Published in final edited form as:
Chronobiol Int. 2010 July ; 27(6): 1242–1258. doi:10.3109/07420528.2010.487965.

Evening daylight may cause adolescents to sleep less in spring than in winter

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Abstract

Sleep restriction commonly experienced by adolescents can stem from greater sleep pressure by the homeostatic processes and from phase delays of the circadian system. With regard to the latter potential cause, we hypothesized that because there is more natural evening light during the spring than winter, a sample of adolescent students would be more phase delayed in spring than in winter, would have later sleep onset times and, because of fixed school schedules, would have shorter sleep durations. Sixteen eighth-grade subjects were recruited for the study. We collected sleep logs and saliva samples to determine their dim light melatonin onset (DLMO), a well-established circadian marker. Actual circadian light exposures experienced by a subset of twelve subjects over the course of seven days in winter and in spring using a personal, head-worn, circadian light measurement device are also reported here. Results showed that this sample of adolescents was exposed to significantly more circadian light in spring than in winter, especially in the evening hours when light exposure would likely delay circadian phase. Consistent with the light data, DLMO and sleep onset times were significantly more delayed, and sleep durations were significantly shorter in spring than in winter. The present ecological study of light, circadian phase, and self-reported sleep suggests that greater access to evening daylight in the spring may lead to sleep restriction in adolescents while attending school. Therefore, lighting schemes that reduce evening light in the spring may encourage longer sleep times in adolescents.

Keywords

Circadian rhythms; light measurement; DLMO; adolescents; sleep deprivation

INTRODUCTION

Sleep restriction is common in adolescents and has received growing attention in the past few years. Pubertal changes in sleep regulation mechanisms are believed to underlie the tendency toward later bed and rise times experienced by adolescents (Carskadon et al., 1993, 1999; reviewed in Hagenauer et al., 2009). Because school times are fixed during the week, later sleep onset on week nights results in chronic sleep restriction, which in turn has been associated with poor school performance, mood changes, obesity, depression, and even suicidal thoughts (reviewed in Spiegel, 2008; Wolfson et al. 1998; reviewed in Wolfson et al., 2003; Wolfson et al., 2007).

It has been postulated that the timing of sleep onset is governed by two endogenous components: a circadian timing system and homeostatic drive or sleep pressure (Borbély et

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Conflict of interest: None

al., 2000). The suprachiasmatic nuclei (SCN) of the hypothalamus generate and regulate circadian rhythms in mammals (Refinetti, 2006; Duguay & Cermakian, 2009). In the absence of environmental cues, the period of circadian rhythms generated by the SCN in humans (tau) is, on average, slightly greater than 24 h (Czeisler et al., 1999). Environmental cues, of which light/dark patterns are the most important, synchronize circadian rhythms to the 24 h solar day (Moore, 1997). According to published phase response curves (PRCs), light applied during the early morning hours (after minimum core body temperature) will advance the clock, while light applied in the evening and early part of the night will delay the circadian clock (Khalsa et al., 2003). Therefore, on a relative basis, morning light will facilitate earlier sleep times, while evening light will facilitate later sleep times.

Some evidence has emerged suggesting that the endogenous circadian period is longer (Carskadon et al., 1999; reviewed in Crowley et al., 2007) and the sensitivity to evening light by the circadian system is greater in adolescents, especially for those suffering from delayed sleep phase disorder (Aoki et al., 2001). Both of these phenomena would functionally delay the timing of the adolescent circadian clock, thereby contributing to later bed and rise times. Moreover, it has been suggested that adolescents accumulate sleep pressure more slowly, and progressively more slowly as they get older (Jenni et al., 2005), further contributing to a later sleep onset (reviewed in Hagenauer et al., 2009).

