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Measurements of light at night (LAN) for a sample of female school teachers

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Abstract

Epidemiological studies have shown an association between rotating shiftwork and breast cancer (BC) risk. Recently, light at night (LAN) measured by satellite photometry and by self-reports of bedroom brightness has been shown to be associated with BC risk, irrespective of shiftwork history. Importance has been placed on these associations because retinal light exposures at night can suppress the hormone melatonin and/or disrupt circadian entrainment to the local 24-h light-dark cycle. The present study examined whether it was valid to use satellite photometry and self-reports of brightness to characterize light, as it might stimulate the circadian system and thereby affect BC incidence. Calibrated photometric measurements were made at the bedroom windows and in the bedrooms of a sample of female school teachers, who worked regular dayshifts and lived in a variety of satellite-measured sky brightness categories. The light levels at both locations were usually very low and were independent of the amount of satellite-measured light. Calibrated photometric measurements were also obtained at the corneas of these female school teachers together with calibrated accelerometer measurements for seven consecutive days and evenings. Based upon these personal light exposure and activity measurements, the female teachers who participated in this study did not have disrupted light-dark cycles like those associated with rotating shiftworkers who do exhibit a higher risk for BC. Rather, this sample of female school teachers had 24-h light-dark and activity-rest patterns very much like those experienced by dayshift nurses examined in an earlier study who are not at an elevated risk of BC. No relationship was found between the amount of satellite-measured light levels and the 24-h light-dark patterns these women experienced. It was concluded from the present study that satellite photometry is unrelated to personal light exposures as they might affect melatonin suppression and/or circadian disruption. More generally, photometric devices calibrated in terms of the operational characteristics of the human circadian system must be used to meaningfully link LAN and BC incidence.

Keywords

Breast cancer; Melatonin; Circadian light; Light pollution

Introduction

The World Health Organization (WHO) has concluded that shiftwork is a probable carcinogen (Straif et al., 2007). This conclusion stems from animal studies showing that nocturnal melatonin suppression and/or disruption of circadian clock genes result in faster

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tumor growth, and from epidemiological studies showing that women who have performed shiftwork for several years are at greater risk to breast cancer (BC) than those women who have not (Blask et al., 2005; Davis et al., 2001; Filipski et al., 2004, 2006; Hansen et al., 2001; Schernhammer et al., 2001; Stevens et al., 2007; Tynes et al., 1996). Recently, three studies by one group show a statistical association between BC incidence (without consideration of shiftwork history) and light-at-night (LAN) characterized either by satellite photometry (Kloog et al., 2008, 2010) or by self-reports of bedroom brightness (Kloog et al., 2011).

In their first study, Kloog and colleagues (2008) investigated the co-distribution of LAN and BC incidence in Israel. They utilized the Israel National Cancer Registry to identify BC incidence and photometric values derived from the US Air Force Defense Meteorological Satellite Program Operation Linescan System (DMSP-OLS) images to characterize LAN in 147 communities in Israel. The analyses showed a significant association between LAN (from satellite measurements) and BC incidence in Israel, but no significant relationship between LAN and incidence of lung cancer was found. In a follow-up study, Kloog et al. (2010) compared incidence rates of five types of cancers in women who had been observed in 164 countries and were part of the GLOBOCAN 2002 database administered by the International Agency for Research on Cancer (IARC). The IARC maintained a database on cancer incidence in individual countries between 1998 and 2002. The authors found a significant positive association between country LAN level (again, using DMSP-OLS satellite data) and BC incidence between 1998 and 2002 from the IARC database, but not with other types of cancer. According to the authors, a sensitivity analyses yielded a 30–50% higher BC risk in countries where LAN exposures were highest, compared to countries where LAN exposures were lowest. Very recently, Kloog and colleagues (2011) interviewed 1679 Israeli women (794 cases of BC and 885 controls) about their lifestyles. They found a significant association between BC incidence and self-reports of bedroom and ambient nighttime light levels. Although the authors made no physical measurements of levels or durations of light exposures, their conclusion was that LAN, both in the working and sleeping environments, should be considered a potential risk for BC (Kloog et al., 2011).

