹⁴ Seasonal variations in light exposure may also affect patterns of eye growth.⁴⁰ In children, progression of myopia has been shown to be slower in summer months, which has been attributed to children spending fewer hours in school, more hours in sports, and increased time outdoors.^{32, 41, 42}

Animal studies have provided support for the hypothesis that increased light exposure is protective against myopia. Studies in chicks and Rhesus monkeys have shown that high ambient lighting significantly reduces the development of form deprivation myopia^{43, 44}; however, high light was not found to affect lens induced myopia in either animal model.^{45, 46} Results from a study in which infant Rhesus monkeys were exposed to natural outdoor light suggest that exposure to sunlight, especially early in life, may promote normal emmetropization.¹³

With growing evidence to suggest that light exposure plays a significant role in eye growth, the current study was designed to objectively measure ambient light exposure and activity

patterns longitudinally in young children, compare light exposure patterns between school and summer months, and investigate relationship between light exposure and axial elongation. We also sought to investigate associations between parent and child behaviors to understand parental influences and identify potentially modifiable behaviors.

METHODS

Subjects

Children between the ages of 5–10 years ($n = 64$) were recruited for this longitudinal study. All parents provided written permission and children provided assent. The study was approved by the Committee for Protection of Human Subjects at the University of Houston and procedures followed the tenets of the Declaration of Helsinki.

At enrollment, a complete optometric exam was performed, including visual acuity, binocular assessment and anterior segment evaluation. All children had best corrected visual acuity of 20/25 or better. Eyes were dilated with 0.5% proparacaine, 1% tropicamide and 2.5% phenylephrine, and a fundus exam was performed. Axial length, central corneal thickness, anterior chamber depth and lens thickness were measured (LenStar, Haag-Streit AG, Switzerland). Three measurements were recorded and averaged for each eye. Cycloplegic refractive error and corneal power were measured (WAM-5500, Grand-Seiko, Tokyo, Japan). Five or more measurements were recorded, and the spherical equivalent refraction (SER) was calculated for each eye. SER was similar between right and left eyes ($P = 0.798$) with a mean difference of 0.39 ± 0.42 D. Children were classified as hyperopic ($> +2.00$ D), emmetropic ($+2.00$ to -0.25 D) or myopic (< -0.25 D) based on the right eye refraction. Exclusion criteria included ocular pathology and treatment for myopia, including multifocal contact lenses or atropine drops. Children returned for a comprehensive eye exam at one year. Biometric and cycloplegic refraction measurements were repeated as described above.

Parents were asked to complete an ocular history questionnaire for themselves and their children at the time of enrollment, including items about parent and child refractive history. Additionally, parents were asked to complete a custom written visual activity survey for their children. Items were adapted from the Sydney Myopia Study Questionnaire⁵, and included questions regarding time spent outdoors and time doing near work (books, computers and hand held devices asked as separate items). Questions were asked with respect to school and summer sessions separately.

Objective Measurement of Light, Activity and Sleep

Following the baseline eye exam, an actigraph device (Actiwatch Spectrum, Philips Respironics, Bend, OR) was dispensed for children to wear continuously for 2 weeks. Children were asked to wear the device for two additional 2 week sessions over the year, for a total of three 2 week sessions, encompassing two school sessions and one summer session. Data derived from the Actiwatch were divided as follows: spring school session (January – May), summer session (June – August), and fall school session (September – December).

For school sessions, spring break and winter break were avoided, so that children were in class for the two weeks that the device was worn.

The Actiwatch Spectrum is a non-invasive wrist-worn activity monitoring method that measures ambient light exposure and activity continuously at 32 Hz. The device is light weight, and has been actively used in both children and adults in various applications, including light exposure, activity and sleep related studies.^{39, 47–49} The light sensor in the Actiwatch Spectrum consists of color sensitive photodiodes to measure illuminance of white light in units of lux (range 0.1 to 200,000 lux), and the irradiance of the red, green and blue spectral components in $\mu\text{W}/\text{cm}^2$ (red channel: 400–500 nm, green channel: 500–600 nm, blue channel: 600–700 nm). Physical activity is measured via a solid-state piezoelectric accelerometer, and is expressed in “counts per minute” (cpm). The device is waterproof for up to 30 minutes and resistant to heat, perspiration, and cold. The device displays the time and date, and a sensor detects “off-wrist” time to monitor subject compliance. The device software (Actiware 6.0.4, Philips Respironics, Bend, OR) determines active and rest time, as well as sleep parameters such as bed time, sleep duration and sleep efficiency.

