Light Exposure and Eye Growth in Childhood

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Purpose. The purpose of this study was to examine the relationship between objectively measured ambient light exposure and longitudinal changes in axial eye growth in childhood.

Methods. A total of 101 children (41 myopes and 60 nonmyopes), 10 to 15 years of age participated in this prospective longitudinal observational study. Axial eye growth was determined from measurements of ocular optical biometry collected at four study visits over an 18-month period. Each child's mean daily light exposure was derived from two periods (each 14 days long) of objective light exposure measurements from a wrist-worn light sensor.

Results. Over the 18-month study period, a modest but statistically significant association between greater average daily light exposure and slower axial eye growth was observed ($P = 0.047$). Other significant predictors of axial eye growth in this population included children's refractive error group ($P < 0.001$), sex ($P < 0.01$), and age ($P < 0.001$). Categorized according to their objectively measured average daily light exposure and adjusting for potential confounders (age, sex, baseline axial length, parental myopia, nearwork, and physical activity), children experiencing low average daily light exposure (mean daily light exposure: 459 ± 117 lux, annual eye growth: 0.13 mm/y) exhibited significantly greater eye growth than children experiencing moderate (842 ± 109 lux, 0.060 mm/y), and high (1455 ± 317 lux, 0.065 mm/y) average daily light exposure levels ($P = 0.01$).

Conclusions. In this population of children, greater daily light exposure was associated with less axial eye growth over an 18-month period. These findings support the role of light exposure in the documented association between time spent outdoors and childhood myopia.

Keywords: myopia, light exposure, refractive error, outdoor activity

There is growing evidence from both human and animal studies of refractive error showing that ambient light exposure is an important environmental factor involved in the regulation of eye growth. Refractive development of chickens raised under normal diurnal light/dark cycles with unrestricted vision appears to be influenced by light levels, with chicks raised under high light levels (10,000 lux) developing significantly fewer myopic refractive errors than chicks raised with daily exposure to low light levels (50 lux).[1] Exposure to high-intensity light also appears to protect against development of form deprivation myopia in both chicks[2,3] and primates.[4] High light levels also slow the rate of myopic eye growth in response to negative lenses in chicks, although the refractive endpoint from negative lens treatment does not appear to be altered.[5] The course of negative lens-induced myopia in primates, however, does not appear to be significantly altered by high light levels, indicative of some differences in the influence of light on form deprivation and lens-induced myopia development.[6]

Documented seasonal variations in eye growth and refractive error progression in childhood (with slower eye growth seen in summer months and faster rates of eye growth in winter months) support a potential role for ambient light exposure in the control of human eye growth.[7–10] Evidence from a number of human epidemiologic studies that report significant associations between less time outdoors and the presence,[11–14] development,[15–18] and progression[19,20] of myopia in children

also lends support to an involvement of ambient light exposure in refractive error development in humans, as being outdoors typically involves exposure to much higher amounts of light than being indoors (see Sherwin et al.[21] and French et al.[22] for comprehensive reviews of these studies). Interventions aimed at increasing children's time spent outdoors have also been reported to reduce the development of myopia in childhood[23] (Morgan IG, et al. *IOVS* 2014;55:ARVO E-Abstract 1272). Although most studies report a significant relationship between less time outdoors and myopia, some studies have found no significant relationship between outdoor time and the presence,[24,25] progression,[26] or stabilization of myopia.[27]

Although it has been postulated that the association between less myopia and more time outdoors is due to increased light exposure when outdoors,[12] most studies examining the relationship between outdoor activity and myopia have used questionnaires to estimate outdoor activity. These questionnaires rely upon the accurate recall and perception of previous activities, and there is evidence that questionnaire-derived outdoor time does not correlate strongly with objectively measured light exposure.[28,29] A small number of recent cross-sectional studies have used wearable light sensors in order to objectively measure the light exposure of children[28,30] and adults[29,31] with a range of refractive errors. We recently reported (objectively measured) light exposure and physical activity patterns of a pediatric population and found a significantly lower average light exposure in myopic

children than in nonmyopic children.[30] In contrast, there were no significant differences in physical activity between refractive error groups, supporting a potential role of light exposure in childhood refractive error.

Although these recent studies have provided detailed cross-sectional analyses of the typical environmental light exposure of children and young adults, to date there have been no longitudinal studies examining the influence of objectively measured light exposure upon eye growth in humans. In this longitudinal study, we aimed to examine the relationship between objectively measured ambient light exposure and axial eye growth over 18 months, in a population of myopic and nonmyopic children.

METHODS

Subjects and Procedures

This prospective, observational longitudinal examination of axial eye growth and objectively measured light exposure involved 102 children between 10 and 15 years of age enrolled in the Role of Outdoor Activity in Myopia (ROAM) study.[30] Most subjects resided in urban regions of the greater Brisbane area, in the state of Queensland, Australia. Approval from the Queensland University of Technology human research ethics committee was obtained before commencement of the study, and all parents provided written informed consent, and children written assent prior to participation. All children were treated in accordance with the tenets of the Declaration of Helsinki.