In any meaningful discussion of LAN as it relates to BC incidence, it is important that the characteristics of the photometric measurements of LAN can be related to the operational characteristics of the biological system under consideration, namely the human circadian system. Figure 1 shows the spectral sensitivity of the human circadian system for narrow band spectra as reported independently by Brainard et al. (2001) and by Thapan et al. (2001). The peak spectral sensitivity of the human circadian system is approximately 460 nm, with limited sensitivity at long wavelengths (>580 nm) where the human visual system is still very sensitive. Figure 1 also provides the spectral response characteristics of the photomultiplier tube (PMT) currently used by the U.S. Air Force. This spectral response function is based upon what is termed the F16 response characteristic (Ziskin, 2010), which extends from about 500 nm into the invisible, infrared region of the electromagnetic spectrum and is typical of those exhibited by earlier satellite PMTs (F12, F14, and F15). To restrict the sensitivity range of the PMT to the visible portion of the electromagnetic spectrum, an astronomical V-band filter (Mermilliod et al., 2008) is commonly used with raw satellite PMT data. This filter provides photometric values more comparable to those based upon V(λ), the orthodox spectral weighting function used in commercial photometry. As illustrated in Figure 1, the V-band spectral weighting function is, in fact, quite close to V(λ). As can be readily appreciated from Figure 1, however, photometric measurements based upon the V(λ), ones based on the V-band filter, and certainly ones based upon raw PMT data will not accurately characterize the effectiveness of optical radiation incident on the human retina for circadian system stimulation.

Since shiftwork, rather than LAN *per se*, has been consistently identified as a probable carcinogen (Straif et al., 2007), a homogeneous population of 72 female school teachers with minimal exposure to shiftwork were chosen for the present study. These women each worked and resided, however, in environments with different exterior, nighttime light levels as measured by satellite photometry. Calibrated light measurements were made at their bedroom windows and inside their bedrooms for seven consecutive nights. If satellite photometry is predictive of these nighttime light levels inside bedrooms as they might suppress nocturnal melatonin, then women might be at greater risk of BC in locations with high levels of satellite-measured exterior lighting even though they had not been exposed to shiftwork. Calibrated personal light-dark exposures at the plane of the cornea together with simultaneously recorded patterns of activity-rest were also recorded from these women to measure circadian disruption, another possible cause for increased risk of BC.

Methodology

Participants

Female teachers were recruited for the study by contacting administrators of local (near Albany, NY) elementary and secondary schools. Seventy-two female teachers served as subjects from urban, suburban, and rural schools near Albany, New York (10 schools) and in southwestern Vermont (2 schools) following permission from the school principals or superintendents. To be accepted into the study, all subjects had to agree to use the instrumentation (described below) provided to them for seven consecutive days and nights. All but five teachers who were recruited for the study completed it. Thirty-nine teachers participated during their Spring semester (January–June 2010) and 33 participated in the fall semester (September–December 2010). The mean ± standard deviation (SD) age of the participants were 36.25 ± 7.86 yrs. They all completed the Munich Chronotype Questionnaire (Roenneberg et al., 2003): 4% were extreme early chronotype, 28% were moderate early, 15% were slightly early, 18% were neutral, 14% were slightly late, 18% were moderately late, and 3% were extremely late chronotypes. Subjects were each paid $100 to participate in the 7-day study, with a prorated amount for early withdrawal. The study was approved by Rensselaer's Institutional Review Board; written informed consent was obtained from each participant (Portaluppi et al., 2010).