Implicit in these discussions about delayed sleep in adolescents is the assumption that evening light, particularly electric light in the home, delays the circadian clock of adolescents. Circadian light exposures by adolescents have never actually been measured in a field setting; this is likely because photometric devices calibrated in terms of circadian light have not existed until recently (Bierman et al., 2005). It is now well accepted that the human circadian system is maximally sensitive to short-wavelength (“blue”) light (Brainard et al., 2001; Rea et al., 2005; Thapan et al., 2001). Commercially-available photometric devices are all calibrated in terms of the photopic luminous efficiency function [$V(\lambda)$] which is relatively insensitive to short-wavelength light. Moreover, commercially-available photometric devices are all hand-held (or tripod mounted) and are designed for instantaneous light measurements. Because phototransduction by the circadian system occurs at the retina, circadian light measurements should be obtained at the plane of the cornea. Furthermore, because light *exposure* is important to entrainment of the circadian system to local time, light should be sampled continuously. Consequently, light measurements made using commercially-available light meters are inappropriate for quantifying retinal circadian light exposures. Instead, the Daysimeter, a head-worn calibrated circadian light meter (Bierman et al., 2005), was used to measure the light-dark exposure patterns actually experienced by the sample of adolescent students in the present study. Saliva samples were also collected from these students to determine their dim light melatonin onset (DLMO), a well-established marker of circadian phase (reviewed in Benloucif et al., 2008). Sleep logs were used to estimate sleep onset times and sleep durations. Given the hypothesized enhanced sensitivity to light in the delayed portion of the adolescent PRC, adolescent students should be more phase-delayed in the spring, relative to the winter, when more daylight is available in the evening hours. Thus, we hypothesized that the present sample of adolescent students would experience more circadian light in the spring and, thus, would exhibit later DLMO, later sleep onset times, and reduced sleep durations than they did during the winter.

METHODS

General study design

The present study consisted of three phases. Assent forms were obtained from the participants and consent forms were obtained from each student’s parents or guardian for

each phase of the project. Rensselaer Polytechnic Institute's Institution Review Board (IRB) approved the study protocol which adheres to the ethical criteria set by the Journal (Portaluppi et al., 2008). In Phase 1, eighth-grade students enrolled at Algonquin Middle School in Averill Park, NY were invited to complete a series of self-report measures. A subset of those participating in Phase 1 completed Phase 2, which was a one-week study beginning in February 2009. In Phase 2, all participants were asked to wear a circadian light meter (Daysimeter) for seven consecutive days, to maintain a sleep log for those days, and to provide saliva samples during one evening. Phase 3, which began in May 2009, was a repetition of Phase 2. Reported here are the results from sixteen subjects who completed all three phases of the study and complied with the experimental protocol. Valid Daysimeter data were obtained for 12 subjects (7 males/5 females), so separate analyses using data from these subjects are also presented here.

Site selection

Algonquin Middle-School was chosen for this study because most of its classrooms had window glazing on one façade, common for school construction in New York State. Continuous light measurements were obtained in five classrooms for 18 days and nights in October and November 2008 from a light-logger mounted on a wall near the center-line of the classroom, about 2 m above the floor. The window wall in two classrooms faced east, two faced west, and one faced south. The glazing for all classrooms was tinted ($t = 0.7$); all classrooms were equipped with manually-operated, light-colored perforated window blinds. The calibrated light sensor was oriented toward the center of the classroom, thus recording vertical illuminance incident on the wall from both daylight and electric lighting. Electric light operation and window blind usage were not monitored. Recorded illuminance levels ranged from 100 to 500 lux on cloudy days and from 300 to 1300 lux on sunny days. To provide a sense of the amount of daylight available in the Algonquin Middle-School classrooms, an average of 200 lux was obtained in a windowless New York school using comparable recording methods.

Subject selection

The school administrators and science teachers helped recruit participants for Phase 1 in December 2008. One hundred fifty eighth-grade students (75 female/75 male) were invited to complete self-report measures of psychosocial stress, mood, and sleep quality. The following questionnaires were used for subject selection: Sleep Habits Survey, Child Behavior Checklist (CBCL; parent to complete) (Achenbach & Rescorla, 2001), Youth Self-Report (YSR) (Achenbach & Rescorla, 2001), Perceived Stress Scale (PSS) (Cohen et al., 1983), the Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988), the Munich Chronotype Questionnaire (MCQT) (Roenneberg et al., 2003), and the Center for Epidemiologic Studies Depression Scale (CES-D) (Radloff, 1977). The MCQT quantitatively assesses chronotype and is based upon the adjusted mid-sleep time on "free" nights (MSFSC). A $5 (US) incentive was offered to those students completing and returning the series of questionnaires.