Prior to enrolment in the study, all children underwent an initial ocular examination to determine their refractive error (a noncycloplegic subjective refraction aiming for maximum plus/least minus for best visual acuity, followed by binocular balancing) and binocular vision and ocular health status. All children enrolled in the study exhibited best corrected visual acuity of logMAR 0.00 or better in each eye and no history or evidence of significant ocular disease. Given the documented association between hyperopia and binocular anomalies such as amblyopia and strabismus,[32] children with noncycloplegic hyperopic refractive errors of greater than +1.25 diopter (D) were excluded from the study. Eligible subjects were classified based upon their noncycloplegic spherical equivalent refractive error (SER) as either myopic (average SER from right and left eyes of −0.50 D or more, with at least one eye exhibiting 0.75 D or more myopia) or nonmyopic (average SER from right and left eyes less than +1.25 D and greater than −0.50 D, with neither eye exhibiting 0.75 D or more myopia). Myopic children all wore conventional single-vision spectacle correction (although four children also wore spherical soft disposable contact lenses) and were excluded if they were under any optical or pharmacologic treatments to slow myopia progression. One of the nonmyopic participants developed signs of a retinal dystrophy at the second study visit and was therefore excluded from all analyses.

Of the 101 children included in the final analysis, 41 were classified as myopes (mean ± SD subjective SER of −2.39 ± 1.50 D; mean cylinder: −0.38 ± 0.47 DC) and 60 as nonmyopes (mean subjective SER of +0.34 ± 0.30 D; mean cylinder: −0.10 ± 0.19 DC). No children exhibited anisometropia of >1.25 D, and the mean interocular difference in SER was 0.17 ± 0.22 D. Myopic and nonmyopic children were well matched for both age (mean age: 13.0 ± 1.5 years of age in the myopia group and 13.1 ± 1.2 years of age in the nonmyopia group) and sex (51% of the myopes and 52% of the nonmyopes were female). Baseline ocular biometric measurements were collected between May and November 2012. Each child then had ocular

measurements made every 6 months over an 18-month period (i.e., a total of four ocular measurement visits conducted over 18 months), and objective measurements of ambient light exposure were made in two separate periods over the first 12 months of the study. Questionnaires detailing each child's typical nearwork and outdoor activities performed in the preceding 6 month period were also completed at each follow-up visit, using a previously validated questionnaire.[33]

Over the 18-month study period, three children were lost to follow-up (two after their baseline visit and one after the second ocular measurement visit), and four children were excluded from analysis after they began orthokeratology contact lens wear (after their second [n = 3] or third [n = 1] ocular measurement visit), which meant that 99 subjects had data from at least two visits, and 94 subjects (59 nonmyopes and 35 myopes) had complete data from all four visits.

At each 6-month ocular measurement visit, axial length (AxL) was measured using an optical biometer, which is based on the principles of optical low coherence reflectometry (Lenstar LS 900; Haag Streit AG, Koeniz, Switzerland) and provides highly precise measures.[34] At each visit, five repeated measurements of ocular biometry were collected from both eyes of each child. All ocular biometry measurement visits were scheduled between 3 PM and 5 PM, to limit the potential confounding influence of diurnal variations in AxL[35] upon the data.

Objective ambient light exposure measures were collected using a wrist-worn light sensor device (Actiwatch 2; Philips Respironics, Pittsburgh, PA, USA). This is a light weight, waterproof (up to 30 minutes in water) wristwatch device that contains a silicone photodiode light sensor that measures visible light (the sensor measures over a wavelength range from 400 to 900 nm, has a peak sensitivity of 570 nm, and a dynamic range from 5 to 100,000 lux). Each subject wore a light sensor for two separate 14-day periods, separated by approximately 6 months (mean ± SD time between the two light exposure measurements was 6.4 ± 0.7 months, ranging from 5.3 to 9.4 months). The first period of light measurements was conducted between July and December 2012 (i.e., between the first and second ocular measurement visits) and the second between February and August 2013 (between the second and third ocular measurement visits). Each light measurement period was categorized as being from a "longer/warmer day" period (summer, early autumn, or late spring) or a "shorter/cooler day" period (winter, late autumn, or early spring), based upon climate conditions recorded by the Australian Bureau of Meteorology for Brisbane, Queensland. Each child had one measurement period in each category and wore the light sensor on the nondominant wrist, for 24 hours a day over each 14-day period during the school academic term (i.e., excluding vacation periods). All devices were programmed to instantaneously record light exposure every 30 seconds (i.e., 2880 measures per day for 14 days). Measurement protocol and data screening procedures used for the light exposure measurements have been previously described in detail.[30] A questionnaire regarding each child's typical use of sun protection strategies while outdoors (i.e., whether hats and sunglasses were worn "never," "less than half the time," "half the time," "more than half the time" or "always") was also completed following each period of light exposure measurements.

Data Analysis

Following data collection at each visit, the AxL data of right and left eyes were averaged. Light exposure data were then analyzed to calculate the mean daily light exposure (between 6 AM and 6 PM) for each subject, for each of the two 14-day

TABLE 1. Mean ± SD Average Environmental Climate Conditions and Day Length Experienced Over the Periods of Light Exposure Measurements in Warmer and Cooler Periods

Period	Minimum Temperature, °C	Maximum Temperature, °C	Day Length, h
Warmer days			
All children	18.5 ± 2.2	28.2 ± 1.0	12.9 ± 0.6
Myopes	18.2 ± 2.3	27.9 ± 0.7	12.7 ± 0.5
Nonmyopes	18.6 ± 2.2	28.3 ± 1.1	13.0 ± 0.6
Cooler days			
All children	13.1 ± 2.0	24.0 ± 2.0	10.9 ± 0.6
Myopes	13.1 ± 2.1	24.5 ± 2.1	11.1 ± 0.6
Nonmyopes	13.1 ± 1.9	23.7 ± 1.9	10.8 ± 0.6

