ORIGINAL ARTICLE

Lack of short-wavelength light during the school day delays dim light melatonin onset (DLMO) in middle school students

Mariana G. Figueiro and Mark S. Rea

Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York, USA

Correspondence to: Mariana Figueiro
Lighting Research Center
21 Union St., Troy, NY 12180, USA.
TEL: +1 (518) 687-7100; FAX: +1 (518) 687-7120; E-MAIL: figuem@rpi.edu

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Abstract

OBJECTIVE: Circadian timing affects sleep onset. Delayed sleep onset can reduce sleep duration in adolescents required to awake early for a fixed school schedule. The absence of short-wavelength ("blue") morning light, which helps entrain the circadian system, can hypothetically delay sleep onset and decrease sleep duration in adolescents. The goal of this study was to investigate whether removal of short-wavelength light during the morning hours delayed the onset of melatonin in young adults.

METHODS: Dim light melatonin onset (DLMO) was measured in eleven 8th-grade students before and after wearing orange glasses, which removed short-wavelength light, for a five-day school week.

RESULTS: DLMO was significantly delayed (30 minutes) after the five-day intervention, demonstrating that short-wavelength light exposure during the day can be important for advancing circadian rhythms in students.

CONCLUSIONS: Lack of short-wavelength light in the morning has been shown to delay the circadian clock in controlled laboratory conditions. The results presented here are the first to show, outside laboratory conditions, that removal of short-wavelength light in the morning hours can delay DLMO in 8th-grade students. These field data, consistent with results from controlled laboratory studies, are directly relevant to lighting practice in schools.

INTRODUCTION

In terrestrial mammals, circadian rhythms are regulated by the interaction of the internal biological clock located in the suprachiasmatic nuclei (SCN) of the hypothalamus with the earth's natural 24-hour light-dark pattern (Refinetti 2006). The SCN are self-sustaining oscillators with an intrinsic period that is typically slightly longer or shorter than 24 hours. The timing of the SCN is set by the local light-dark pattern, usually ensuring that the organism's behavioral and physiological rhythms are synchronized with its photic niche (nocturnal, diurnal, or crepuscular).

Light incident on human retinas will entrain or phase shift SCN timing, depending upon the time, duration, spectrum and intensity of the stimulus (Stevens & Rea 2001). These fundamental light characteristics affect the circadian system differently than they affect the visual system. Although we now know the human circadian system is more sensitive to light than was originally thought (Lewy *et al.* 1980), it is much less sensitive to light than the visual system (Rea *et al.* 2002). It is also well established that the human circadian system is maximally sensitive to short-wavelength (450 nm to 480 nm) light (Brainard *et al.* 2001, Thapan *et al.* 2001, and Rea *et al.* 2005). Most electric light sources illuminating our indoor environments are designed to support the visual system by providing relatively low levels of light dominated by wavelengths near 555 nm, the peak of the photopic luminous efficiency function (CIE 1978). Moreover, for convenience, electric light sources are available night or day and for variable durations. More and more then, people throughout the world are living under a roof illuminated by electric light sources, exposing them to dim days and extended dim light at night, separating them from the robust, natural light-dark cycle.

Studies have shown that adolescents report going to bed later as they get older (Crowley *et al.* 2007). These age-related changes in bedtimes have been associated with reduced parental influence on bedtimes, increased homework and extra-curricular activities, and other activities such as playing on computers and watching television. Evidence to date supports the hypothesis that adolescents have a late circadian phase, contributing to these late bed times. With a highly structured school schedule requiring early rising, these adolescents typically experience reduced sleep durations. Indeed, on unrestricted weekends, adolescents rise 1.5 to 3 hours later than they do on weekdays (Crowley *et al.* 2007).

Light during the day is important for entrainment; that is, for aligning circadian phase to the rest-activity cycle required by attending school. For reasons described above, however, electric lighting, including that common in schools, may not provide adequate light for circadian entrainment. Without a robust light stimulus during the day then, adolescents would logically be expected to exhibit late circadian phase and therefore go to bed late and experience restricted sleep.

Daily morning short-wavelength light exposures (after minimum core body temperature) are expected to slightly advance the clock every day and thereby maintain entrainment to the solar day (Jewett *et al.* 1997). The impact of reduced daily short-wavelength light exposure on the circadian system of young adults, as might be experienced by students without adequate daylight (or electric light) exposure, has never been formally investigated. A simple before-and-after, within-subjects field experiment was conducted in a school with documented good daylight design to determine whether removal of short-wavelength light on five consecutive school days would delay circadian phase relative to a baseline measurement obtained prior to the intervention.

METHODS

Site

The study was conducted at Smith Middle School, Chapel Hill, North Carolina in May 2009. Smith Middle School is unusual with respect to current architectural practice in terms of the amount of daylight provided to interior spaces (LRC 2004). The building uses south-facing roof monitor skylights in most spaces to deliver daylight to the interior spaces. Diffuse toplighting prevents occlusions due to blinds or wall displays typical of sidelighting. To minimize glare from direct sunlight entering the spaces, light entering the roof monitor is baffled with cloth partitions; only diffuse light enters the conditioned room. The electric lighting system is controlled with motion sensors and photosensors that modulate the fluorescent lamp output with dimming ballasts. This strategy allows electric lights to be off most of the day for electric energy savings.