Thirty packets of complete questionnaires were returned, 11 from female students and 19 from male students. Although we had hoped for a much larger response rate, we selected, as originally planned, only those subjects who were within the normal ranges on every questionnaire. Therefore, all students who participated in Phase 2 were within the normal the ranges on the self-report scales and were also willing (with parent consent) to serve as subjects by wearing the Daysimeter, completing sleep logs, and providing saliva samples. Although the number of surveys to complete in Phase 1 may have been daunting for many of the potential subjects (thus the poor response rate), there is no reason to suppose that, with respect to the outcome measures employed in this study, the final subject pool was

unusual, because all subjects in Phase 2 and Phase 3 were within the normal ranges on every self-report scale. Sixteen subjects (ten males/six females, ages 13–14 yrs) were arbitrarily selected from among the thirty respondents who completed the questionnaires in Phase 1. These subjects were paid $70 for their participation in the one-week protocol of Phase 2, from February 27 to March 6, 2009 (winter). All subjects who participated in Phase 2 were invited to participate in Phase 3 for the same remuneration; all of these subjects completed Phase 3, which took place from May 14 to 21, 2009 (spring).

Daysimeter apparatus

The Daysimeter is a calibrated light exposure, activity, and temperature measurement device that is designed to be worn on a person's head (Bierman et al., 2005). An on-board clock controls the data sampling at a rate of 1 Hz and a logging interval of 30 sec. This scheme and careful power management allows for continuous measurement of light exposures and activity for at least 30 days without coin-cell battery replacement. The light, activity, and local temperature data are stored in flash memory for subsequent processing. The Daysimeter employs two photosensors separately calibrated to provide photopic (visual) and short-wavelength ('blue') responses to optical radiation (Figure 1). The two photosensors are juxtaposed at the end of a printed circuit board. This creates a compact, in-line package that rests on the side of a subject's head and places the photosensors near the plane of the subject's corneas. The photopic sensor is calibrated to directly measure illuminance in units of lux (lx). The "blue" sensor has peak sensitivity at short wavelengths, near the peak of the spectral sensitivity of the human circadian system, and is calibrated in arbitrary units. Post-processing software uses the photopic and "blue" photosensor data to calculate circadian light, CL_A, which, for white light, has spectrally weighted irradiance units of approximately the same magnitude as illuminance, in lux (Rea et al., 2010). Two on-board, orthogonally oriented, accelerometers are used to quantify activity. Root-mean-square (rms) deviations in head acceleration in the up/down and forward/back directions are calculated during logging. Local temperature is measured using a solid-state thermometer. These calibrated temperature values are used as part of the light-calibration routine and to help confirm that the subject was wearing the Daysimeter throughout the experiment.

Procedures

Every student was asked to wear the Daysimeter during waking hours except during strenuous exercise and when bathing. When it was not being worn, they were asked to place the Daysimeter beside them; when asleep, they were asked to place it next to their bed. The one-week session in the winter began at the school on a Friday morning. Each student was asked to keep a sleep log as well as record any times the Daysimeter may have been removed (e.g., for bathing or for strenuous exercise). On the following Friday evening, the students returned to school at 17:30 h. From 18:00 until 22:00 h, the ceiling lights in the meeting room were kept off, and the room was lit with dim red light (<2 lux at the cornea). This time bracket was selected based on subjects' predicted DLMO. DLMO predictions were determined from the MCQT reported bedtimes during the school week. Students were not allowed to perform extraneous exercise during that period; rather, they were asked to sit quietly by playing games, doing homework, watching movies, or working on filtered computers (computers were filtered with orange filters that removed light <525 nm). They were also specifically required to remain sitting still for 5 min prior to each saliva sample collection. Saliva samples from all students (Salivette, Sarstedt, Newton, NC, USA) were collected every 30 min to determine DLMO. Students were not allowed to eat during this period and were only allowed to drink water immediately following each sample collection. No water was allowed 20 min prior to each sample collection. The subjects chewed on a plain cotton cylinder until saturated. These samples were then, in turn, centrifuged (yielding at least 1 ml of saliva) and refrigerated by the researcher. The samples were subsequently

frozen and sent to Pharmascan in Osceola, WI for melatonin radioimmuno-assay. The same procedure was repeated during the spring. The only difference in the spring testing was that, because of a scheduling conflict, the one-week set of data was collected from Thursday to Thursday. Thus, saliva samples for DLMO determinations were collected on Thursday evening.