periods of light sensor wear. These light exposure values for each subject were derived from an average of 26.2 ± 3.1 days of valid light exposure data (including a mean ± SD of 13.4 ± 1.5 days from the first period of light sensor wear and 13.1 ± 1.7 days from the second session of light sensor wear). An intraclass correlation of the between-session reliability of the average daily light exposure measurements was 0.759. The mean light exposure between 6 AM and 6 PM was used as our primary light exposure measure in the study, as this encompassed the period during the day where the vast majority of light exposure occurred for all subjects in the study across all measurement times. Mean light exposure over other times of the day was uniformly low (mean night time light exposure between 6 PM and 6 AM was 7 ± 5 lux, with children being exposed to light of >1000 lux on average for less than 30 seconds per day between 6 PM and 6 AM). In order to examine whether exposure to light above a certain threshold intensity was also an important factor associated with eye growth, we also calculated the average time of exposure per day to bright light above various intensity thresholds (>1000 lux, >2000 lux, >3000 lux, and >5000 lux).

The average minutes per day of nearwork and outdoor activities were also calculated based upon the questionnaire responses at each visit, using the criteria described by Rose et al.[12] The wearable sensors used in this study also measure physical activity data, expressed in the arbitrary unit of activity "counts per minute" (from a solid-state piezo-electric accelerometer),[36] enabling the average daily physical activity (between 6 AM and 6 PM) for each child to be calculated.

All statistical analyses were carried out using SPSS version 21 software (IBM, Armonk, NY, USA). Normality of data was confirmed using the Kolmorogov-Smirnov test ($P > 0.05$ for all variables). A repeated measures ANOVA with one within-subject factor (season of measurement, i.e., warmer period versus cooler period) and one between-subject factor (refractive error group) was used to examine whether the average light exposure varied according to the season of measurement or between the two refractive groups. The longitudinal changes in AxL and their association with a range of predictor variables over the 18 months of the study were then examined using linear mixed model (LMM) analyses, with restricted maximum likelihood estimation. Linear mixed model analyses examined the effect of study visit time (in years from baseline visit, as a continuous variable) upon AxL, assuming a first-order autoregressive covariance structure (this assumes the correlation between measurements is lower for measurements taken farther apart in time). Individual subject's slopes and intercepts were included as random effects in the model (assuming an unstructured covariance type). Categorical predictor variables (refractive error group, parental myopia, and sex) were included in the model as fixed factors; and continuous predictor variables (age at baseline visit, average daily light exposure, average minutes of nearwork per day, average minutes of self-reported outdoor time per day and average daily physical activity per day) were included as covariates. Because the human eye typically exhibits a logarithmic response to light, analyses regarding eye growth and light exposure were performed on the log of the average daily light exposure data. Additional mixed models were also carried out, including quadratic and cubic time terms, but because the inclusion of these terms did not alter the overall statistical outcomes nor improve Akaike's information criteria associated with the model, only the linear models are presented.

To provide further insight into the influence of light exposure upon eye growth, an additional LMM analysis was conducted that categorized the children according to their average daily light exposure. In this model, children were classified as habitually experiencing "high daily light exposure" (average daily light exposure ≥ 1020 lux), "moderate daily light exposure" (average daily light exposure between 652 and 1019 lux), or "low daily light exposure" (average daily light exposure ≤ 651 lux) based upon a tertile split of the average daily light exposure data. Additionally, this model also used baseline AxL as the variable describing refractive error (given that AxL is the major biometric correlate of refractive error), in order to provide an analysis that did not rely upon the noncycloplegic refractive error grouping. Changes in AxL over the course of the study were then examined, including categorical predictor variables (light exposure group, parental myopia, and sex) in the model as fixed factors, and continuous predictor variables (AxL at baseline, age at baseline visit, average minutes of nearwork per day, average minutes of questionnaire-derived outdoor time per day, and average daily physical activity per day) as covariates.

RESULTS

Objective Light Exposure Measurements

The average environmental climate and day length (i.e., hours between sunrise and sunset) conditions experienced across the two periods of light exposure measurements are shown in Table 1. These day length and climate conditions were not significantly different between myopic and nonmyopic children (all, $P > 0.05$).

The average objectively measured light exposure for this population of children is summarized in Table 2. Repeated measures ANOVA revealed a significant effect of season for the average daily light exposure and for the time exposed to various bright light levels (all, $P < 0.05$), indicative of significantly greater light exposure on warmer days than on cooler days. Myopic children (mean ± SD daily light exposure across all measurement days: 805 ± 427 lux; range, 225–2264 lux; median: 716 lux) also exhibited significantly lower average daily light exposure than nonmyopic children (mean daily light exposure: 999 ± 468 lux; range, 265–2125 lux; median: 921 lux; $P < 0.05$). Differences in average daily light exposure between the two refractive error groups, however, were not season-dependent (refractive group by season interaction, $P > 0.05$). Although questionnaire data revealed that, on average, the myopic children spent more time on nearwork (428 ± 153 minutes per day) and less time on outdoor activities (132 ± 72 minutes per day) than nonmyopic children (390 ± 132 minutes per day on nearwork and 159 ± 82 minutes per day on outdoor activities), these differences did not reach statistical significance (both, $P > 0.05$).

