The Daysimeter: a device for measuring optical radiation as a stimulus for the human circadian system

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Abstract

Optical radiation incident on the human retina stimulates vision as well as provides time-of-day information to the brain's circadian clock. The visual and circadian systems respond very differently to optical radiation. A device, the Daysimeter, was developed and tested to help progress toward a system of circadian dosimetry. The Daysimeter is a light-weight, head-mounted device that records radiation exposure estimates for both the visual and circadian systems, and is specifically designed for field use. In addition to logging spectrally weighted radiation measurements, it records head position and motion to be utilized as a representation of human circadian activity. This manuscript provides background on the differences between radiation for the visual and circadian systems, as well as a description of the development and testing of this prototype device.

Keywords: photometry, light, circadian system

Short title: A measurement device for human optical stimulation

1. Introduction

Light is a fundamental quantity, just like mass and time, with its own base unit, the candela. Unlike any other physical quantity, however, light is defined in terms of a set of visual responses by humans to radiant power transduced by the retina. Figure 1 shows the photopic luminous efficiency function (V_λ) that underlies the formal definition of light and that is incorporated into all commonly available light meters. Other species with visual capabilities will have different retinal photopigments for converting radiant power into neural impulses. So, light, as formally defined, has limited utility for characterizing the visual stimulus for any species other than humans. Indeed, the biology literature is fraught with errors based upon the (implicit) assumption that V_λ provides a suitable rectifying variable for characterizing the visual stimulus for species other than humans.

Interestingly, optical radiation incident on the retina has two very distinct effects on humans, each emanating from physiologically distinct neural pathways linking the retina to the brain. One, obviously, provides the brain with visual information, while the other provides the brain with solar time-of-day information. As with errors associated with using V_λ for characterizing optical radiation transduced by the retinas of other species, characterizing optical radiation transduced by the human retina for this latter, so called, circadian (circa – approximately; dian – day) system also will be associated with significant errors.

Until about 25 years ago, it was thought that a circadian pathway did not exist in humans, but, rather, was only found in phylogentically older species. Indeed, until about four years ago the photopigments responsible for circadian phototransduction in humans, as well as other species, were essentially unknown [1]. Such research would only be of academic interest, except that applied and clinical research is beginning to demonstrate that disruption of the time-of-day information from the retina to the circadian system in the brain can have significant implications for the human condition.

Seasonal Affective Disorder (SAD) or the "winter blues" is recognized by the medical community as a psychiatric disorder. Apparently, seasonal reductions in the amount of natural light available in the winter at extreme northern (and southern) latitudes can induce depression in some people [2]. Persons with Alzheimer's disease exhibit random periods of sleep and wakefulness unless they are provided with light treatment at specific times of the solar day [3, 4]. Premature infants have a difficult time adjusting to hospital environments during early periods of primary care and also exhibit difficulties in adjusting to regular sleep-wake cycles when discharged into the care of their parents. After infants born premature are presented cycled light during their last few weeks in the hospital, they show, among other improvements, greater weight gain and faster adjustments to home life [5–7]. It has also been shown through epidemiological studies that light at night may be associated with a greater likelihood of developing breast cancer in female night-shift workers due to a disruption in the solar light-dark cycle in the circadian system [8–11]. All of these findings suggest that optical radiation to the circadian system can have a dramatic impact on the health and well-being of humans, perhaps even mainstream populations. Importantly then, it seems necessary to begin to formally quantify optical radiation transduced by the retina as it affects the human circadian system.

This paper describes a prototype instrument for characterizing optical radiation for the circadian system, called here the Daysimeter. The Daysimeter is so named because it can begin to form the basis for a 24-hour, daily dosimeter where both the duration and the quantity of optical radiation can be integrated into estimates of circadian stimulus.[1] In general, light transduced by the retina must be defined along at least five dimensions: quantity, spectrum, spatial distribution, duration, and timing [12]. Relative to the visual system, which underlies conventional photometry, the circadian system has a much higher threshold for activation [13, 14]; it has a peak spectral sensitivity at a much shorter wavelength [15, 16]; it has greater sensitivity to light in the inferior retina (viewing the sky) than in the superior retina [17]; it requires much longer exposures for activation [13, 14, 18]; and, most importantly, it is differentially sensitive to light depending upon the time of day [19, 20]. The present prototype was designed with these dimensions in mind, but as the science of circadian phototransduction continues to emerge, refinements to the system will undoubtedly be necessary.