DEPENDENT MEASURES

Light and activity

The Daysimeter simultaneously records two photosensor (photopic and "blue") and two activity (x and y planes) samples every sec during a 30 sec logging interval. The two sets of sampled photosensor values are each averaged and stored in flash memory for post-processing software computations of photopic illuminance and CL_A. Using on-board software, the activity samples are used to calculate a 30 sec activity index (AI) with the following equation:

$$\text{ActivityIndex} = k\sqrt{\frac{\left(SS_x + SS_y\right)}{n}},$$

where SS_x and SS_y are the sums of the squared deviations from the mean digital value for each accelerometer (x and y planes) over the 30 sec logging interval, n is the number of samples (30), and k is a calibration factor converting the measured output voltage of the accelerometers in arbitrary analog-to-digital converter counts to units of g-force (1 g-force = 9.8 m/s^2). Thus, AI is the rms deviation in acceleration in the×and y planes measured every 30 sec and the values stored in flash memory.

Daysimeter light, activity, and temperature data were examined by a technician for subject compliance before data analyses. When, for example, recorded temperatures dropped significantly and no activity was present in the data record, it was clear that the Daysimeter had not been worn (e.g., at night). Because the protocol provided for subjects to not wear the Daysimeter during sleep and during exercise, average light and activity values used for analysis only reflect those intervals when the Daysimeter was determined to be worn for more than 30 consecutive minutes.

Dim light melatonin onset (DLMO)

In a typical diurnally active person, melatonin concentrations in saliva rise in the early evening, typically after 19:00–20:00 h, reach a peak in the middle of night, and by 10:00 h have declined to daytime levels (Arendt, 1995). DLMO is commonly used as a phase marker of the melatonin rhythm. Typically, DLMO is observed 2–3 h prior to a person's habitual sleep time. DLMO can be determined from a pre-set threshold (usually 4 pg/ml in saliva) using a partial melatonin profile. In general, the partial melatonin profile is established from samples collected every 30 min for 4–5 h in the early evening (usually 2 h prior to estimated DLMO to 2 h after estimated DLMO) while subjects are sitting in a dim room (<10 lux of white light at the cornea). For this study, subjects were placed in a dim red light room (<2 lux at the cornea) for data collection. DLMO was calculated for each subject using linear interpolation between two sample concentrations, one sample below and one sample above 4.0 pg/ml, under the constraint that the higher sample concentration was followed by a sample concentration also above 4.0 pg/ml. The sensitivity of the saliva assay was 0.7 pg/ml, and the intra- and inter-assay coefficients of variability were 12.1% and 13.2%, respectively.

Sleep logs

Students were asked to keep a sleep log during both weeks of the study (spring and winter) by reporting their bedtimes, sleep latencies, wake-up times, and rise times.

RESULTS

Light and activity

Due to several technical difficulties with four of the deployed Daysimeters, the summary statistics in Table 1 are based on the results of the light and activity measurements for 12 subjects using data collected from Sunday 18:00 h to Thursday 18:00 h for the winter and the spring recording weeks. These four days of the week were selected for analysis because they were common for both study weeks and because many students did not wear the Daysimeter during the weekends. Table 1 lists the mean and standard error of the mean (S.E.M), AI values as well as photopic and CL_A light exposures values for spring and winter. Again, these values are based upon those times when the Daysimeter was determined to have been worn for more than 30 consecutive minutes. Log transforms of the photopic and CL_A data are included because of the highly skewed distributions of recorded light exposures values; infrequent but extremely high light levels were recorded during daylight hours. The log transforms did not completely normalize the sampled log photopic and log-CL_A light distributions as revealed by a one-sample Kolmogorov-Smirnov test; therefore, two-tailed related-samples Wilcoxon signed ranks tests were performed. The non-parametric statistical analyses revealed that students were exposed to significantly lower levels of light (both photopic and CL_A) in the winter than in the spring even though, as might be expected, students were equally active in the winter and spring. Table 1 shows the light and activity data and the respective *p* values comparing spring and winter.