TABLE 2.   Average Daily Light Exposure Results From Wristwatch Light Sensors

| | Mean ± SD | | P Values* | |
Exposure	Warmer Days	Cooler Days	Season	Refractive Group
Mean daily light exposure, lux				
All children	987 ± 547	857 ± 525	0.05	0.04
Myopes	818 ± 487	793 ± 497		
Nonmyopes	1099 ± 559	900 ± 542		
Daily bright light exposure, min				
>1000 lux				
All children	106 ± 46	83 ± 41	<0.001	0.005
Myopes	90 ± 43	72 ± 38		
Nonmyopes	117 ± 46	90 ± 42		
>2000 lux				
All children	72 ± 37	54 ± 31	<0.001	0.02
Myopes	60 ± 35	48 ± 29		
Nonmyopes	79 ± 37	58 ± 33		
>3000 lux				
All children	51 ± 31	38 ± 25	<0.001	0.02
Myopes	42 ± 25	34 ± 22		
Nonmyopes	57 ± 33	41 ± 27		
>5000 lux				
All children	30 ± 21	24 ± 17	0.01	0.06
Myopes	24 ± 17	22 ± 15		
Nonmyopes	33 ± 22	25 ± 18		

* P values show results from repeated measures ANOVA examining the influence of season (warmer day versus cooler day period) and refractive group (myopic versus nonmyopic children). None of the considered variables exhibited a significant season by refractive group interaction (all $P > 0.05$).

Bivariate correlation analysis revealed a significant association between daily light exposure measurements from the two seasons of measurement for the average daily light exposure ($r = 0.48$, $P < 0.001$), time exposed to >1000 lux ($r = 0.62$, $P < 0.001$), time exposed to >2000 lux ($r = 0.55$, $P < 0.001$), time exposed to >3000 lux ($r = 0.49$, $P < 0.001$), and time exposed to >5000 lux ($r = 0.45$, $P < 0.001$) (Fig. 1). The average questionnaire-derived outdoor time was also significantly correlated with average daily light exposure for both the

warmer days ($r = 0.53$, $P < 0.001$) and the cooler days ($r = 0.58$, $P < 0.001$).

Across each of the two light exposure measurement periods for all children, the reported frequency of hat usage when outdoors ranged from "never" to "all the time" (median response was "less than half the time"), and reported usage of sunglasses ranged from "never" to "half the time" (median response was "never"). Distribution of the reported frequencies of hat and sunglasses use did not differ significantly between the myopic and nonmyopic children (Mann-Whitney
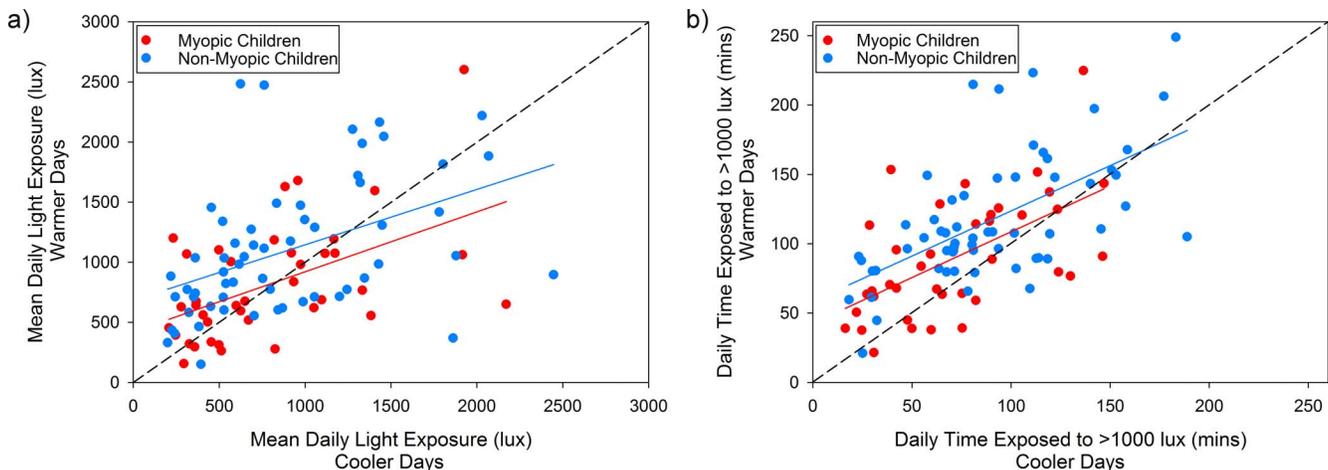

FIGURE 1.   Relationship between objectively measured mean daily light exposure (from 6 AM–6 PM) (a) and mean daily exposure to bright light (>1000 lux) (b) in warmer days measurement period and cooler days measurement period for myopic children (*red circles*) and nonmyopic children (*blue circles*). *Solid lines* indicate best fit regression line for myopic (*red*) and nonmyopic (*blue*) children, and *dashed black line* is the line of equality (1:1) between the warmer days and the cooler days.
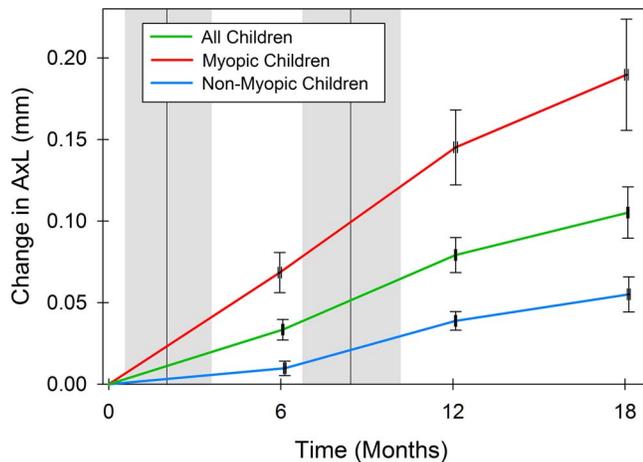
FIGURE 2. Mean change in axial length (AxL) from baseline to 18 months for the myopic (*red line*), nonmyopic (*blue line*) and all (*green line*) children in the study. *Vertical error bars* represent the standard error of the mean change in axial length, and *horizontal error bars* represent the standard error of the study visit time. *Vertical black lines* indicate mean timing of the first and second light exposure measurements in the study (*gray shading* around the *vertical lines* illustrates the standard deviation of the mean timing of light exposure measurements).