The Actiwatch device was set to average over one minute epochs. Children were instructed not to remove the device for the entire measurement period. Light exposure and activity counts were only included in the analysis when the subject wore the device for the entire day. Therefore, partial first and last days were excluded. Days were also excluded if the subject removed the device for more than 30 minutes, or if the light exposure dropped to zero for 30 minutes or more during daylight hours, indicating that the sensors on the device were obstructed by clothing. Mean daily activity was calculated by averaging counts per minute for the hours the subject was awake. Activity and light parameters were adapted from previous validation studies using a similar wrist-worn Actiwatch accelerometer in children.^{32, 33} Minutes exposed to >1000 lux was used as an approximation for time spent outdoors during daylight hours.^{37,39}

Thirty-three parents of 31 children, representing 18 different families, wore the actigraph device during the first session that their children participated to evaluate the relationship between objectively measured light exposure, activity, and sleep within families. Additionally, the parents completed a similar activity survey for themselves as they did for their children so that parent and child behaviors could be compared.

Data Analysis

Only right eyes are included in the analysis. Results are presented as mean values $\pm$ standard deviation. Watch metrics analyzed included mean daily white (broad band) light exposure (lux), red and blue light exposure ($\mu\text{W}/\text{cm}^2$), mean minutes outdoors per day (>1000 lux), mean daily activity (cpm), and mean daily sleep duration (minutes). Statistical analyses were conducted using SAS 9.3.

To evaluate the potential bias due to differences in intervals of time of watch wear and to detect outliers, a multilevel (time within person) linear modeling approach was used. Each watch metric was modeled as a function of potential sunlight available during each actual session of watch wear centered at the grand mean. Daily duration of Houston daylight was

downloaded from the United States Naval Observatory, and matched to the watch wearing date for each subject. The intercept value of each watch metric was assumed to vary across children and the fixed effect of potential sunlight exposure was tested. A measure of expected mean light exposure was estimated for each individual adjusting for the potential exposure and included to conduct a sensitivity analysis for the primary analysis of white light exposure on axial length. This strategy accounts for the potential bias due to children not being observed at the same time point. Univariate and bivariate residual plots were constructed to detect outliers. Quantile-normal plots, histograms, and formal tests for normality were conducted to verify assumptions for parametric statistical analyses. Natural log transformations of mean light exposures for white, red, and blue were used as dependent outcomes for all parametric testing.

Changes in biometric parameters, including central corneal thickness, anterior chamber depth, lens thickness and axial length, over one year were compared between refractive error groups. Two sample t-tests (adjusting for unequal variance where necessary) and Wilcoxon rank sums tests were used for refractive error group comparisons.

To determine bivariate relationships between each raw watch metric and axial length at the one year follow-up, Spearman partial correlations were estimated separately for each metric adjusting for baseline age and axial length. Multiple linear regression analysis was performed to determine the relationship between mean white light exposure (natural log transformed) and one year axial length, controlling for baseline axial length, age, sex, activity, and parental myopia status determined a priori. Additionally, multiple linear regression analysis was performed to determine the relationship between mean white light exposure (natural log transformed) and one year SER, controlling for baseline SER, age, sex, activity, and parental myopia status. We repeated the analysis using the expected mean light exposure that was estimated for each individual after adjusting for the potential exposure.

To examine the impact of increasing bright light intensities, we calculated the mean exposure time per day to five white light intensities (>1000, >2000, >5000, >10,000, and >50,000 lux) for each session for each individual. Repeated measures ANOVA was used to assess whether each mean white light exposure intensity differed by session, and between refractive groups, and whether session effects differed between refractive error groups. Specifically, we tested for effects of within-subject factor (session - spring, summer, fall), between-subject factor (refractive error group – emmetrope, myope), and a session by refractive group interaction. Bonferroni correction was used to account for each of the outcome variables derived from average white light exposure and tested main effects and interaction at the critical level of 0.01. In the presence of a statistically significant interaction, post hoc comparisons were conducted with multiple comparison adjustments.

For parent and child comparisons, Pearson and Spearman correlations, where appropriate, were used to evaluate the relationship between mean parent and mean child objective measures within a family, including times spent outdoors, light exposure, activity and sleep.

RESULTS

Demographics

Over one year, four children were lost to follow up, with a total of 60 children presenting for the one year eye exam, comprised of 24 females and 36 males from 38 families. Ethnic makeup included 45 Caucasian, 8 Asian, 4 Hispanic, and 3 African American. Compliance wearing the Actiwatch was high, with a mean number of 13.9 ± 2.9 days included in the analysis per subject per session. For all subjects over all three sessions, approximately 18 days ($< 1\%$) of Actiwatch data were removed from the analysis due to the light sensor being obstructed.