To better understand the patterns of circadian light exposures in the spring and winter, log-CL_A exposure levels for different times of day were examined. Specifically, it was important to determine whether these subjects might have received more circadian light during the phase delay portion of their PRC in the spring than in the winter, as hypothesized. Figure 2 shows the log-CL_A exposures between 06:00 (the earliest rise time) and 23:00 h (the latest bedtime) sub-divided into five periods, demarcated with a precision of quarter-hours (i.e., 15 min). These log-CL_A values are based upon Daysimeter data collected on the three complete and common school days of light recordings in the winter and spring (Monday, Tuesday, and Wednesday) prior to saliva sample collections for DLMO (Friday in winter and Thursday in spring). The first sub-division in Figure 2 was between 06:00:00 h, earliest rise time, and 08:00:00 h, the start of school time. The second sub-division was between 08:00:01 and 15:00:00, the subjects' school hours. The third sub-division was between the end of school, 15:00:01, and 17:45:00 h, near the time of sunset in Albany NY on Monday, March 2 (17:48 h). The fourth sub-division was between 17:45:01 and 20:15:00 h, near the time of sunset in Albany NY on Monday, May 18 (20:09 h). The fifth, and last, sub-division was between 20:15:01 and 23:00:00 h, the latest bedtime. The fourth sub-division was that period of time when there would have been more daylight available in spring than in winter and, therefore, that time period when there might be differentially more light available during the phase delay portion of the PRC.

A two-tailed related-samples Friedman's two-way analyses of variance by ranks was performed using the log-CL_A data and revealed that the log-CL_A distributions were significantly different ($n = 12$, $X^2 = 83.836$, $p<0.0001$). As shown in Figure 2, there was much greater circadian light exposure during the fourth sub-division period in spring than in winter, whereas there were much smaller differences in effective circadian light exposure during the other sub-divisions, including the first sub-division (06:00:00 to 08:00:00 h)

when there was greater potential for higher light exposures during the phase-advanced portion of the PRC in the spring relative to that in the winter. Two-tailed related-samples Wilcoxon signed ranks test were performed to compare light exposures during each subdivision in the winter and spring. During the spring, students were exposed to significantly more light in the fourth sub-division period (p=0.002) than during the same period in the winter. There were no significant differences in light exposures between winter and spring for any other sub-division.

DLMO

The average (±SD) DLMO for the sixteen subjects who completed all phases of the experiment was 20:02 ± 0:44 h in the winter and 20:22 ± 0:39 h in the spring. The DLMO data were normal; therefore, parametric statistics were utilized. A paired two-tail student's t-test revealed a significant difference in DLMO between winter and spring (p=0.001). The DLMO for the 12 subjects who completed all phases of the study and also provided complete Daysimeter data was 20:08 ± 0:46 h in the winter and 20:25 ± 0:40 h in the spring. Using a two-tail paired student's t-test, this difference was also statistically significant (p=0.02). Table 1 shows the DLMO data and the respective p values comparing spring and winter.

Sleep logs

One subject did not complete a sleep log during the spring, so sleep onset times and sleep durations for 15 subjects were compared for winter and for spring. The sleep log data from bed times on Sunday evening to wake-up times on Thursday morning were selected for analysis because these days corresponded to the days on which subjects consistently wore their Daysimeter. Sleep onset times were calculated by adding the reported sleep latency times to their reported bedtimes. The sleep logs showed that all but one of the 15 subjects was asleep before 23:00 h every night. Because it was expected that parents would consistently enforce bedtimes and rise times during the school week and because of the likely greater exposure to daylight during the phase-delay portion of the PRC, it was hypothesized that sleep onset times would be more delayed toward the end of the school week in spring relative to winter. In fact, the average ± (SD) of sleep onset on Wednesday evening was 22:14 h ± 43 min in the winter and 22:30 h ± 32 min in the spring and, using a two-tail paired student's t-test, this difference was statistically significant (p=0.03). Wednesday nights were chosen for analysis, because this was the latest night in the week common to the sampling periods in winter and in spring. Sleep onset times for Sunday evenings in the winter and spring were not significantly different (p>0.05). Sleep durations for all subjects were also calculated for Wednesday and Sunday nights by differencing sleep onsets with reported wake-up times. A two-tail paired student's t-test showed that sleep durations on Wednesday nights were significantly shorter in the spring than in the winter (p=0.03). Based upon the sleep log information, students slept on average ± standard deviation 7 h and 51 min ± 42 min on Wednesday night in the winter and 7 h and 36 min ± 38 min on Wednesday night in the spring. Sleep durations on Sunday nights in the winter and spring were not statistically significantly different (p>0.05).