Instrumentation

Calibrated light measurements were obtained from three types of Daysimeters (Bierman et al., 2005), each designed to measure optical radiation for stimulating the human visual and circadian systems; most participants utilized all three types, as detailed below. Every Daysimeter used in the present study had two optical sensors with a cosine spatial response, meaning that the sensors were most sensitive to light at normal incidence with sensitivity at other angles decreasing proportional to the cosine of the incident angle (van Derlofske et al., 2002). One sensor was a conventional glass-filtered silicon photodiode (Hamamatsu model S1286, custom glass filter) having a spectral sensitivity closely matching the standard photopic luminous efficiency function, $V(\lambda)$. The other sensor was a short-wavelength (blue) sensor fabricated from a gallium arsenide phosphide (GaAsP) photodiode (Hamamatsu model GA5645), having an intrinsic long-wavelength response cutoff at ~580 nm, together with an ultraviolet (UV) blocking glass filter (Schott GG395). This “blue” sensor had a spectral response peaking at approximately 460 nm with an 80 nm full width half maximum (FWHM) bandpass.

The optical radiation data obtained by a Daysimeter from both sensors were stored and then downloaded to a computer for processing into units of photopic illuminance, in lux, and circadian light, in units of CL_A (Rea et al., 2010). The sensor with the $V(\lambda)$ spectral weighting provides photopic illuminance directly. Circadian light levels were approximated from algorithms that combine the data from both channels. Circadian light levels were scaled so that 1000 lux of CIE Illuminant A (a blackbody radiator at 2856 K) equals 1000 circadian light units (CL_A). The human circadian system response to light, as measured by acute nocturnal melatonin suppression, follows a logistic function (Rea et al., 2005, 2010). This response function is used to transform CL_A into circadian stimulus (CS) values. CS levels are directly related to the amount of predicted nocturnal melatonin suppression. For example, a CS level of 0.42 would be expected to suppress 42% of available melatonin at a given circadian time. CS is considered to be a better measure of the effectiveness of the light stimulus for the human circadian system because it is defined in terms of the circadian system's input-output relationship, including both threshold and saturation.

Every Daysimeter used in the present study had two orthogonally oriented accelerometers contained within a single electronic sensor package (model number ADXL330, Analog Devices, Norwood, MA, USA) and mounted on the Daysimeter's circuit board. The solid-state accelerometers responded to movements with respect to Earth's gravitational field. The outputs of the sensor package were voltages that were proportional to the instantaneous acceleration of each accelerometer. These voltages were converted to digital values using the 12-bit analog-to-digital converter of the microprocessor (, MSP430F169, Texas Instruments, Dallas, TX, USA) that controls operation of the Daysimeter. The digital data were acquired once per second, and then used to calculate an activity index (AI) every 30 s using 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) over the 30-s 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). In other words, the activity index is the root-mean-square (rms) deviation in acceleration in two dimensions measured for every 30-s logging interval. Only those activity data acquired from the head-worn Daysimeters were used.

Procedures

As previously described, teachers had to agree to use the Daysimeters as instructed for seven consecutive days and nights. They were asked to wear the headband-Daysimeter from the time they awoke until they went to bed at night, except during bathing (Figure 2a). When sleeping, they were instructed to place the headband-Daysimeter on their nightstand, adjacent to their sleeping location, facing upwards towards the ceiling. Complete data from the headband-Daysimeters were obtained from 58 teachers. Data sets lost for analysis were the result of either device failure or lack of compliance over the course of the seven-day data collection period.

During this 7-day period, the teachers were instructed to mount a window-Daysimeter on their bedroom window using a suction cup, with the optical sensors pointed outdoors, to measure light incident on their bedroom window at night (Figure 2b). Teachers were instructed to use their bedroom window treatment (i.e., shades or blinds) as they normally would during the study period. The window-Daysimeter had the same spectral and spatial calibration as the headband-Daysimeter, but was calibrated to a higher absolute sensitivity. It could reliably measure illuminance ≥0.01 lux, whereas the headband-Daysimeter could only reliability measure illuminance ≥0.1 lux. Valid data were obtained with the window-Daysimeter for 71 bedroom windows. One subject could not use the device, because she utilized winter insulating plastic film on her bedroom window. It is worth noting that one teacher alternated between two residences during her study week. Except for one night, she affixed the window-Daysimeter to the bedroom window where she slept.