U test; all, *P* > 0.05) and was also not significantly different between the two light exposure measurement periods (Wilcoxon signed rank test, all *P* > 0.05).

Light Exposure and Longitudinal Changes in Axial Length

The mean ± SD increase in AxL observed over the 18 months of the study for all children was 0.11 ± 0.15 mm. At the baseline visit, the mean AxL in the myopic children was 24.46 ± 1.05 mm and 23.24 ± 0.65 mm in the nonmyopic children. Over the course of the study, a mean axial eye growth (i.e., change in AxL from baseline) of 0.19 ± 0.20 mm was found in the myopic children and 0.05 ± 0.05 mm in the nonmyopic children (Fig. 2). Linear mixed model analysis examining the longitudinal changes in AxL (Table 3) revealed a significant main effect of refractive group and sex, consistent with a significantly smaller baseline AxL in the nonmyopic children compared to the myopic children (the myopic children were estimated to have a 1.2-mm longer AxL than that of the nonmyopic children, *P* < 0.001) and smaller AxL in girls than in boys (boys were estimated to have an AxL 0.7 mm longer than that of the girls, *P* < 0.001). Axial length also changed significantly over time (*P* < 0.001), and there was a significant time by refractive group interaction indicative of significantly greater (*P* < 0.001) linear growth in AxL for the myopic children than for the nonmyopic children (axial growth rate was estimated to be 0.08 mm/y greater in the myopes). Significantly greater AxL change was also observed in boys than in girls (boys were found to exhibit an AxL growth of 0.04 mm/y greater than that in girls, *P* = 0.027). A significant time by age at baseline interaction was also observed, consistent with a younger age at baseline being associated with a greater linear growth rate in AxL (β = −0.02 mm/y; *P* = 0.008).

A significant relationship between the average daily light exposure and the longitudinal changes in AxL over time was also found, as shown by a significant time by log average daily light exposure interaction (*P* < 0.05). This demonstrates that greater light exposure was associated with smaller changes in AxL over the course of the study (β = −0.12; *P* < 0.05) and

indicates that for every 1 log unit of increase in average daily light exposure, the axial growth rate decreased by 0.12 mm/y. There was no significant effect of self-reported nearwork, outdoor activity, average daily physical activity, or parental history of myopia observed upon the changes in AxL over the course of the study (all main effects and interactions, *P* > 0.05). The effects of average daily light exposure remained significant (β = −0.10; *P* < 0.05), even if self-reported outdoor activities were removed from the model.

To further explore the relationship between light exposure and axial eye growth, we performed LMM analyses that included mean daily times exposed to the various bright light levels (i.e., time exposed to >1000 lux, or >2000 lux, or >3000 lux, or >5000 lux) as the light parameter in the model. These analyses also revealed associations between greater light exposure and less axial eye growth; however, statistically significant associations were found only for the mean (log) daily minutes of exposure to light levels >3000 lux (β = −0.12; *P* = 0.04) and >5000 lux (β = −0.09; *P* = 0.049).

Additional analyses were carried out after categorizing the children based upon their average daily light exposure regardless of refractive status. Ocular and demographic characteristics of the children habitually experiencing "high daily light exposure (≥1020 lux)," (*n* = 33, mean daily light exposure: 1454 ± 317; range, 2264–1044; median: 1467 lux), "moderate daily light exposure (652–1019 lux)" (*n* = 33; mean: 842 ± 109; range, 1008–662; median: 836 lux), and "low daily light exposure (≤ 651 lux)," (*n* = 33; mean: 459 ± 117; range, 629–225; median: 478 lux) are reported in Table 4.

The LMM examining the changes in AxL in each of these three light exposure groups, revealed that the changes in AxL over time varied significantly with baseline AxL (with longer AxL at baseline being associated with faster axial growth: β = 0.03; *P* = 0.008), age at baseline (with younger age at baseline being associated with faster axial eye growth: β = 0.03; *P* = 0.005), and with light exposure group (*P* = 0.01). There was no significant interaction between age and light exposure upon changes in AxL over time (*P* = 0.6). Children categorized as habitually experiencing low daily light exposure exhibited significantly greater axial eye growth (β = 0.13 mm/y) than those experiencing high (β = 0.065 mm/y) and moderate (β = 0.060 mm/y) light exposure (*P* < 0.05) (Fig. 3). The rate of axial eye growth observed in the high and moderate light exposure groups were not significantly different from one another (*P* = 0.8). We also examined the effects of light exposure group upon axial eye growth in an additional LMM including refractive group as a factor, and this analysis revealed that both light exposure group (*P* = 0.02) and refractive group (*P* = 0.001) were significantly associated with axial eye growth over time. However, there was no significant interaction between refractive group and light exposure group upon the changes in AxL over time (*P* = 0.45), suggesting that the effects of light exposure and refractive group upon axial eye growth were independent (Fig. 3).