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[1] In the context of this report, we use the term "dose" to mean the amount of energy (the product of spectrally weighted irradiance, pupil area, and time) incident on the cornea.

2. System conceptual design

Conventional photometry is defined in terms of both geometry and spectrum. The geometric specifications of light determine the spatial units used in photometry; light (*luminous flux*) incident on a plane is *illuminance* (flux per element area), light distributed within a solid angle is *intensity* (flux per solid angle), and light distributed within a solid angle from a planar element is *luminance* (intensity per element area). The spectral specifications of light weight radiant flux according to either the photopic (emulating the human cone photoreceptor class) luminous efficiency function (V_λ) or the scotopic (emulating the human rod photoreceptor class) luminous efficiency function (V'_λ). Parenthetically, very few photometric instruments incorporate V'_λ and no commercially available instrument incorporates the mesopic luminous efficiency function, where both rod and cone photoreceptors are functioning [21, 22].

Similar to conventional photometry, intended to emulate the geometric and spectral characteristics of human vision, a measurement system designed to emulate human circadian phototransduction must also specify the geometric and spectral characteristics of radiation affecting the circadian system. As will be discussed in subsequent sections, however, the circadian system differs from the visual system both in terms of its geometric and spectral responses. Simplified assumptions about the geometric and spectral aspects of the circadian system were employed in the prototype instrument described here.

Unlike conventional photometry, the temporal aspects of radiation are paramount to the measurement of the circadian stimulus. Compared to the visual system, the circadian system is quite slow to respond to radiation (several seconds or minutes), and even more importantly, it is differentially sensitive to radiation throughout the solar day. Therefore, the duration of the radiation stimulus and when the stimulus is presented during the solar day must also be specified in a functional measurement system. The Daysimeter described in the present paper utilizes complete, real-time information to characterize radiation exposure for the circadian system.

Also unlike conventional photometric instruments, the instrument described in the present report records the position and the amount of movement of the instrument during recording sessions. Body and head movements can create large variation in circadian radiation exposure. Since the circadian system is much slower to respond than the rate at which these body and head movements occur, it is necessary to integrate circadian radiation exposure over an extended period of time to quantify the circadian stimulus accurately. Since circadian radiation exposure is only through the eyes, the device was designed to be mounted on the human head and to record its position throughout a recording session. In this way, it would be possible to more accurately represent circadian radiation exposures for practical applications where people constantly move head and body positions during the periods when optical radiation is affecting the circadian system. Moreover, activity patterns have often been used as a measure of the timing of the circadian systems in animals as well as humans [23–25]. It is envisioned that activity patterns recorded by this device can be used to characterize the magnitude of the effect of circadian radiation exposure during different times of the solar day.

3. Embodiment

A schematic and photograph of the Daysimeter are provided in figure 2. The key functionalities include photopic and estimated circadian radiation exposure measurements, head angle and activity measurement, and data logging.

3.1 Light and circadian-effective radiation measurement

3.1.1 Measured radiation signals and associated spectral response curves

Two photosensors separately measure photopic and "blue" signals; the latter is used to estimate circadian radiation exposure. Figure 1 illustrates the instrument's photopic and blue spectral response curves (characterized using a grating monochromator) along with the photopic luminous efficiency function (V_λ) and a circadian spectral response function defined by Rea *et al* [18].

The spectral response of the blue sensor is derived from the action spectra published by Brainard *et al* [15] and Thapan *et al* [16] and modeled according to a spectral response function published by Rea *et al* [18]. Like the photopic luminous efficiency function, any spectral power distribution can be linearly weighted according to the blue response function in figure 1. Figueiro *et al* [26] showed, however, that the circadian system responds to light through a non-linear, sub-additive mechanism that cannot be modeled with a simple additive action spectrum like that shown in figure 1. Nevertheless, for the purposes of this prototype instrument, an additive spectral response function was utilized for the blue sensor with the expectation that the sub-additive circadian phototransduction mechanism could be modeled in the future through post-detector processing of the signals generated from the photopic and the blue sensors.