Measured mean daily white, red, and blue light exposure and average time outdoors were statistically dependent upon the potential amount of exposure to sunlight available at the time of watch wear ($P < 0.0001$). Measured activity had no bearing on the amount of potential exposure to light that was available during watch wear ($P = 0.71$).

Refractive and Biometric Changes

At baseline, mean SER of right eyes was $+0.85 \pm 1.49$ D (range -2.41 to $+7.75$ D) and mean axial length was 22.61 ± 0.84 mm (range 20.85 to 24.9 mm). The subject population included 5 hyperopes, 47 emmetropes, and 8 myopes. At one year, mean SER was $+0.66 \pm 1.58$ D (range -2.88 to $+7.88$), representing a significant decrease of -0.18 D (range $+1.02$ to -1.57 D, $P = 0.003$), and mean axial length was 22.83 ± 0.88 mm (range 20.95 to 25.16), representing a significant increase of 0.22 mm (range -0.03 to $+0.82$, $P < 0.0001$). SER change in D/yr was associated with axial length change in mm/yr ($R^2 = 0.207$, $P = 0.0004$, Figure 1). At one year, refractive error groups included 3 hyperopes, 47 emmetropes, and 10 myopes. For the remainder of the analyses, children were grouped according to SER measured at baseline, except for parental myopia analysis in Table 2.

Over the one year period, a myopic shift in SER was exhibited in the myopic group (-0.44 ± 0.40 D, $P = 0.054$, Table 1). After one year, children who were identified as hyperopic and emmetropic at baseline had on average change in SER of -0.33 ± 0.46 D ($P = 0.18$) and -0.12 ± 0.43 D ($P = 0.06$), respectively. All three refractive error groups experienced significant increases in axial length, with the myopic group having the greatest change (0.40 ± 0.18 mm). Corneal power significantly decreased in the emmetropic group, and anterior chamber depth significantly increased in myopic group. The lens thinned in all groups, but was only significant in the emmetropic group. Central corneal thickness was not significantly different between baseline and one year for any refractive error group.

Subjective vs. Objective Measures

According to the questionnaire, parents reported that children spent 65.5 ± 35.2 minutes per day outdoors during school sessions and 115.8 ± 83.0 minutes per day during the summer. Objectively measured mean time outdoors (i.e. time exposed to >1000 lux) during the school sessions was 84.6 ± 25.5 minutes per day (average of spring and fall school sessions) and during the summer was 111.0 ± 47.1 minutes per day. Parents significantly underestimated children's time outdoors during school sessions by 19 minutes compared to objective

measures ($P = 0.0006$, Figure 2A). Parents estimates of children's time outdoors during the summer were not significantly different than those measured objectively with the device ($P = 0.66$, Figure 2B), despite wide variability in the results.

School vs. Summer Measures

From objective measures, children spent a mean of 92.4 ± 24.9 minutes per day exposed to outdoor light (>1000 lux) for the year. Compared across sessions, children had significantly more time exposed to outdoor light lux in the summer (110.5 ± 45.8 minutes) than in spring (94.2 ± 30.4 minutes) or fall (72.2 ± 31.0 minutes, $P < 0.0001$, Figure 3A). Additionally, children received the highest light dose (mean daily light exposure) during the summer compared to spring and fall school sessions ($P < 0.0001$, Figure 3B).

Mean daily activity was 571 ± 111 cpm in the spring session, 564 ± 138 cpm in summer session, and 556 ± 132 cpm in the fall session, with no significant differences between sessions ($P = 0.73$, Figure 3C). Sleep duration was 544 ± 38 minutes in the spring school session, 555 ± 37 minutes in the summer session, and 556 ± 37 minutes in the fall school session, with no significant differences between sessions ($P = 0.06$, Figure 3D).

Parent and Child Characteristics

Parental refractive error (biological mother and father) was characterized from the ocular history questionnaire, and for this analysis, children's refractive error groups are based on refraction at 1 year. 80% of the myopic children had two myopic parents, whereas 45% of the emmetropic children and 0% of the hyperopic children had two myopic parents (Table 2).

