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Light Exposure and Eye Growth in Childhood

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**Abstract:**

**Purpose:** To examine the relationship between objectively measured ambient light exposure and longitudinal changes in axial eye growth in childhood.

**Methods:** One hundred and one children (41 myopes and 60 non-myopes) aged 10-15 years participated in this prospective longitudinal observational study. Axial eye growth was determined from measures of ocular optical biometry collected at 4 study visits over an 18-month period. Each child’s mean daily light exposure was derived from 2 periods (each 14-days long) of objective light exposure measurements from a wrist worn light sensor (Actiwatch-2).

**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), gender (p<0.01) and age (p<0.001). When categorized according to their objectively measured average daily light exposure and adjusting for potential confounders (age, gender, 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/year) exhibited significantly greater eye growth compared to children experiencing moderate (842 ± 109 lux, 0.060 mm/year) and high (1455 ± 317 lux, 0.065 mm/year) 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 a role of light exposure in the documented association between time outdoors and childhood myopia.
Introduction:

There is growing evidence from both human and animal studies of refractive error, that ambient light exposure is an important environmental factor involved in the regulation of eye growth. The 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 less myopic refractive errors compared to chicks raised with daily exposure to low light levels (50 lux).\textsuperscript{1} Exposure to high intensity light also appears to protect against the development of form deprivation myopia in both chicks\textsuperscript{2,3} and primates.\textsuperscript{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.\textsuperscript{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.\textsuperscript{6}

The 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.\textsuperscript{7-10} Evidence from a number of human epidemiological studies that report significant associations between less time outdoors and the presence,\textsuperscript{11-14} development\textsuperscript{15-18} and progression\textsuperscript{19,20} of myopia in children also lends support to an involvement of ambient light exposure in refractive error development in humans, since being outdoors typically involves exposure to much higher amounts of light compared to being indoors (see Sherwin et al\textsuperscript{21} and French et al\textsuperscript{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 childhood23 (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 stabilisation of myopia.27

While it has been postulated that the association between less myopia and more time outdoors is due to increased light exposure when outdoors,12 the vast majority of studies examining the relationship between outdoor activity and myopia have used questionnaires to estimate outdoor activity. These 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 children28,30 and adults29,31 with a range of refractive errors. We recently reported upon the (objectively measured) light exposure and physical activity patterns of a pediatric population, and found a significantly lower average light exposure in myopic children compared to non-myopic 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 non-myopic children.

**Methods:**

**Subjects and Procedures**

This prospective, observational longitudinal examination of axial eye growth and objectively measured light exposure involved 102 children aged between 10 and 15 years of age enrolled in the Role of Outdoor Activity in Myopia (ROAM) study. The vast majority of 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 non-cycloplegic subjective refraction aiming for maximum plus/least minus for best visual acuity followed by binocular balancing), 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, children with non-cycloplegic hyperopic refractive errors of greater than +1.25 DS were
excluded from the study. Eligible subjects were classified based upon their non-cycloplegic spherical equivalent refractive error (SER) as either myopic (average SER from right and left eyes of -0.50 DS or more, with at least one eye exhibiting 0.75 DS or more myopia) or non-myopic (average SER from right and left eyes less than +1.25 DS and greater than -0.50 DS, with neither eye exhibiting 0.75 DS or more myopia). The myopic children all wore conventional single vision spectacle corrections (although 4 children also wore spherical soft disposable contact lenses) and were excluded if they were under any optical or pharmacological treatments to slow myopia progression. One of the non-myopic 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 -2.39 ± 1.50 DS, mean cylinder -0.38 ± 0.47 DC) and 60 as non-myopes (mean subjective SER +0.34 ± 0.30 DS, mean cylinder -0.10 ± 0.19 DC). No children exhibited anisometropia of >1.25 DS, and the mean interocular difference in SER was 0.17 ± 0.22 DS. The myopic and non-myopic children were well matched for both age (mean age 13.0 ± 1.5 years in the myopes and 13.1 ± 1.2 years in the non-myopes) and gender (51% of the myopes and 52% of the non-myopes were female). Baseline ocular biometric measurements were collected between May and November 2012. Each child then had ocular measurements collected every 6 months over an 18 month period (i.e. a total of 4 ocular measurement visits conducted over 18 months) and objective measurements of ambient light exposure were collected in two separate periods over the first twelve 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. Over the 18 month study period, three children were lost to follow-up (two after their baseline visit, and one after their 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 2 visits, and 94 subjects (59 non-myopes and 35 myopes) had complete data from all 4 visits.