The 11 subjects who provided complete sleep log and Daysimeter data had sleep onset and sleep duration estimates completely consistent with those provided by the 15 subjects described above. All 11 subjects were in bed before 23:00 h. For this smaller set of subjects, the average ± (SD) of sleep onset on Wednesday evening was 22:15 h ± 36 min in the winter and 22:31 h ± 26 min in the spring, statistically significant difference using a two-tail paired student's t-test (p=0.003). Sleep onset times for Sunday evenings in the winter and spring were not significantly different, however (p>0.05). Sleep durations for these subjects were also calculated. The sleep logs data were normal; therefore, parametric statistics were

utilized. A two-tail paired student's t-test showed that reported sleep durations on Wednesday nights were significantly shorter in the spring than in the winter (p=0.04). Sleep durations were, on average, 7 h and 47 min ± 38 min in the winter and 7 h and 30 min ± 37 min in the spring. Sleep durations on Sunday nights in the winter and spring were not statistically different (p>0.05).

DISCUSSION

The present results are the first to relate field measurements of circadian light exposures to a well-established circadian marker and to self-reports of sleep onset times and sleep durations during two seasons of the year. The DLMO values measured in this field study were similar to those previously measured in adolescents (13–16 yrs of age) (Crowley et al., 2006) and in young adults (18–45 yrs of age) (Burgess & Fogg, 2008). Prior studies have demonstrated that adolescents have later bedtimes in summer months compared to school months (Crowley et al., 2006; Hansen et al., 2005). The present results further support the inference that adolescents are exposed to significantly more circadian light in the phase-delay portion of their PRC in spring than in winter, and that this increase in evening light exposure leads to delayed DLMO and, shorter self-reported sleep durations. Thus, the present results underscore the importance of measuring circadian light exposures in order to draw valid inferences from field studies of this kind. Specifically, it is important to collect circadian light exposures when studying sleep and circadian phase in the field.

In this regard, the extended daylight hours in the spring, not evening electric lighting after dark in the home (last sub-division in Figure 2), seemed to have led to the effects reported here. There was no evidence from the light measurements that electric light usage changed from winter to spring. Measured exposures to light, including both daylight and electric light sources at home, were nearly the same in winter and in spring as shown by the relatively small differences in the log-CL_A values for the first, second, third, and fifth subdivisions in Figure 2. The circadian light exposures during the fourth subdivision, corresponding to the times between sunset in March and sunset in May, showed the greatest difference for the two seasons. These results suggest that exposure to the increased length of day in the evenings of the spring months, not to seasonal differences in electric light usage in the home after dark, produced the significant delay in DLMO and sleep onset and, thus, the significant reduction in sleep duration among these adolescents. Consistently, Thorne et al. (2009) measured short-, medium-, and long-wavelengths light using a wrist-watch light-measurement device during the summer and winter months in England. They showed that, even though overall light exposure was greater in the summer than in the winter, there was a significantly greater level of exposure to short-wavelength light during the summer evenings (17:00–21:00 h) compared to the same time during winter evenings.

From a practical perspective, some researchers have advocated for a change in school schedules in order to accommodate sleep changes common among adolescents, but this solution appears to be difficult for society to implement because of parental obligations. Parents and children could, instead, adopt a lighting scheme that: a) enhances circadian light exposure in the morning (that is, after minimum core body temperature) *and* b) limits circadian light exposure in the evening (before minimum core body temperature). However, rather than simply providing more circadian light exposure in the morning as some have suggested, this lighting strategy would, in addition to or perhaps instead of, provide *less* circadian light exposure during the evening hours. Designing schools with access to daylight in classrooms and scheduling outdoor activities exclusively during the morning hours can certainly increase morning circadian light exposures (Figueiro & Rea, 2010) and undoubtedly help advance, and thereby entrain, the circadian systems of adolescents. Although not tested in the present study, we hypothesize that taking measures to curtail

short-wavelength daylight exposures during the delay phase of the PRC may be effective for limiting light-induced phase delays of the circadian systems of adolescents, particularly those who are extremely delayed (i.e., cannot fall asleep before midnight). The efficacy of an evening light-curtailment intervention may be more effective for improving sleep in delayed adolescents than a morning light-enhancing intervention, because delaying circadian phase seems to be much easier to accomplish than advancing circadian phase (Jewett et al., 1999). Of course this idea would have to be directly tested in the field, particularly considering the active life-style of most adolescents.