Initially, the headband-Daysimeter was to be used to measure bedroom ambient light levels during the night. After analyzing the data from the first 15 teachers, it was determined that the headband-Daysimeter, when placed on the nightstand while sleeping, was not sensitive enough to make reliable measurements. An additional nightstand-Daysimeter, with a spectral, spatial and absolute sensitivity calibration equal to that of the window-Daysimeter, was deployed for use by the teachers during their study week (Figure 2c). Valid data were obtained with the nightstand-Daysimeter from the remaining 57 teachers.

Environmental Sky Brightness

Cinzano et al. (2001), *World Atlas of the Artificial Night Sky Brightness*, was used to characterize the nighttime exterior light levels in the areas where the teachers worked and slept. These sky brightness values employ an astronomical V-band spectral sensitivity (Figure 1) and are color-coded bands from the lowest, blue, to the highest, white, in units of μ cd/m^2. Google Earth software (Google, 2010) enables superimposition of address data with the Cinzano et al. (2001) sky brightness maps. Table 1 provides the range of V-band luminance levels for each sky brightness category and the number of schools and the number of teacher residences in each.

Results

Phasor Analyses

Female school teachers were selected for this study because it was expected that this sample of subjects would not be exposed to shift work and would exhibit behavioral circadian entrainment patterns similar to those exhibited by dayshift nurses previously studied (Miller et al., 2010; Rea et al., 2008). Phasor analysis, based on signal processing techniques, was used to quantify the levels of behavioral circadian entrainment exhibited by these teachers using the light and activity data from the headband-Daysimeter (Rea et al., 2008). The similarity between the light-dark (CS) and activity-rest (AI) patterns, sampled together over several consecutive days with the headband-Daysimeter, was computed and analyzed in terms of the phase angle and magnitude of the joint 24-h patterns. Phasor magnitude is a measure of how well a person is entrained to a 24-h light-dark cycle; the longer the phasor magnitude, the more the person's behavior is entrained to a 24-h cycle. In a previous study, nurses working dayshift (N=38) exhibited a scalar mean (± SD) phasor magnitude of 0.46 (± 0.11) compared to that of rotating shift nurses of 0.16 (± 0.14) (Miller et al., 2010); thus, as expected, dayshift nurses are better entrained to the 24-h light-dark cycle than rotating shift nurses. Phasor angle reflects the temporal relationship between the light-dark exposure pattern and the activity-rest behavior pattern. Nurses working dayshift exhibit an mean phasor angle of 0.79 (± 0.76) h, while rotating shift nurses exhibit a wide range of, and often indeterminate, phasor angles. A phasor angle of 0.79 indicates that the 24-h activity-rest pattern is delayed about 48 min with respect to the 24-h light-dark pattern. Typically, this means that during their active period dayshift nurses commonly experience more bright light during the morning and midday than during the evening (Miller et al., 2010).

Figure 3 shows the relationship between the *World Atlas* sky brightness categories and phasor magnitudes for the 58 female school teachers who provided valid data to compute phasors. The scalar mean ± SD phasor magnitudes for the samples of dayshift and rotating shift nurses examined in a previous study (Miller et al., 2010; Rea et al., 2008) are shown for comparison. For these teachers, using the "all-at-once" method described by Miller et al. (2010), the scalar mean ± SD phasor magnitude was 0.52 ± 0.07 and the mean ± SD vector mean angle was +0.94 ± 0.72 h. As shown in this figure, the phasor magnitudes for these teachers are similar to those exhibited by dayshift nurses and are independent of sky brightness category.

Bedroom light levels

Light levels measured from the window-Daysimeters and from the nightstand-Daysimeters between midnight (00:00 h) and 04:00 h were examined, because this was the time interval when the participants would be expected to be asleep and bedrooms dark. Measurements made outside this time interval could reflect either natural daylight or electric light operation while awake and active, which would have been captured by the headband-Daysimeter measurements and the subsequent phasor analyses. 100% of the measurements were <1 CL_A, and 99% were <1 lux. In fact, most of the recorded values from both the window- and nightstand-Daysimeters were below the absolute limits of Daysimeter sensitivity (0.01 lux). Figure 4 shows how the measured values are distributed across the different *World Atlas* sky brightness categories associated with the participants' residences. This sample of female school teachers resides in dark areas, not accurately characterized by the *World Atlas* sky brightness category, and there is no apparent relationship between *World Atlas* sky brightness category for the participants' residences and the measured light levels at their bedroom windows.