For the subset of children who were included in family analyses, parents' subjective report of time spent performing near work per day was 564 ± 281 minutes, while the estimate for their children was 480 ± 82 minutes. Objectively, parents spent 111 ± 55 minutes per day exposed to outdoor light, and children spent 97 ± 48 minutes per day exposed to outdoor light (Figure 4). Parent and child times spent outdoors were significantly correlated ($r = 0.76$, $P = 0.0002$). The relationship between parental mean daily white light exposure and that of their children did not reach significance ($r = 0.42$, $P = 0.081$). Parent's objectively measured daily activity was not statistically correlated with their children ($r = 0.30$, $P = 0.226$). Parent's objectively measured sleep duration was significantly correlated with their children's ($r = 0.52$, $P = 0.026$); i.e. parents who had longer mean sleep duration had children who also had longer mean sleep duration.

Objective Light, Activity, and Sleep Measures with Eye Growth

Spearman correlations were used to estimate the partial correlations of axial length growth with increased light exposure and time exposed to outdoor light while controlling for age and baseline axial length. None of the individual estimated correlations met the criteria of statistical significance, but the directionality was consistently negative [mean daily white light exposure ($r = -0.154$, $P = 0.248$), mean daily red light exposure ($r = -0.151$, $P = 0.259$), mean daily blue light exposure ($r = -0.159$, $P = 0.234$), and time exposed to outdoor light ($r = -0.176$, $P = 0.187$)]. In an adjusted multiple linear regression analysis controlling

for baseline axial length, age, sex, mean daily activity (cpm), and parental myopic status, we estimated log daily white light exposure effect of -0.094 mm/yr on axial length at 1 year, which indicates that for every 1 log unit increase in average daily white light exposure, axial growth rate decreased by 0.094 mm/yr, although this effect did not reach statistical significance (*adjusted* $R^2 = 0.978$, $b = -0.094$, $SE: 0.052$, 95% $CI: -0.198$ to 0.009 , $P = 0.073$, Table 3). An influential observation was detected during modeling diagnostic evaluation, and the regression analysis was performed with the removal of this data point to determine its influence on our results (*adjusted* $R^2 = 0.980$, $b = 0.050$, $SE: 0.047$, 95% $CI: -0.143$ to 0.044 , $P = 0.291$). In the repeated analysis that used estimated amounts of light exposure (in lieu of actual) adjusted for amount of sunlight available during the time of each child's session, we observed similar estimates and findings (results not reported).

When analyzing the effect of white light exposure on dependent variable SER at year 1 ($n = 57$), we observed a decreased rate of -0.006 D in refractive error at 1 year per 1 log unit increase in average daily white light exposure ($b = -0.006$, $SE: 0.184$, 95% $CI: -0.37, 0.363$, $P = 0.474$, Table 4). Upon performing model diagnostics, we detected the same influential observation and performed the analysis with removal of the influential point (*adjusted* $R^2 = 0.9185$, $b = -0.127$, $SE: 0.176$, 95% $CI: -0.482$ to 0.227 , $P = 0.474$).

Average time spent exposed to levels of ambient illumination thresholds from $>1,000$ lux to $>50,000$ lux across sessions and myopic groups are reported in Table 5. On average, the overall amount of time spent per day above varying thresholds of ambient light exposure ranged from 6.8 ($>50,000$ lux) to 95.8 ($>1,000$ lux) minutes per day for emmetropes, and 5.5 ($>50,000$ lux) to 76.3 ($>1,000$ lux) minutes per day for myopes. In a repeated measures ANOVA with refractive group and session as main effects, and including the refractive group by session interaction (Table 5), using Bonferroni correction at 0.01 , we observed a statistically significant main effect of session for $>1,000$ lux, $>2,000$ lux and $>5,000$ lux ($P < 0.01$ for all). There were no significant main effects of refractive group nor were there statistically significant differences in seasonal effects observed between myopic and emmetropic groups regardless of light intensity threshold, indicating that the seasonal effect is constant across refractive groups (refractive group by session interaction, $P > 0.05$ for all).

DISCUSSION

Our findings have quantified minutes per day children spend outdoors during school and summer sessions. We showed that children spent more time outdoors and received a higher light dose in the summer than during school sessions, as found with objective measures. Physical activity and sleep were not significantly different between summer and school. Objectively measured time outdoors for parents and children was correlated, as was sleep duration. However, daily light exposure between parent and child was not correlated, which could be due to parents and children being outdoors at different times of day, or in varying degrees of sun exposure, such as shade versus full sun. While trends suggested that axial growth rate over one year was associated with decreased light exposure, the relationship did not reach statistical significance after controlling for multiple factors. Additionally, trends suggesting that myopic children spent less time exposed to bright outdoor light in summer compared to emmetropic children did not reach statistical significance following Bonferroni

correction, despite myopes spending 39.6 minutes less per day outdoors in the summer compared to emmetropes. Parent estimations of time spent outdoors by their children was poorly correlated to objective measures.