DISCUSSION

This study, examining the longitudinal changes in AxL of children, demonstrates a modest but statistically significant relationship between objectively measured daily light exposure and axial eye growth (adjusting for potential confounders), indicating that greater average daily light exposure results in less axial growth of the eye in childhood. Children habitually experiencing low average daily light exposure were found to exhibit statistically significantly faster axial eye growth compared to children habitually experiencing moderate and high average daily light exposure. Although previous studies

TABLE 3. Statistically Significant Fixed Effects and Parameter Estimates From the LMM Examining Influences on Axial Length Over the 18-Month Period of the Study

Parameter	df	F	Parameter Estimates	P Value
Intercept	1,89	89,415	24.83	<0.001
Time	1,90	78	0.13	<0.001
Refractive group	1,89	42	−1.2*	<0.001
Sex	1,89	89	−0.7†	<0.001
Time by refractive group	1,89	14	−0.08*	<0.001
Time by age at baseline	1,89	7	−0.02	0.008
Time by sex	1,88	5	−0.04†	0.027
Time by log mean daily light exposure	1,89	4	−0.12	0.047

Other parameters included in the model (parental myopia, questionnaire derived near work and outdoor activity, and physical activity) did not show statistically significant effects (all $P > 0.05$). LMM, linear mixed model.

* Parameter estimate for nonmyopic children.

† Parameter estimate for girls.

have reported a significant association between time spent outdoors, derived by questionnaires, and the prevalence,[11-14] development,[15-18] and progression[19,20] of myopia, our study provides the first evidence of a significant influence of (objectively measured) daily ambient light exposure upon eye growth in childhood.

Our findings are consistent with the previous hypothesis[12] that the documented association between less outdoor activity and more myopia is driven by differences in light intensity levels between indoor and outdoor environments. The lack of a significant relationship between physical activity and eye growth also suggests that differences in physical activity associated with being outdoors are not a major factor in the relationship between myopia and time outdoors. Our analyses indicate that increased daily time exposed to light levels >3000 lux per day (light levels that would typically only be encountered outdoors) was significantly associated with less axial eye growth. However, the daily time exposed to light >1000 lux (and >2000 lux) did not show a significant association with eye growth. Taken together, these results suggest that the mechanisms controlling eye growth may be sensitive to the intensity of light outdoors, and brighter light intensities of more than 3000 lux may have a greater influence on eye growth than intensities of 1000 to 3000 lux. Although our results indicate that the magnitude of daily light exposure appears to contribute to the apparent protective effects of outdoor activities, it does not rule out the potential involvement of other factors.[37,38]

We found evidence of significantly faster axial eye growth in children habitually experiencing low daily light exposure but no significant difference in the rate of eye growth between children experiencing moderate and high daily light exposure. This finding supports the notion that there may be a threshold of daily light exposure required in childhood in order to slow axial eye growth. Although additional research with larger samples, followed over longer periods of time, is required to more precisely define such a threshold, our results demonstrate that the children habitually experiencing low daily light exposure on average spent only approximately 20 minutes per day exposed to bright outdoor light levels >3000 lux, compared to 40 and 70 minutes per day in the moderate and high light exposure groups respectively. This suggests that less than 40 minutes per day of bright light exposure may predispose children to faster axial eye growth.

Our results support the potential for interventions aimed at increasing average daily light exposure in order to reduce the progression of childhood myopia, and also help to improve our understanding of the potential magnitude of the effects of such interventions. For the myopic and nonmyopic children in our current study, a 1 log unit increase in average daily light exposure was associated with ∼0.12 mm/y less eye growth (approximately 0.3–0.4 D slower myopia progression). In our population, a 1 log unit increase in average daily light exposure is equivalent to increasing exposure to light levels >3000 lux for approximately 90 to 100 minutes per day. Considered as non-log-transformed data, an increase in average daily light exposure of 1000 lux, was associated with ∼0.05 mm/y slower annual axial eye growth. Although increased daily light exposure could be achieved through a variety of means (e.g., according to Golden et al.[39]), the simplest method to increase light exposure in childhood is to increase children's daily time spent outdoors. Results from a small number of such interventions do appear to suggest a positive effect in reducing myopia progression[23] (Morgan IG, et al. *IOVS* 2014; 55:ARVO E-Abstract 1272), although the exact magnitude of increase in light exposure resulting from these interventions has not been reported.

Although only a small number of studies have examined the relationship between myopia progression and outdoor activities in childhood, these previous reports have presented some conflicting results. In a cohort of myopic children participating in a myopia intervention trial, Parssinen and Lyyra[19] found a significant association between greater (questionnaire-derived) outdoor activity and less myopia progression but only in boys. Conversely, in a large population of myopic children, Jones-Jordan et al.[26] reported no significant influence of the time involved in sports and outdoor activities (or nearwork) upon myopia progression, based upon questionnaire data. More recently, in a population of myopic and nonmyopic Chinese schoolchildren, Guo et al.[20] reported a significant relationship between less axial eye growth over a 12-month period and

TABLE 4. Mean ± SD Ocular, Demographic, and Light Exposure of Children Categorized According to Mean Daily Light Exposure

Light Exposure Group	Baseline AxL, mm	Baseline SER, D	Axial Growth Rate, mm/y	Baseline Age	% of Females	% of Myopes	Mean Daily Light, lux	Time Exposed to >1000 Lux, min	Time Exposed to >3000 Lux, min
High	23.67 ± 0.94	−0.32 ± 1.18	0.07 ± 0.10	12.5 ± 1.3	39%	30%	1455 ± 317	137 ± 29	70 ± 21
Moderate	23.70 ± 1.16	−0.65 ± 1.89	0.04 ± 0.05	12.9 ± 1.2	48%	36%	842 ± 109	91 ± 13	41 ± 8
Low	23.86 ± 0.98	−1.34 ± 1.76	0.11 ± 0.12	13.75 ± 1.33	63%	55%	459 ± 117	56 ± 18	21 ± 7
P value*	0.7	0.04	0.04	0.001	0.14	0.12	<0.001	<0.001	<0.001

Data provide an overview of (unadjusted) parameter values of children exhibiting either high daily light exposure ($n = 33$), moderate daily light exposure ($n = 33$), or low daily light exposure ($n = 33$). AxL, axial length; D, diopter; SER, spherical equivalent refractive error.