Evening light exposures

Evening light exposures between civil twilight and bedtime were obtained from the headband-Daysimeter. The specific locations of these measurements were not documented, so the recorded personal light exposures may have been inside or outside the home and bedroom. The mean ± SD and median evening photopic illuminance levels were 28 ± 24 lx and 12 lx, respectively and the mean ± SD and median circadian light levels were 21 ± 20 CL_A and 9 CL_A, respectively. The mean ± SD and median CS levels at the cornea were 0.07 ± 0.05 and 0.05, respectively, suggesting that personal light levels in the evening would, on average, suppress melatonin by about 7%. The distribution of mean evening CS levels across sky brightness zones is shown in Figure 5.

Discussion

Presented here are calibrated photometric measurements made at the bedroom windows and in the bedrooms of female school teachers, who were selected for the present study because they were expected to have a highly regular life style, with no signs of light-induced circadian disruption. Personal light exposures were also collected using the Daysimeter, a circadian light meter. Our results showed that these teachers, like the dayshift nurses previously studied (Rea et al., 2008; Miller et al., 2010), showed no evidence of behavioral circadian disruption. This sample of women lived and worked, however, in a range of *World Atlas* sky brightness category areas (Table 1). In contrast with the conclusions by Kloog and colleagues (2008, 2010, 2011), who *do* show an association between BC incidence in Israel and other countries and LAN measured by satellite photometry and by self-reports of brightness, the photometric data we collected at the bedroom windows and on the bedside table in the bedrooms of our school teachers do not support the inference that satellite-measured LAN is predictive of actual nighttime light exposures in the sleeping environment of homes. Moreover, personal light exposures as measured by the headband-Daysimeter, as they might affect circadian disruption, had no relationship to satellite-measured LAN. Although the participants did not experience circadian disruption, as characterized by their large phasor magnitude, their evening light exposures (prior to bedtimes), which may have been recorded inside or outside the built environment, can result in some level of evening melatonin suppression, although, again, sky brightness was not correlated with evening CS exposures.

The statistical association between LAN and BC shown by Kloog and colleagues appear to be, then, coincidental with one or more other factors that affected the likelihood of BC. It is worth noting, for example, that Kloog et al. (2008) showed a stronger statistical association between BC incidence in Israel and per capita income in Israel ($p < 0.01$) than between BC incidence and satellite-measured LAN for Israel ($p < 0.05$). Since it is unlikely that per-capita income in and of itself increases cancer risk, it seems equally unlikely, supported by the evidence presented in this study, that satellite-measured LAN increases cancer risk either. It seems more likely that BC incidence is associated with personal lifestyle factors associated with developed areas. In particular, none of the statistical models offered by Kloog and colleagues incorporate the shift work history of the studied women. This lifestyle factor associated with more affluent cultures, i.e., those with higher income and more street lights, might directly affect nocturnal melatonin levels or disrupt circadian rhythms. Electric light provides the means by which shift work can be done, but it may or may not be a causative agent in increasing BC risk.

It can be concluded, based on first principles of photometry presented in the background and on the data reported here, that satellite photometry and self-reports of brightness are not an effective or appropriate means of characterizing light as it might affect BC incidence through the circadian system. Proper photometric assessments must be applied to establish a causal link between personal light exposures and BC risk.

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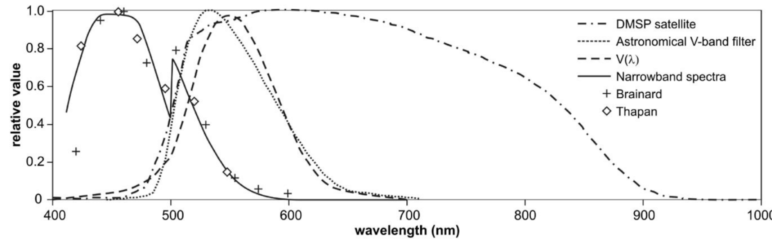

FIGURE 1.