Although this was the first ecological study measuring circadian light and a circadian phase marker (DLMO) in adolescents, there are several limitations worth noting. First, we relied on self-reports of sleep, so we do not know exactly the sleep duration nor do we know how different stages of sleep might have been affected. There may also be sex differences among adolescents, but our sample was not large enough to explore this possibility. Of related interest, we did not account for pubertal differences among our subjects, and it is reasonable to suppose that this variable might systematically affect light sensitivity for the PRC. Social activities were not monitored either, and these might, indeed, affect sleep duration and sleep onset. Despite these limitations that may increase the variance in our outcome measures, no systematic confounds could be identified as they might affect the measurements of circadian light, DLMO, and sleep duration. Therefore, the results of the present ecological study appear to offer a promising foundation for the development of practical, non-pharmacological interventions for improving sleep in delayed adolescents (Urner et al., 2009).

Acknowledgments

The authors would like to acknowledge the U.S. Green Building Council (USGBC) for sponsoring this research. Support for the work presented here was also given by the Trans-NIH Genes, Environment and Health Initiative Grant U01 DA023822, and the Office of Naval Research (ONR). The authors would also like to thank Dr. Mary Carskadon and Dr. Stephanie Crowley of Brown University and Bradley Hospital for helping with the DLMO calculations. Dr. Christopher Steele (ONR) is also acknowledged for lending the PDAs for the study, although these data are not reported here. Andrew Bierman, Jennifer Brons, Brian Dolan, Dennis Guyon, Ranjith Kartha, Terry Klein, Karen Kubarek, Nick Meyer, Barbara Plitnick, Dan Wang, and Brittany Wood of the Lighting Research Center and Kathleen Ackerbauer of Russell Sage College are acknowledged for their contributions to this project. We would also like to thank the staff, teachers, and principal of Algonquin Middle School for making this project possible. We would also like to thank the students and parents who participated in this research project.

Funding Source: US Green Building Council (USGBC), Trans-NIH Genes, Environment and Health Initiative Grant U01 DA023822 and Office of Naval Research

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Figure 1.
Student wearing a Daysimeter.