* P values are from a 1-way ANOVA (except for the percent of females and percent of myope values, which are from the Kruskall-Wallis test) investigating significant differences across the 3-light exposure groups in each parameter.
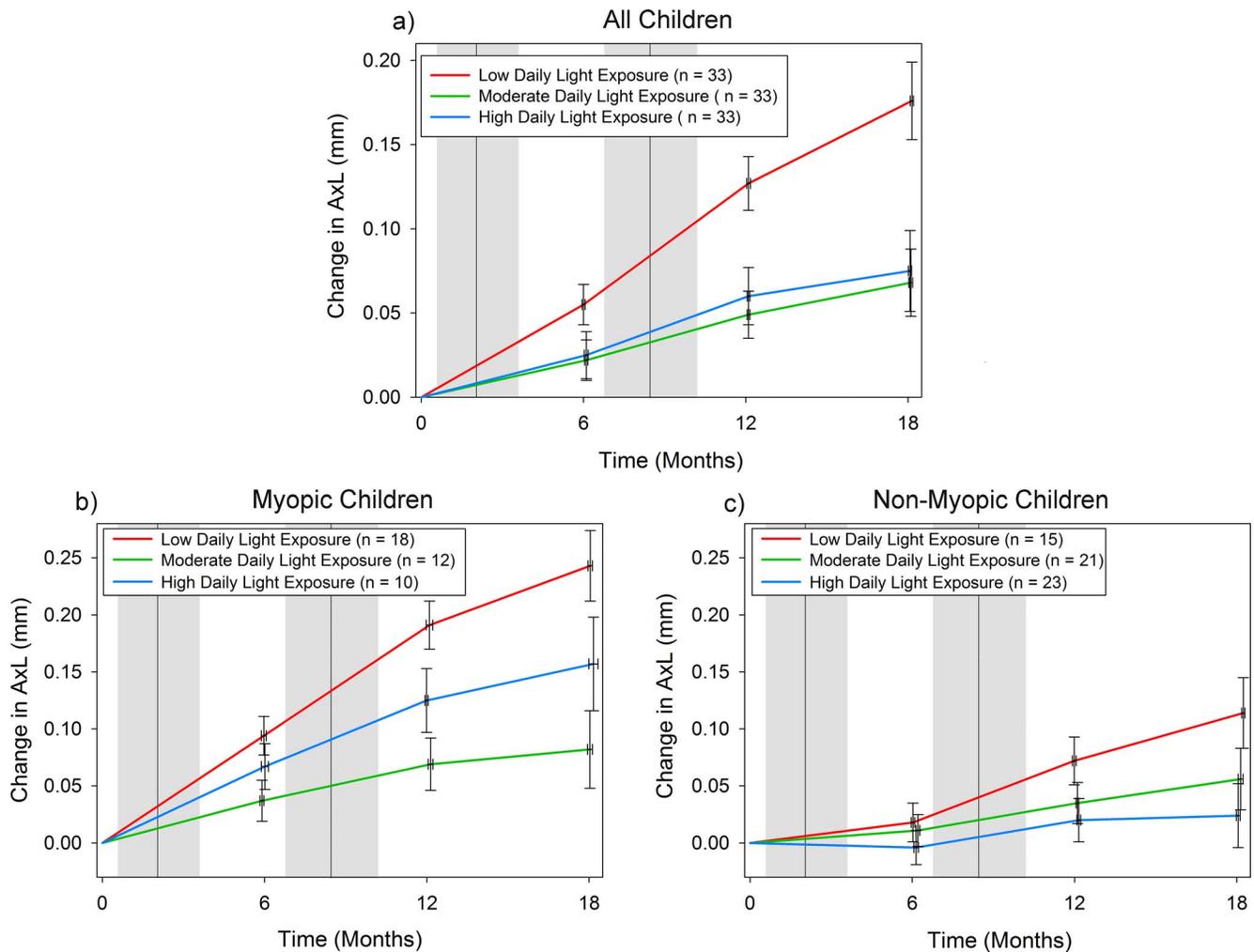
FIGURE 3. Estimated mean change in axial length (AxL) from baseline to 18 months for the children habitually exposed to high light levels (≥ 1020 lux) (*blue line*), moderate light levels (652–1019 lux) (*green line*), and low light levels (≤ 651 lux) (*red line*), adjusted for all measured covariates in the study. Data for all children (**a**), myopic children only (**b**), and nonmyopic children only (**c**) are shown. *Vertical error bars* represent standard error of the mean change in AxL, and *horizontal error bars* represent standard error of the study visit time. *Vertical black lines* indicate mean timing of the first and second light exposure measurements in the study (*gray shading* around the *vertical lines* illustrates the standard deviation of the mean timing of the light exposure measurements).

more time outdoors, again derived from questionnaires. In our current study, outdoor time derived from questionnaires was significantly correlated with the average daily light exposure. An inverse relationship between questionnaire derived outdoor time and eye growth was also found ($\beta = -0.01$), but this association did not reach statistical significance ($P = 0.45$). This suggests that directly measured personal light exposure is providing different or additional information compared to outdoor time derived from questionnaires, which is consistent with previous work comparing the agreement between personal light exposure and questionnaire data.[28,29]