Spectral response characteristics relevant to the present study. V(λ), shown with the dashed line, is the photopic luminous efficiency curve used in commercial photometry, closely mimicking the spectral sensitivity of the human fovea. The data points from Brainard et al. (2001) and from Thapan et al. (2001) represent the spectral sensitivity of the human circadian system to narrowband spectra measured in terms of their effectiveness to each suppress the synthesis of melatonin at night. The solid line represents the predictions from Rea et al. (2005) for the spectral sensitivity of the human circadian system to these narrow band spectra. The spectral sensitivity of the satellite PMT currently used in the DMSP-OLS (F16) and those data filtered with an astronomical V-band filter (Mermilliod et al., 2008) are shown as dot-dashed and dotted lines, respectively. The maximum value from all spectral response characteristics has been normalized to unity.

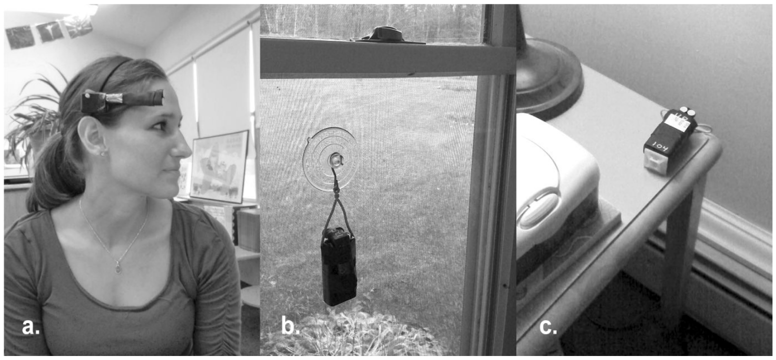

FIGURE 2.

Daysimeters with different form factors used in the study. Figure 2a shows the headband-Daysimeter used to collect light and activity data which were then transformed and used to perform phasor analyses. Figure 2b shows the window-Daysimeter attached to a bedroom window with a suction cup to measure exterior light incident on the bedroom window. Figure 2c shows the nightstand-Daysimeter to measure ambient light levels in the bedroom.

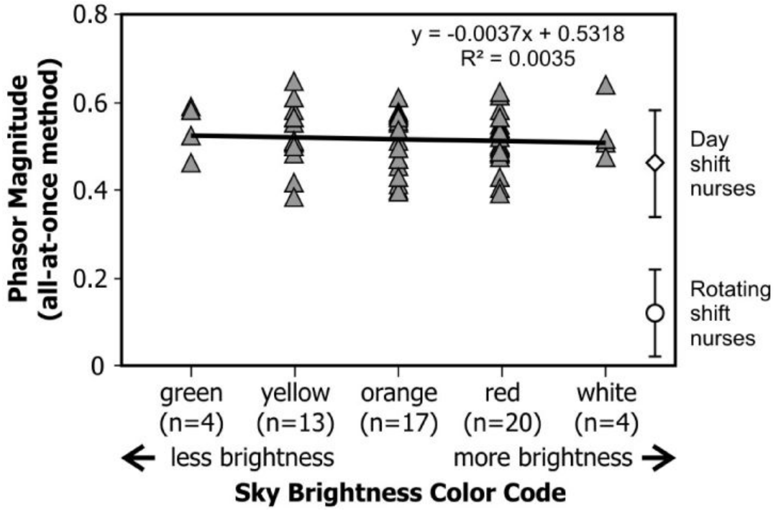

FIGURE 3.