At each 6 monthly 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. At each visit, 5 repeated measurements of ocular biometry were collected on both eyes of each child. All ocular biometry measurement visits were scheduled between 3pm and 5pm, to limit the potential confounding influence of diurnal variations in axial length upon the data.

Objective ambient light exposure measures were collected using a wrist-worn light sensor device (Actiwatch 2, Philips Respironics, USA). This is a lightweight, waterproof (up to 30 minutes in water) wristwatch sized device that contains a silicone photodiode light sensor to measure visible light illuminance (the sensor measures over a wavelength range from 400-900 nm, has a peak sensitivity of 570 nm and 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 (the mean ± SD
The 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 were conducted between July and December 2012 (i.e. between the first and second ocular measurement visit), and the second between February and August 2013 (between the second and third ocular measurement visit). Each light measurement period was categorized as being either 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 their non-dominant 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). The 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 the right and left eye were averaged. The light exposure data were then analysed to calculate the mean daily light exposure (between 6am and 6pm) for each subject, for each of the two 14-day 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 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 (ICC) of the between session reliability of the average daily light exposure measurements was 0.759. The mean light exposure between 6am and 6pm was used as our primary light exposure measure in the study, since 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. The mean light exposure over other times of the day was uniformly low (mean night-time light exposure between 6pm and 6am was 7± 5 lux, with children being exposed to light of >1000 lux on average for less than 30 seconds per day between 6pm and 6am). 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.\textsuperscript{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),\textsuperscript{36} enabling the average daily physical activity (between 6am and 6pm) for each child to be calculated.

All statistical analyses were carried out using IBM SPSS Statistics Version 21. Normality of the 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 eighteen months of the study were then examined using linear mixed model (LMM) analyses, with restricted maximum likelihood estimation. The LMM 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 further 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 gender) 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. Since 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 since 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 $\geq 1020$ lux), “moderate daily light exposure” (average daily light exposure between 652 and 1019 lux) or “low daily light exposure” (average daily light exposure $\leq 651$ lux) based upon a tertile split of the average daily light exposure data. Additionally, this model also used baseline axial length as the variable describing refractive error (given that axial length is the major biometric correlate of refractive error), so as to provide an analysis that did not rely upon the non-cycloplegic refractive error grouping. The changes in AxL over the course of the study were then examined, including categorical predictor variables (light exposure group, parental myopia and gender) 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 the myopic and non-myopic children (all $p>0.05$).
The average objectively measured light exposure for this population of children is summarised 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 in warmer days compared to cooler days. The myopic children (mean ± SD daily light exposure across all measurement days: 805 ± 427, range: 225-2264, median: 716 lux) also exhibited significantly lower average daily light exposure compared to the non-myopic children (mean daily light exposure: 999 ± 468, range: 265-2125, median: 921 lux) (p<0.05). The difference in average daily light exposure between the two refractive error groups however, was not season-dependent (refractive group by season interaction, p>0.05). Although the 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) compared to the non-myopic 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).

Bivariate correlation analysis revealed a significant association between the 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), 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) (Figure 1). The average questionnaire derived outdoor time was also significantly correlated with the 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 use when outdoors ranged from “never” to “all the time” (median response was “less than half the time”) and the reported use of sunglasses ranged from “never” to “half the time” (median response was “never”). The distribution of the reported frequency of use of hats and sunglasses did not differ significantly between the myopic and non-myopic children (Mann-Whitney 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 axial length observed over the 18 months of the study for all children was 0.11 ± 0.15 mm. At the baseline visit, the mean axial length of the myopic children was 24.46 ± 1.05 mm, and of the non-myopic children was 23.24 ± 0.65 mm. Over the course of the study, a mean axial eye growth (i.e. change in axial length from baseline) of 0.19 ± 0.20 mm was found in the myopic children, and 0.05 ± 0.05 mm in the non-myopic children (Figure 2). LMM analysis examining the longitudinal changes in axial length (Table 3) revealed a significant main effect of refractive group and gender, consistent with the baseline axial length being significantly smaller in the non-myopic children compared to the myopic children (the myopic children were estimated to have a 1.2 mm longer axial length compared to the non-myopic children, p<0.001) and smaller in girls compared to boys (boys were estimated to have an 0.7 mm longer axial length compared to 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 axial length for the myopic children compared to the non-myopic children.
Significantly greater axial length change was also observed in boys compared to girls (boys were found to exhibit an 0.04 mm/year greater axial growth than 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 axial length \( (\beta = -0.02 \text{ mm/year}, p=0.008) \).