Previous studies have reported that childhood eye growth shows significant seasonal variations.[7-10] Our finding of greater light exposure being associated with slower axial eye growth tends to support a role for light exposure in the previously documented seasonal variations in eye growth, as the summer months (when eye growth is typically documented to be slowest) afford greater opportunities for increased light exposure. Our objectively measured light exposure data also demonstrated that children experienced significantly greater light exposure during warmer day periods of the year compared to cooler day periods, suggesting some seasonal differences in

the children's typical daily activities. Given these seasonal differences in light exposure, we ran additional analysis of the axial eye growth data, including the two separate light exposure measurements as a time varying covariate in the model (instead of using the average of the two measures). Although this analysis revealed a similar negative association between light exposure and eye growth ($\beta = -0.12$) as was found when using the average of the two light exposure measures, this association did not reach statistical significance ($P = 0.1$). This could potentially be related to the considerable variation in the light exposure measures between the two separate periods observed in some of the children in the study (indicative of variability in children's activity patterns throughout the year) (Fig. 1). It should also be noted that our eye growth data collected every 6 months did not exhibit clear evidence of strong seasonal effects (Fig. 2). This is probably due to the fact that the eye growth measurements in our study at each visit were not restricted to a single season and, in fact, were conducted over a 5-month period, which is likely to have masked any seasonal effects upon the average 6-month changes in eye growth. The timing of our light exposure measures also did not closely coincide with the exact time of the eye growth measures or with the season, which appears to have

limited our ability to correlate any seasonal variations in light exposure with seasonal variations in eye growth. Future studies that more closely synchronize both eye growth and light exposure measurements to the seasons are required to more clearly elucidate the underlying role of light exposure upon the previously documented seasonal variations in eye growth.

Aside from average daily light exposure, the two other factors that were significant predictors of axial eye growth in this population of children were refractive error group (i.e., the presence of myopia) and age at baseline. Faster eye growth in younger children has been a consistent finding in a range of studies of eye growth in childhood.[40–44] The annual axial eye growth rate in our nonmyopic children is similar to that in previous reports of emmetropic children of similar age,[43,44] although the growth rate in our myopic children appears to be slightly smaller in magnitude than that in a number of previous reports of eye growth in myopic children.[8,20,40,42] This may reflect the slightly older mean age of our cohort compared to cohorts in previous studies or alternatively may be related to differences in environmental exposures between groups. Dharani et al.[28] reported that the mean (objectively measured) light exposure of a group of Singaporean children was 702 lux ($\sim$60 minutes per day exposed to light >1000 lux), which is substantially lower than our mean daily light exposure of 922 lux (95 minutes per day exposed to light >1000 lux) in children of similar age. According to criteria used in our current study, most Singaporean children in the Dharani et al.[28] study would be classified as having low daily light exposure, which might be expected to predispose these children to faster axial eye growth, and is consistent with the high prevalence and progression of myopia in Singaporean children.[41]

The slightly older age range of the children in our current study may also account for the relatively modest differences observed in the absolute rate of eye growth amongst the different light exposure groups in our study. For example, the children habitually experiencing low light exposure were found on average to exhibit only approximately 0.1 mm greater increase in AxL over the 18 months of the study compared to those children habitually experiencing moderate and high light exposure (Fig. 3a). However, if we consider this modest 0.1 mm difference in eye growth as a percentage of the eye growth observed in the low light exposure group, the moderate and high light exposure groups exhibited on average 59% slower axial eye growth over the course of the study compared to the low light exposure group.

A limitation of our study is the relatively small sample size, and short follow-up time. Future studies objectively measuring eye growth and light exposure in larger populations with longer follow-up are likely to provide more precise estimates regarding the magnitude of the effects of light exposure on eye growth, and may provide increased power to explore in greater detail the relationship between the average daily pattern of light exposure (in terms of timing and magnitude of light exposure) and eye growth. Given that our current study was only of 18 months duration, future longer term studies will provide greater insights into whether the influence of light upon axial eye growth is time restricted or time varying across different ages, refractive groups or rates of eye growth in childhood.

The lack of cycloplegic refraction data is another limitation, as this reduces the reliability of refractive error data in children.[45] For this reason, our analysis concentrated upon changes in AxL (with aspects of the analyses relying entirely upon AxL data), which are highly precise and unlikely to be substantially influenced by cycloplegia.[46] Changes in choroidal thickness have previously been documented during accommodation, which could potentially influence noncycloplegic AxL measurements.[47] However, these changes are of small magnitude and only appear significant with relatively large accom-

modative demands (4 D), which suggests that our AxL measurements are unlikely to have been substantially influenced by such changes. An additional study limitation is the fact that the measurements from the wrist watch light sensors may not always reflect the light reaching the eye over the same time interval (depending upon wrist positioning). However, it should be noted that previous studies of adult populations have reported that light exposure measures from the wrist are significantly correlated with[48] and show reasonable agreement[49] with eye level light exposure measures. Jardim et al.[49] reported that 69% of light exposure measures collected concurrently at both wrist and eye level, differed by 50 lux or less between the wrist and eye.

CONCLUSIONS

In conclusion, this study provides the first evidence of a modest but statistically significant relationship between objectively measured daily ambient light exposure and eye growth in children, consistent with more light exposure resulting in slower axial growth of the eye. These findings indicate a role for ambient light exposure in the previously documented association between outdoor activity and myopia and provide evidence to support interventions aimed at increasing daily light exposure in order to slow childhood myopia progression.

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