Distribution of phasor magnitudes for different sky brightness categories (closed triangles) together with the mean (open symbols) and standard deviations (SD) of phasor magnitudes obtained for dayshift and rotating shift nurses from Miller et al. (2010)

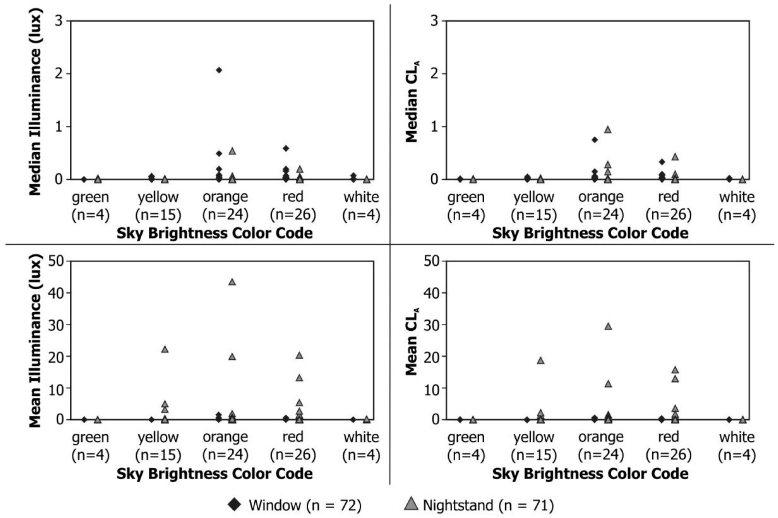

FIGURE 4.

Nighttime light measurements vs. sky brightness categories. Photopic (left column) and circadian (right column) illuminance levels were recorded from the window-Daysimeters and the nightstand-Daysimeters. Median and mean values are shown in the top and bottom rows, respectively. “Night” is defined here as midnight (00:00 h) to 04:00 h.

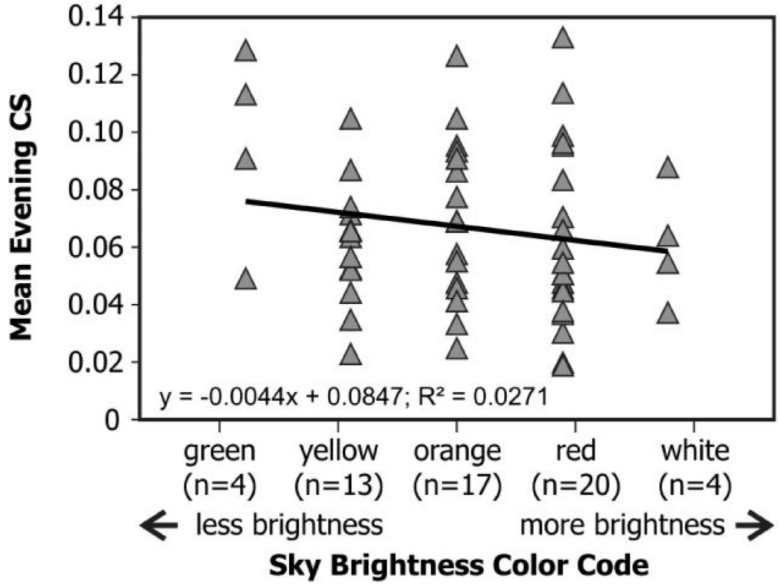

FIGURE 5.
Distribution of the mean evening (civil twilight until bedtime) CS values recorded from the headband-Daysimeter for different sky brightness categories.

TABLE 1

World Atlas sky brightness categories and the frequency of the participants' schools and residences in each category

World Atlas of Artificial Night Sky Brightness **(Cinzano et al., 2001)**		**Teachers**	
Color code	**Luminance range (temporal average)***	**Residences (n=73**)**	**Schools (n=12)**
blue	27.7–83.2 μ cd/m^2	0	0
green	83.2–252 μ cd/m^2	4 (5%)	0
yellow	252–756 μ cd/m^2	15 (21%)	3 (25%)
orange	756–2268 μ cd/m^2	24 (33%)	6 (50%)
red	2268–6804 μ cd/m^2	26 (36%)	3 (25%)
white	> 6804 μ cd/m^2	4 (5%)	0

*Cinzano and colleagues report luminance ranges in microcandelas/m^2. However, their data are based on an astronomical V-band filter, which is a spectral weighting function similar, but not equivalent, to V(λ). (Figure 1)

**One teacher alternated sleeping locations between two residences (one "yellow" and one "red") during her participation; thus, there are a total of 73 residences for 72 subjects.