A significant relationship between the average daily light exposure and the longitudinal changes in axial length over time was also found, as evidenced 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 axial length over the course of the study \( (\beta = -0.12, p<0.05) \), and indicates that for every 1 log unit increase in average daily light exposure, the axial growth rate decreased by 0.12 mm/year. There was no significant effect of self-reported nearwork, or outdoor activity, average daily physical activity, or parental history of myopia observed upon the changes in axial length over the course of the study (all main effects and interactions \( p>0.05 \)). The effects of average daily light exposure remained significant \( (\beta = -0.10, p<0.05) \), even if self-reported outdoor activities were removed from the model.

To further explore the relationship between light exposure and axial eye growth, we ran LMM analyses including the mean daily time 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 only found for the mean (log) daily minutes of exposure
to light levels >3000 lux ($\beta = -0.12$, p = 0.04) and >5000 lux ($\beta = -0.09$, p = 0.049).

Additional analysis was carried out after categorizing the children based upon their
average daily light exposure regardless of refractive status. The 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 axial length in each of these three light
exposure groups, revealed that the changes in axial length over time varied
significantly with baseline axial length (with longer axial length at baseline being
associated with faster axial growth: $\beta = 0.03$, p = 0.008), age at baseline (with
younger age at baseline being associated with faster axial eye growth: $\beta = 0.03$, p =
0.005) and with light exposure group (p = 0.01). There was no significant interaction
between age and light exposure upon the changes in axial length over time (p = 0.6).
Children categorised as habitually experiencing low daily light exposure exhibited
significantly greater axial eye growth ($\beta = 0.13$ mm/year) compared to those
experiencing high ($\beta = 0.065$ mm/year) and moderate ($\beta = 0.060$mm/year) light
exposure (p<0.05) (Figure 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 the axial eye growth over time. However, there was no significant interaction between refractive group and light exposure group upon the changes in axial length over time (p = 0.45), suggesting that the effects of light exposure and refractive group upon axial eye growth were independent (Figure 3).

Discussion:

This study, examining the longitudinal changes in axial length 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 have reported a significant association between time spent outdoors, derived by questionnaires, and the prevalence, development and progression 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 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 1000-3000 lux. Although our results indicate that the magnitude of daily light exposure appears to contribute to the apparent protective effects of outdoor activities, it doesn’t rule out the potential involvement of other factors.\textsuperscript{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 around 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 non-myopic children in our current study, a 1 log unit increase in average daily light exposure was associated with ~0.12 mm/year less eye growth (approximately 0.3-0.4D 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 around 90-100 minutes per day. When considered as non-log-transformed data, an increase in average daily light exposure of 1000 lux, was associated with ~0.05 mm/year slower annual axial eye growth. Although increased daily light exposure could be achieved through a variety of means (e.g. Golden et al.), 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 (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, Parssinnen and Lyyra 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. 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 non-myopic Chinese schoolchildren, Guo et al\textsuperscript{20} reported a significant relationship between less axial eye growth over a twelve month period and 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 ($\beta = -0.01$), however 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.\textsuperscript{28,29}

Previous studies have reported that childhood eye growth shows significant seasonal variations.\textsuperscript{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, since 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 (β = -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)(Figure 1).
It should also be noted, that our eye growth data collected every 6 months did not
exhibit clear evidence of strong seasonal effects (Figure 2). This is likely 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-monthly 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 synchronise
both eye growth and light exposure measures 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 non-myopic children is similar
to 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 a number of previous reports of eye growth in myopic children.\textsuperscript{8,20,40,42} This may reflect the slightly older mean age of our cohort compared to previous studies, or alternatively may be related to differences in environmental exposures between groups. Dharani et al\textsuperscript{28} reported that the mean (objectively measured) light exposure of a group of Singaporean children was 702 lux (~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 the criteria used in our current study, the majority of the Singaporean children in the Dharani et al\textsuperscript{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.\textsuperscript{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 axial length over the 18 months of the study compared to those children habitually experiencing moderate and high light exposure (Figure 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, since this reduces the reliability of refractive error data in children. For this reason, our analysis concentrated upon changes in axial length (with aspects of the analyses relying entirely upon axial length data), which are highly precise and unlikely to be substantially influenced by cycloplegia. Changes in choroidal thickness have previously been documented during accommodation, which could potentially influence non-cycloplegic axial length measures. However, these changes are of small magnitude and only appear significant with relatively large accommodative demands (4 D), which suggests that our axial length 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\textsuperscript{48} and show reasonable agreement\textsuperscript{49} with eye level light exposure measures.