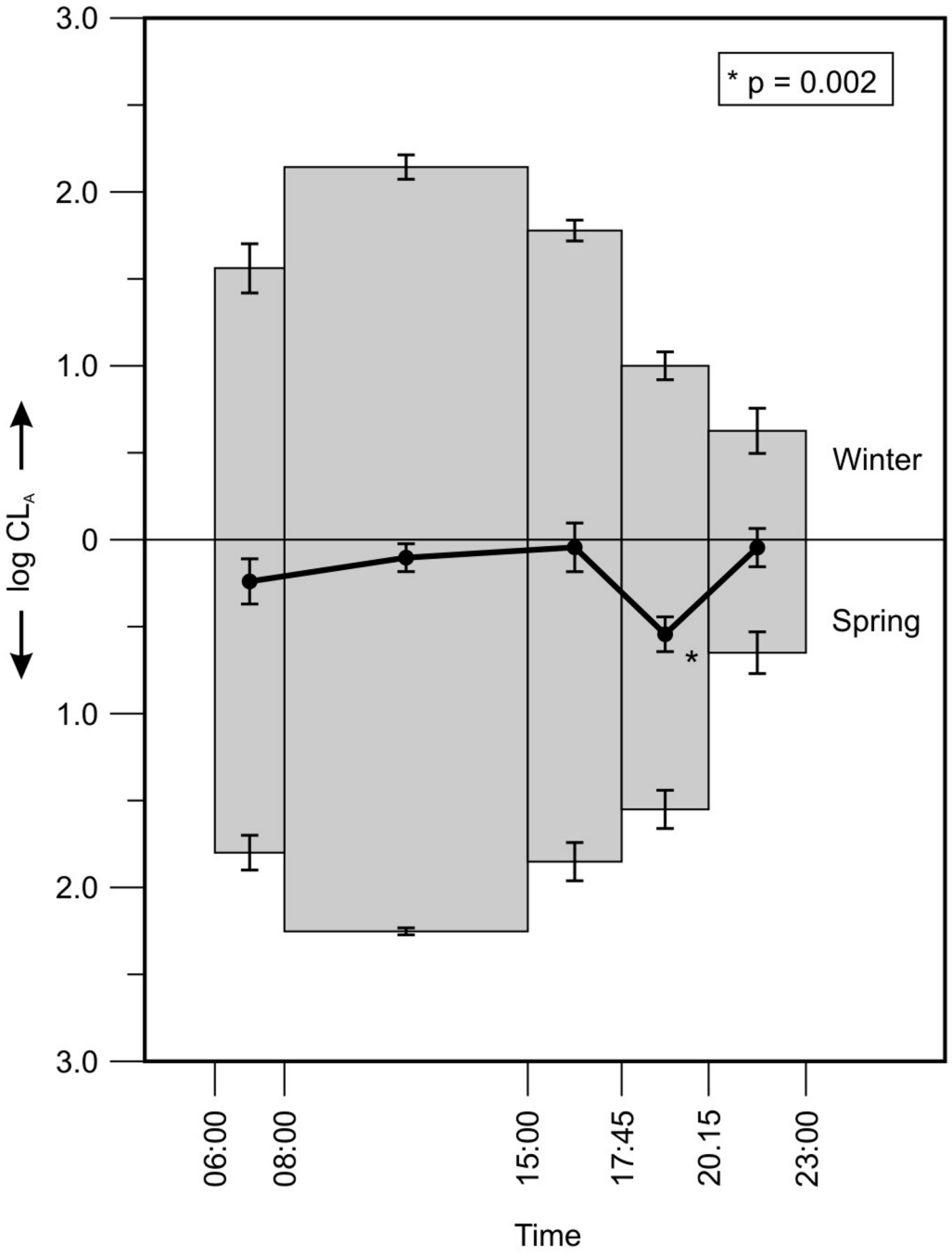

Figure 2.

Log-CL_A exposure values with associated SEMs between 06:00:00 and 23:00:00 h for winter and spring, subdivided into five periods: 06:00:00 and 08:00:00 h (morning light), 08:00:01 and 15:00:00 h (school hours), 15:00:01 to 17:45:00 h (near sunset time on March 2, 2009), 17:45:01 to 20:15:00 h (near sunset time on May 18, 2009), and 20:15:01 to 23:00:00 h (latest bedtime). The differences in log-CL_A values for each of the five subdivisions are shown with their associated SEMs, and connected with solid lines for visual clarity. Log-CL_A values for winter and spring were significantly different during the fourth subdivision when there was differentially more daylight available in the spring evenings than during the winter evenings (p=0.002, Cohen's d = 1.6, indicated with an asterisk).

Table 1

Mean and SEM values for photopic light (lux) and log-lux exposures, circadian light (CL_A) and log-CL_A exposures, together with activity index (AI) values obtained from 12 adolescent subjects during one week in the winter and one week in the spring. Mean (± SD) values for DLMO (n = 12), sleep onset on Wednesday evening, and sleep duration on Wednesday night (n = 11) for winter and spring are also listed. All statistical tests were two-tailed. Non-parametric statistical tests were used for photopic, log photopic, circadian light (CL_A) and log-CL_A exposures, and activity and parametric statistical tests were used for DLMO, sleep onset, and sleep duration.

	Photopic Light Exposure (lux)	**Log Photopic Light Exposure (log-lux)**	**Circadian Light Exposure (CL_A)**	**Log Circadian Light Exposure (log-CL_A)**	**Activity Index (AI)**	**DLMO (hh:mm)**	**Sleep Onset (hh:mm)**	**Sleep Duration (hh:mm)**
Winter	215 (14.0)	**1.66 (0.03)**	222 (15.3)	**1.67 (0.05)**	0.0134 (0.00050)	20:08 (0:46)	22:15 (00:36)	07:47 (00:38)
Spring	440 (50.5)	**1.79 (0.05)**	510 (57.3)	**1.89 (0.04)**	0.0132 (0.00048)	20:25 (0:40)	22:31 (00:26)	07:30 (00:37)
P value	**0.004**	**0.034**	**0.004**	**0.006**	**0.48**	0.02	0.003	0.04
Cohen's d	**1.8**	**1.0**	**2.0**	**2.0**	**0.1**	0.5	0.7	0.5

Chronobiol Int. Author manuscript; available in PMC 2012 May 10.