The daylighting conditions were evaluated as part of an extensive case study in 2004 (LRC 2004). On a sunny afternoon in March 2004, researchers measured light levels on several surfaces in a classroom with a calibrated illuminance meter having a photopic spectral response (CIE 1978). At the time of the site measurements, all illumination was provided by daylight. Horizontal light level measurements were made by placing the illuminance meter on desks; these ranged from 1330–2150 lux. Vertical illuminances on the chalkboard ranged from 996–1 265 lux. The vertical light measurements were made by placing the illuminance meter on the chalkboard at eye level. Typical levels found in spaces illuminated only by electric light sources are approximately 80% lower. That is, these illuminance levels were approximately 5× higher than commonly found in buildings only illuminated by electric lights. Based on calculations using the model of human circadian phototransduction developed by Rea and colleagues (2005), these vertical illuminance levels would result in at least 60% melatonin suppression (at night), suggesting that the light stimulus students receive in Smith's classrooms is strong enough to activate the circadian system. Based upon results by Zeitzer *et al.* (2000) who showed that the half maximum saturation for phase shifting was 80–160 lux from cool white fluorescent light sources for a 6.5 hr exposure, the light levels measured in Smith Middle School would also be highly effective for phase shifting and, therefore, entrainment. Battery-powered monitoring devices also recorded illuminances on the teacher's desk over a long period of time. The desk was located near the perimeter of the room rather than directly under the roof monitor. These illuminance levels averaged 550 lux on sunny days and 320 lux on partly cloudy days. Based upon the previous measurements, it was expected that students at Smith Middle School would be exposed to some of the highest illuminances typically found in an indoor classroom environment, making this an appropriate site for the study.

Procedures

The within-subjects study began at the school on a Friday morning. Eleven subjects (nine males and two females, ages 13–14 years) were given an explanation about the study and were asked to wear orange glasses that attenuated all light of wavelengths shorter than about 525 nm from reaching the eyes (Figure 1) during the study period, Monday to Friday on the following week, from the time they awoke until they returned home after school (approximately 15:00); thus, subjects were required to wear the orange glasses during school and on the commute to school in the morning when they are likely to be exposed to daylight. Participants were then asked to refrain from consuming caffeinated products for the remainder of the day because saliva samples would be gathered from them in the evening. Finally, subjects were instructed to return to the school at 19:00 for saliva sample collection. The participants stayed in the dimly illuminated school library during sample collection. All electric lighting was kept off and all blinds were pulled down to avoid daylighting in the space. The room was lit with a dim red light (less than 5 lux at the cornea), during which time the participants were allowed to watch movies, play games, read or study. Serial saliva samples (Salivette, Sarstedt, Newton, NC, USA) were collected every 30 minutes (from 19:30 to 23:00) to determine DLMO. The subjects chewed on a plain cotton cylinder until saturated. These samples were then, in turn, centrifuged and refrigerated by the researcher. To prevent contamination of the saliva samples, the subjects were not allowed to eat or drink between sample times. The refrigerated samples were later sent to Pharmascan, Osceola, WI, for melatonin assay. On the next Friday evening, participants returned to school at 19:00 to repeat the saliva sample data collection in the dimly illuminated library. The study was approved by Rensselaer Polytechnic Institute's Institutional Review Board and meets the international ethical standards of this journal (Portaluppi *et al.* 2008).

RESULTS

DLMO, in decimal hours, was calculated for each subject using a threshold of 4.0 pg/ml. DLMO was determined by using linear interpolation between the melatonin values that fell above and below threshold. DLMO for the eleven subjects on the Friday prior to wearing the orange glasses averaged 21.15±0.61 and DLMO for the same subjects averaged 21.66±0.81 after five consecutive days of wearing the orange glasses. One subject had not achieved the threshold value (4 pg/ml) at 23:00 on the second Friday, suggesting that his DLMO occurred later than 23:00, but as a conservative estimate, we used 23:00 as his DLMO time. Using a two-tail paired students' t-test, this difference was significant with a probability of 0.006 of a Type 1 error. Figure 2 shows the cumulative frequencies of DLMO for the participants before and after the orange glasses intervention.