Jardim et al\textsuperscript{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.

Acknowledgements: This work was supported by an Australian Research Council, Discovery Early Career Researcher Award (DE120101434). We thank Katie Dwyer and Dillon Ribeiro for assistance with data analysis procedures in the study, Ed Gosden for his advice regarding the statistical analyses performed in this study and Professor Joanne Wood for her constructive suggestions regarding a draft of this manuscript.
References


Table 1: Overview of the average environmental climate conditions and day length experienced over the periods of light exposure measurements in the warmer and cooler periods.

<table>
<thead>
<tr>
<th></th>
<th>Minimum Temperature (°C)</th>
<th>Maximum Temperature (°C)</th>
<th>Day Length (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Warmer Days</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All children</td>
<td>18.5 ± 2.2</td>
<td>28.2 ± 1.0</td>
<td>12.9 ± 0.6</td>
</tr>
<tr>
<td>Myopes</td>
<td>18.2 ± 2.3</td>
<td>27.9 ± 0.7</td>
<td>12.7 ± 0.5</td>
</tr>
<tr>
<td>Non-Myopes</td>
<td>18.6 ± 2.2</td>
<td>28.3 ± 1.1</td>
<td>13.0 ± 0.6</td>
</tr>
<tr>
<td><strong>Cooler Days</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All children</td>
<td>13.1 ± 2.0</td>
<td>24.0 ± 2.0</td>
<td>10.9 ± 0.6</td>
</tr>
<tr>
<td>Myopes</td>
<td>13.1 ± 2.1</td>
<td>24.5 ± 2.1</td>
<td>11.1 ± 0.6</td>
</tr>
<tr>
<td>Non-Myopes</td>
<td>13.1 ± 1.9</td>
<td>23.7 ± 1.9</td>
<td>10.8 ± 0.6</td>
</tr>
</tbody>
</table>
Table 2: Overview of average daily light exposure results (mean ± SD) from wrist watch light sensors. P-values show the result from a repeated measures ANOVA examining the influence of season (warmer day versus cooler day period) and refractive group (myopic versus non-myopic children). None of the considered variables exhibited a significant season by refractive group interaction (all p>0.05).