Studies suggest that parental role modeling of behaviors, such as having a sedentary lifestyle, is associated with children's behaviors.⁵⁰ For example, previous studies have shown that parental screen time and physical activity are positively associated with their children's screen time and activity.^{50–52} Here, observed associations between parent and child time outdoors are in accordance with previous studies showing that children's behaviors are influenced by their parents. The increased rate of myopia prevalence in children with myopic parents may therefore have a strong parental behavioral component. Our results suggest that time outdoors may be a modifiable behavior that can be influenced by parental role modeling. Subjective measurements of near work were not correlated between parents and children; however, more objective analyses may suggest otherwise, as subjective estimates of parent's and children's behavioral patterns demonstrate high variability.

A main goal of this study was to determine the relationship between light exposure and axial length, and particularly, to estimate the effect of light exposure on axial growth rate. As a first step, we assessed the bivariate strength of the association by computing Spearman partial correlations, a robust technique, using the raw data, while statistically controlling for age and baseline axial length, to account for the natural progression of axial length. While the estimated correlation indicates a potential protective relationship (decreased axial growth rate with increased light exposure), the effect was weak to moderate and we were unable to detect a statistically significant relationship. The multiple regression analysis statistically controlled for factors that influence the relationship between light exposure and axial length, outside of the biological sense, in an effort to obtain the least biased estimate of the relationship. Our results are among the first to provide estimated effect sizes of objective light exposure on axial length in a cohort of children of this age group, and the first in this geographical region. We estimated that for these young children, a 1 log unit increase in daily white light exposure was associated with approximately 0.094 mm/yr decrease in axial length growth and provided 95% CIs around these estimates. The effect size should be interpreted with caution, as the removal of an influential point identified both at the unconditional outcome level and conditional upon predictors resulted in an effect of approximately 0.05 mm/yr decrease in axial growth rate (and did not reach statistical significance). In a previous study, Read et al. observed an estimated effect size of 0.12 mm/yr. The effect of light exposure on axial length in our sample was not statistically significant and not substantially impacted by an influential point. Our analysis and estimation indicate that the effect is small in magnitude relative to its variability and necessitates a larger sample to be detected.

The multiple regression model examining factors that contribute to rate of axial growth over one year shows that baseline axial length and age at enrollment have the most influence on eye growth. Measured axial lengths were similar to those predicted in growth curves by Jones, et al,⁵³ although our myopic and hyperopic groups had slightly longer mean axial lengths, and our emmetropic group had slightly shorter axial lengths than predicted. These

departures from the predicted axial length curves could stem from different mean refractive errors for each group between the two studies.

In the present study, we evaluated the youngest cohort of children yet to be followed objectively and longitudinally. In a cross sectional study by Dharani, et al, a wearable light meter (HOBO) was worn for one week by Singaporean children of a similar age studied here to compare school term and school holiday sessions.³⁷ The authors reported time spent exposed to outdoor light, per the light meter, during school term was 424.8 minutes per week and during school holiday was 588.6 minutes per week. In comparison, we found that children spent 582.4 minutes per week during school sessions and 773.5 minutes per week during the summer session exposed to outdoor light. While differences in study design exist, we speculate that less time exposed to bright outdoor light in Singapore might play a role in the increased prevalence of myopia in Singapore compared to the US.^{31,54}

Using similar methodology to the current study, Read, et al, reported that myopic children, ages 10–15, spent 36 minutes less exposed to outdoor light than emmetropic children.¹⁴ Similarly, we found a difference of 39 minutes during the summer, with differences of 6–12 minutes during school sessions. Mean activity in counts per minute were higher in the current study than found in the Read, et al, study (564 vs 462 cpm), which may be due to the younger cohort here.¹⁴ In the current study, children spent an average of 92 minutes per day outdoors throughout the year, compared to 107 minutes per day in Brisbane, Australia. However, children's mean daily white light exposure was greater in Houston (1627 lux) than reported in Brisbane (1072 lux), despite the two locations being similar distance from the equator (Houston 2046 miles and Brisbane 1889 miles). The previous study used the Actiwatch 2, as opposed to the Actiwatch Spectrum used here. The light sensor of the Actiwatch 2 has a range of 5–100,000 lux, whereas the Actiwatch Spectrum has a range up to 200,000 lux. It is possible that illuminance values reported in the previous study were artificially lowered by a ceiling effect in the light sensor. Other differences in daily light exposure could be due to the time of day that children were outdoors, available shade cover, and other weather related factors.