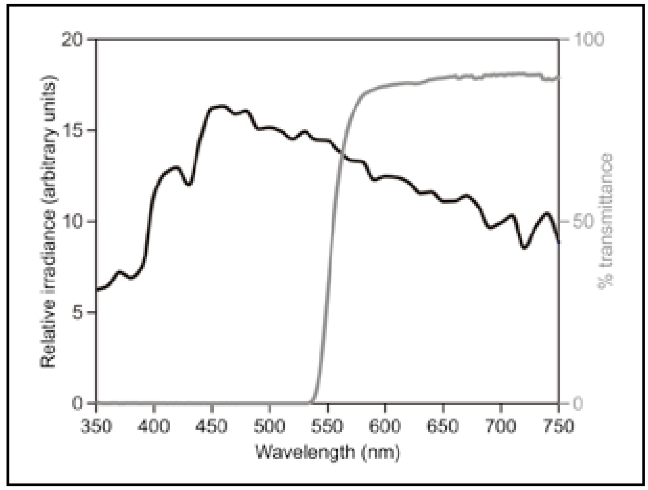

Figure 1. The spectral irradiance distribution (SIR) of daylight varies continuously throughout the day at every location on the earth. Shown here is the relative SIR of one, standard phase of daylight (left ordinate), defined by CIE as illuminant D65 (Wyszecki & Stiles 1982) to represent natural daylight at 6500 K. Also shown is the spectral transmittance of the orange glasses (amber/orange, UV Process Supply), in percent (right ordinate) used in the study. Irrespective of the actual and highly variable SIR in daylight present in Smith Middle School during the experiment, the orange glasses would have attenuated all short-wavelength light from both the natural and the electric sources seen by the students.

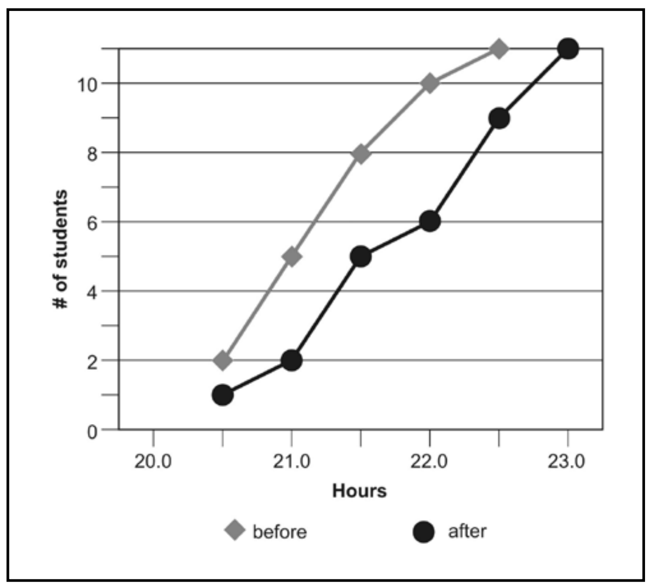

Figure 2. Cumulative frequencies of DLMO for the students before and after the orange glasses intervention.

DISCUSSION

In one respect the results of this field study are trivial because they simply confirm what has been shown before (Warman *et al.* 2003) namely that removing short-wavelength light exposure in the morning delays circadian phase. In another respect, however, the results of this study are quite important because they validate controlled laboratory findings with actual field measurements. Specifically, these data are consistent with the inference that removing short-wavelength light during school days delays circadian phase in 8th-grade students. After five consecutive school days of wearing orange glasses, DLMO was delayed by about 30 minutes. Although it is known that individual SCN clocks can have different periods, the phase delay of about 6 minutes per day observed here is consistent with the typical free-running period in humans of 24.18±0.04 hrs (Czeisler *et al.* 1999). Therefore, both the direction and the magnitude of the predicted effects from laboratory studies were obtained in this field study.

It has been estimated that bedtime occurs approximately two to three hours after DLMO (Burgess *et al.* 2003; Burgess & Fogg 2008). Since the present results showed that removing short-wavelength light during the school day will delay DLMO, sleep times are likely to be delayed as well. Wake-up times are fixed for most students, so those who do not receive short-wavelength light during the day will probably have reduced sleep on school nights. One study showed that students who had poorer performance in school were those who obtained about 25 minutes less sleep per night and went to bed on average 40 minutes later on school nights than those who were good performers (Wolfson and Carskadon 1998). By extension then, those who do not get enough short-wavelength light during the school day would exhibit reduced scholastic performance.

These findings, bridging controlled laboratory results to a real school environment, should have important, and practical, implications for school design because it seems necessary to expose students to short-wavelength light during the early part of the day to maintain entrainment. Conscious delivery of short-wavelength light in schools may be a simple, effective, non-pharmacological treatment for students to help them increase sleep duration and, perhaps, scholastic performance. Daylight in a school like that provided in Smith Middle School appears to be an ideal source to accomplish this goal because it can deliver the proper quantity and spectrum as well as the proper timing and duration of light exposure. Electric lighting could also serve this purpose, but current electric lighting is manufactured, designed and specified to meet visual requirements. Electric lighting could have an advantage over daylight for the purpose of circadian entrainment, because electric lighting can be precisely controlled, not only during the day, but during the night when exposure to light emulating daylight would be counterproductive for entrainment. Indeed, electric lighting can provide a complete 24-hour light exposure pattern to help ensure entrainment, but these deliberations represent an entirely new framework for architectural lighting design and practice (Figueiro 2008).

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