<table>
<thead>
<tr>
<th>Daily light exposure (lux)</th>
<th>Mean ± SD</th>
<th>P-Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Warmer Days</td>
<td>Cooler Days</td>
</tr>
<tr>
<td>Mean daily light exposure (lux)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All children</td>
<td>987 ± 547</td>
<td>857 ± 525</td>
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<tr>
<td>Myopes</td>
<td>818 ± 487</td>
<td>793 ± 497</td>
</tr>
<tr>
<td>Non-Myopes</td>
<td>1099 ± 559</td>
<td>900 ± 542</td>
</tr>
<tr>
<td>Daily bright light exposure (mins)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 1000 lux</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All children</td>
<td>106 ± 46</td>
<td>83 ± 41</td>
</tr>
<tr>
<td>Myopes</td>
<td>90 ± 43</td>
<td>72 ± 38</td>
</tr>
<tr>
<td>Non-Myopes</td>
<td>117 ± 46</td>
<td>90 ± 42</td>
</tr>
<tr>
<td>&gt; 2000 lux</td>
<td></td>
<td></td>
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<tr>
<td>All children</td>
<td>72 ± 37</td>
<td>54 ± 31</td>
</tr>
<tr>
<td>Myopes</td>
<td>60 ± 35</td>
<td>48 ± 29</td>
</tr>
<tr>
<td>Non-Myopes</td>
<td>79 ± 37</td>
<td>58 ± 33</td>
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<tr>
<td>&gt; 3000 lux</td>
<td></td>
<td></td>
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<tr>
<td>All children</td>
<td>51 ± 31</td>
<td>38 ± 25</td>
</tr>
<tr>
<td>Myopes</td>
<td>42 ± 25</td>
<td>34 ± 22</td>
</tr>
<tr>
<td>Non-Myopes</td>
<td>57 ± 33</td>
<td>41 ± 27</td>
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<tr>
<td>&gt; 5000 lux</td>
<td></td>
<td></td>
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<tr>
<td>All children</td>
<td>30 ± 21</td>
<td>24 ± 17</td>
</tr>
<tr>
<td>Myopes</td>
<td>24 ± 17</td>
<td>22 ± 15</td>
</tr>
<tr>
<td>Non-Myopes</td>
<td>33 ± 22</td>
<td>25 ± 18</td>
</tr>
</tbody>
</table>
Table 3: Overview of the statistically significant fixed effects and parameter estimates from the LMM examining the influences of changes in axial length (from baseline) over the 18 months of the study. Other parameters included in the model (parental myopia, questionnaire derived nearwork and outdoor activity, and physical activity) did not show statistically significant effects (all p>0.05).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>df</th>
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<th>Parameter Estimates</th>
<th>P-Values</th>
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<tr>
<td>Intercept</td>
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<td>89415</td>
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<td>Time</td>
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<td>78</td>
<td>0.13</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Refractive group</td>
<td>1,89</td>
<td>42</td>
<td>-1.2</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Gender</td>
<td>1,89</td>
<td>89</td>
<td>-0.7†</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Time by Refractive group</td>
<td>1,89</td>
<td>14</td>
<td>-0.08</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Time by Age at baseline</td>
<td>1,89</td>
<td>7</td>
<td>-0.02</td>
<td>0.008</td>
</tr>
<tr>
<td>Time by Gender</td>
<td>1,88</td>
<td>5</td>
<td>-0.04†</td>
<td>0.027</td>
</tr>
<tr>
<td>Time by log Mean daily light exposure</td>
<td>1,89</td>
<td>4</td>
<td>-0.12</td>
<td>0.047</td>
</tr>
</tbody>
</table>

 Parameter estimate for the non-myopic children.

 Parameter estimate for girls.
Table 4: Overview of the (unadjusted) mean ± SD ocular, demographic and light exposure parameters of the children in the study when categorised according to their mean daily light exposure, as exhibiting either high daily light exposure (n = 33), moderate daily light exposure (n = 33) and low daily light exposure (n = 33). P values are from a one-way ANOVA (except for the % females and % myopes, which is from the Kruskall-Wallis test) investigating for significant differences across the 3 light exposure groups in each parameter.

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
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<tbody>
<tr>
<td></td>
<td>Baseline AxL (mm)</td>
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<tr>
<td>High Light Exposure</td>
<td>23.67 ± 0.94</td>
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<tr>
<td>Moderate Light Exposure</td>
<td>23.70 ± 1.16</td>
</tr>
<tr>
<td>Low Light Exposure</td>
<td>23.86 ± 0.98</td>
</tr>
<tr>
<td>P-Value</td>
<td>0.7</td>
</tr>
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</table>
**Figures:**

*Figure 1:* Relationship between the objectively measured mean daily light exposure (from 6am to 6pm) (a) and mean daily exposure to bright light (>1000 lux) (b) in the warmer days measurement period and the cooler days measurement period for the myopic children (red circles) and non-myopic children (blue circles). Solid lines indicate the best fit regression line for the myopic (red) and non-myopic children (blue), and the 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 over eighteen months for the myopic (red line), non-myopic (blue line) and all children (green line) 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 the mean timing of the first and second light exposure measurements in the study (grey shading around the vertical lines illustrates the standard deviation of the mean timing of the light exposure measures).
Figure 3: Estimated mean change in axial length (AxL) from baseline over 18 months for the children habitually exposed to high light levels ($\geq 1020$ lux) (blue line), moderate light levels ($652$-$1019$ lux) (green line) and low light levels ($\leq 651$ lux) (red line) (adjusted for all measured covariates in the study). Data for all children (a), the myopic children only (b) and the non-myopic children only (c) is shown. 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 the mean timing of the first and second light exposure measurements in the study (grey shading around the vertical lines illustrates the standard deviation of the mean timing of the light exposure measures).