According to the NHANES study (1999–2004), approximately 36% of 20–39 year olds in the US are myopic,⁵⁵ with prevalence shown to increase throughout schooling and occasionally into university.⁵⁶ In our sample of young children, 13% were myopic at enrollment, and 18% at one year. Some emmetropic children in this study will likely develop myopia in the future. Due to our young sample and the nature of the development of myopia, it is difficult to know if we are observing, among the emmetropes, future myopes, which leads to an uncertainty in the behaviors observed. Observations from the CLEERE study suggest that children who become myopic have significantly fewer outdoor/sports activity hours than emmetropes beginning 4 years before the onset of myopia.⁶ Therefore, if subjects in the current study are currently classified as an emmetrope but become a myope in the next 4 years, their outdoor time might already be decreased compared to those who will remain emmetropes, thereby adding more variability to the data. Longer follow-up or older subject ages may give us a better representation of the relationships between refractive error and behaviors.

In the United States, children attend school for approximately nine months (fall and spring semesters), and are on summer break for four months; hence, observational periods were broken up as such, with two occurring during school sessions and one during the summer. Our results show an objectively measured increase in time spent exposed bright light and daily mean light exposure during summer sessions compared to school sessions in children, while physical activity was not different between school and summer. These seasonal differences in light exposure are consistent with previously reported decreases in myopia progression and axial length elongation during the summer^{40, 42} being attributable to a light dependent mechanism. More frequent axial length measurements, in addition to baseline and one year, would have potentially provided further support for seasonal light exposure playing a role in eye growth. Another potential mechanism for decreased myopic eye growth during the summer is seasonal differences in near work. Here, near work was assessed at baseline only, so seasonal differences were not assessed. Additionally, time spent in near work is difficult to quantify without objective measures, and previous studies have shown inconsistent results for the associations between near work and myopia progression.^{8,57}

The mechanism of potential protective effects of outdoor light exposure remains unknown. Increased light intensity stimulates the release of retinal dopamine.⁵⁸ Dopamine receptor antagonists have been found to decrease the protective effects of bright light against form deprivation myopia in chicks.⁴³ In addition to light intensity, spectral composition (i.e. wavelength) may also be important. Here, the red, green and blue components of light exposure were measured. However, the spectral components were all highly correlated to white light exposure, and, therefore, difficult to separate the effects of red and blue. Studies in chicks and guinea pigs show that raising animals in red long wavelength light induces myopia,^{59,60} whereas studies in tree shrews and Rhesus monkeys show that red light is protective against myopia (Norton TT, et al. IOVS 2016;57:ARVO E-Abstract 5525).^{61,62} Contradictory results suggest a complex mechanism that may be dependent on photoreceptor subtypes and sensitivities, species differences, and other characteristics of lighting conditions, such as intensity and temporal frequency.

Limitations in the current study include the small sample size and limited number of myopic children. An increased sample size utilizing objective measures of light exposure may help to solidify trends in light exposure and behavioral patterns observed here between refractive error groups, which could help to provide specific recommendations of required time in specific light levels to maintain emmetropia. Additionally, the 60 children included in this study represented 38 different families, and data were analyzed with the children as the unit of analysis; therefore, the estimated standard errors are expected to be biased downward. Another limitation in our study was the use of tropicamide, rather than cyclopentolate, for cycloplegic refractions, which may have resulted in incomplete cycloplegia, likely contributing to variability in the analysis of refractive error change with light exposure. However, our main outcome measure was axial length change, which has been shown to be unaffected by level of cycloplegia.⁶³ Finally, the wrist worn light sensor presents some limitations in terms of representing what the visual system experiences. However, the correlation between light exposure measured at eye level versus the wrist has been reported to be high, at 0.76⁶⁴. Despite limitations, compliance with device wear was very high, and

allowed approximately six weeks of continuous data collection over the year, providing the largest dataset of objectively measured light exposure as of yet.

In conclusion, objective measurements of light exposure showed that children received a higher light dose and spent more time outdoors in summer compared to school sessions, whereas activity and sleep were similar across the year. Results suggest that children's behaviors regarding time outdoors are influenced by their parents, which may represent a modifiable component to potential environmental influences on eye growth. Whether or not myopic children in this young age group spend less time exposed to bright light in summer remains undetermined. Future studies designed to address the limitations in this study, including sample size, are necessary to further explore objectively measured light exposure patterns with emmetropia and myopia.

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Figure 1.

Spherical equivalent refractive error change (D/yr) with axial length change (mm/yr) over one year ($P < 0.001$); solid line is linear regression, $R^2 = 0.207$, $P = 0.0004$

Figure 2.

Subjective versus objective time spent outdoors for all children (**A**) during school sessions and (**B**) during summer sessions ($n = 60$). For objective measurements, minutes exposed to >1000 lux was used as a measure for minutes outdoors; solid lines represent linear regression, dashed lines represent the 1:1 relationship

Figure 3.

Differences for all children ($n = 60$) between the spring school session, summer session, and fall school session for **(A)** mean daily time exposed to outdoor light (minutes), **(B)** mean daily light exposure (lux), **(C)** mean daily activity (cpm), and **(D)** mean daily sleep duration (minutes); * indicates significance at $P < 0.05$

Figure 4.
Time outdoors in minutes per day for parents and their children

Table 1

Refraction (SER) and biometric measures at baseline and one year for hyperopes, emmetropes, and myopes. Subjects are grouped according to refractive error at baseline. Values represent mean $\pm$ SD. * indicates significance at $P < 0.05$ (paired t-test)

	Baseline	1 year	Difference
Cycloplegic SER			
Hyperopes (n = 5)	+4.12 $\pm$ 2.26 D	+3.79 $\pm$ 2.63 D	-0.33 D, $P = 0.184$
Emmetropes (n = 44)	+0.86 $\pm$ 0.50 D	+0.74 $\pm$ 0.58 D	-0.12 D, $P = 0.062$
Myopes (n = 8)	-1.28 $\pm$ 0.67 D	-1.72 $\pm$ 0.74 D	-0.44 D, $P = 0.054$
Axial length			
Hyperopes (n = 5)	21.53 $\pm$ 0.64 mm	21.66 $\pm$ 0.71 mm	+0.13 mm, * $P = 0.016$
Emmetropes (n = 47)	22.55 $\pm$ 0.65 mm	22.76 $\pm$ 0.64 mm	+0.20 mm, * $P < 0.001$
Myopes (n = 8)	23.63 $\pm$ 0.95 mm	24.04 $\pm$ 0.94 mm	+0.40 mm, * $P = 0.002$
Corneal power			
Hyperopes (n = 4)	43.81 $\pm$ 1.53 D	43.47 $\pm$ 1.16 D	-0.35 D, $P = 0.291$
Emmetropes (n = 43)	44.58 $\pm$ 1.49 D	44.35 $\pm$ 1.44 D	-0.23 D, * $P = 0.024$
Myopes (n = 8)	44.28 $\pm$ 1.16 D	44.30 $\pm$ 1.40 D	+0.01 D, $P = 0.944$
Corneal thickness			
Hyperopes (n = 5)	535.6 $\pm$ 47.5 μ m	537.8 $\pm$ 48.6 μ m	+2.20 μ m, $P = 0.395$
Emmetropes (n = 36)	543.6 $\pm$ 28.5 μ m	542.7 $\pm$ 28.8 μ m	-0.94 μ m, $P = 0.688$
Myopes (n = 5)	546.2 $\pm$ 11.7 μ m	549.00 $\pm$ 8.5 μ m	+2.8 μ m, $P = 0.48$
Anterior chamber depth			
Hyperopes (n = 5)	3.42 $\pm$ 0.12 mm	3.44 $\pm$ 0.13 mm	+0.03 mm, $P = 0.251$
Emmetropes (n = 35)	3.68 $\pm$ 0.24 mm	3.71 $\pm$ 0.26 mm	+0.03 mm, $P = 0.195$
Myopes (n = 5)	3.74 $\pm$ 0.23 mm	3.81 $\pm$ 0.22 mm	+0.07 mm, * $P = 0.002$
Lens thickness			
Hyperopes (n = 2)	3.60 $\pm$ 0.21 mm	3.55 $\pm$ 0.16 mm	-0.05 mm, $P = 0.430$
Emmetropes (n = 34)	3.46 $\pm$ 0.15 mm	3.43 $\pm$ 0.16 mm	-0.04 mm, * $P = 0.001$
Myopes (n = 4)	3.37 $\pm$ 0.14 mm	3.35 $\pm$ 0.13 mm	-0.02 mm, $P = 0.319$

Table 2

Number of hyperopic, emmetropic or myopic children with zero, one or two myopic parents, based on refractive error groups at 1 year.

	Hyperopic	Emmetropic	Myopic
0 myopic parents	3 (100%)	7 (15%)	2 (20%)
1 myopic parent	0 (0%)	19 (40%)	0 (0%)
2 myopic parents	0 (0%)	21 (45%)	8 (80%)
Total	3	47	10

Table 3

Multiple linear regression analysis for axial length at one year and mean daily white light exposure, controlling for baseline axial length, age, sex, activity and parental myopia status (n = 60); CI: confidence interval, * indicates significance at $P < 0.05$

Variable	Parameter Estimate	Standard Error	95% CI	P value
Mean daily white light (lux)	-0.094	0.052	-0.198, 0.009	0.073
Baseline axial length (mm)	1.074	0.025	1.023, 1.125	* < 0.0001
Age (years)	-0.047	0.013	-0.073, -0.021	* 0.001
Sex	-0.065	0.043	-0.15, 0.02	0.139
Activity (cpm)	-0.0002	0.0002	-0.001, 0.0002	0.362
Parental myopia status	0.011	0.044	-0.078, 0.099	0.810

Sensitivity analysis removing influential point (*adjusted* $R^2 = 0.980$, $b = 0.056$, $SE: 0.047$, 95% $CI: -0.150$ to 0.037 , $P = 0.231$); Sensitivity analysis using robust regression effect: ($b = -0.026$, $SE: 0.045$, 95% $CI: -0.12$ to 0.063 , $P = 0.561$)

Table 4

Multiple linear regression analysis for refractive error at one year and mean daily white light exposure, controlling for baseline refractive error, age, sex, activity and parental myopia status (n= 57); CI: confidence interval (95% Lower Limit, 95% Upper Limit), * indicates significance at $P < 0.05$

Variable	Parameter Estimate	Standard Error	95% CI	P value
Mean daily white light (lux)	-0.006	0.184	-0.376, 0.363	0.973
Baseline refractive error (D)	1.04	0.050	0.939, 1.139	* < 0.0001
Age (years)	-0.016	0.044	-0.104, 0.073	0.722
Sex	0.029	0.146	-0.265, 0.322	0.845
Activity (CPM)	0.0006	0.0007	-0.001, 0.002	0.458
Parental myopia status	0.192	0.175	-0.160, 0.544	0.279

* Sensitivity analysis removing influential point (n = 56, *adjusted R*² = 0.9185, *b* = -0.127, *SE*: 0.176, *95% CI*: -0.482 to 0.227, *P* = 0.474); Sensitivity analysis using robust regression effect: (*b* = -0.024, *SE*: 0.195, *95% CI*: -0.42 to 0.369, *P* = 0.904)

Table 5

Minutes per day spent in increasing thresholds of ambient illumination from 1,000 to 50,000 lux across sessions for emmetropes (n = 47) and myopes (n = 8). Session and refractive group differences tested with repeated measures ANOVA; raw p-values reported; * indicates significance with Bonferroni correction to $P < 0.01$

	Spring (school)	Summer	Fall (school)	P' value		
				Session	Refractive group	Session by refractive group
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> 1,000 lux						
Emmetropes	95.2 ± 32.0	116.9 ± 44.5	75.4 ± 31.8	* 0.004	0.055	
Myopes	89.2 ± 21.9	77.3 ± 29.6	63.4 ± 27.8			0.222
Difference	6.0	39.6	12.0			
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> 2,000 lux						
Emmetropes	69.5 ± 26.8	84.3 ± 37.2	55.6 ± 23.6			
Myopes	67.3 ± 18.1	49.3 ± 26.3	42.5 ± 22.7	* 0.004	0.036	0.161
Difference	2.2	35.0	13.1			
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> 5,000 lux						
Emmetropes	44.6 ± 19.8	55.8 ± 30.7	33.9 ± 14.9			
Myopes	40.9 ± 20.5	31.9 ± 19.2	26.6 ± 17.7	* 0.008	0.061	0.270
Difference	3.7	23.9	7.3			
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> 10,000 lux						
Emmetropes	29.9 ± 14.5	39.5 ± 24.9	20.8 ± 9.9			
Myopes	29.0 ± 14.0	23.1 ± 15.2	23.1 ± 19.3	0.051	0.327	0.150
Difference	0.9	16.4	-2.3			
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> 50,000 lux						
Emmetropes	5.9 ± 4.0	9.5 ± 6.9	5.1 ± 4.1			
Myopes	5.2 ± 3.2	6.4 ± 5.9	4.9 ± 4.7	0.106	0.334	0.556
Difference	0.7	3.1	0.2			