3.1.2 Sensor design

The photopic sensor is a Hamamatsu S1223-01 silicon photodiode in a hermetic package. Its relatively large 13 mm^2 area provides a bare cell sensitivity of 0.13 µA per lux for CIE Illuminant A [27]. A multi-element subtractive glass filter matches the silicon cell response to the photopic luminous efficiency function. An opal glass diffuser mounted to the front of the detector modifies the spatial characteristics of the sensor to be lambertian, mimicking the eye's spatial response as reported in Van Derlofske *et al* [21]. The cell, filter, and diffuser stack are mounted in a thin-wall brass tube to provide mechanical protection, electrical shielding, and a way to mount the detector to the printed circuit board by soldering. The photocell/filter/diffuser combination has a responsivity of 450 pA per lux.

The blue sensor is a Hamamatsu G1962 GaP photodiode. The response curve of the blue sensor in figure 1 shows how it responds only to light of wavelengths shorter than 570 nm with a peak sensitivity at 470 nm. The sharp long-wavelength cutoff is generated by the bandgap cutoff of the sensor's photodiode material. To limit unwanted UV sensitivity of the blue sensor and provide the proper short-wavelength cutoff, a colored glass filter was used (Schott Glass GG 19). The notch in the blue response at approximately 440 nm is the result of an added gel filter (Roscolux #08, Pale Gold) chosen to fine-tune the match to the circadian action spectrum from Rea *et al* [18]. A photocell with an active area of 5.2 mm^2 was chosen to maximize sensitivity while keeping the detector package small. As with the photopic sensor, the blue sensor incorporates an opal glass diffuser and is similarly mounted in a brass tube. The sensor assembly has a peak responsivity of 60 nA per watt m^{-2}.

The two sensors provide current outputs, which are converted to voltages using a standard transimpedance amplifier. A Texas Instrument OPA2349 dual amplifier was chosen for low power demand and rail-to-rail operation. A significant challenge of the design was that light levels can vary from more than 100 000 lux in direct sunlight to less than 1 lux at night. Given the wide range of light levels to be measured, it was necessary to incorporate some type of automatic gain selection in the amplifier circuit to provide the desired linear response. The automatic gain selection function is accomplished by switching between one of five feedback resistor combinations. This is done by switching resistors in parallel with the most sensitive range resistor using a 4-channel complementary metal-oxide-semiconductor (CMOS) analog multiplexer. The range selection is under microprocessor control. The gain resistors have values of 10^8, 10^7, 10^6, 10^5, and 10^4 ohms. The parallel combination results in resistance values that are not exact powers of 10; a configuration file for the processor compensates for this effect. The positive input of the amplifier is biased at 1.2 V and limited to approximately 1 volt below the positive supply rail to reduce leakage current associated with the CMOS switch; thus, the amplifier can swing from 1.2 V to approximately 2.3 V. This, combined with a 12-bit analog-to-digital converter (ADC) integrated with the processor, provides for a step size of 0.008 nA on the most sensitive scale, and 0.08 µA on the least sensitive scale. The full scale ranges are 21 nA full scale and 210 µA full scale, respectively. These values correspond to a photopic illuminance resolution of 0.018 lux and a full scale maximum reading of 467 000 lux.

The two sensors are mounted side by side 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 diffusers roughly at the same plane as the subject’s cornea.

3.1.3 Radiation measurement verification

Two prototype instruments were evaluated to ensure that they had the same spectral response curves. The closeness of the spectral match for one instrument is shown in figure 1 and quantified by the f_1’ figure of merit, which is 0.038 for the one shown and 0.054 for the other one [28]. This closeness of spectral matching is comparable to portable, commercial illuminance meters.

The linearity of the system also was verified by comparing it to a Photo Research LRS 450 Light Standard system capable of producing illuminance levels ranging from 0.3 lux to 15 000 lux at the exit port of a 6-inch (152 mm) integrating sphere, while maintaining a constant relative spectral output that closely matches CIE Illuminant A at 2856 K. The manufacturer of the LRS450 Light Standard claims a 2% accuracy over the range from approximately 3 to 15 000 lux, and a two-point calibration at approximately 150 and 18 000 lux performed by the National Institute of Standards and Technology (NIST) corroborates both the linearity and correlated color temperature claims of the manufacturer. Figure 3 shows the ratio of the instrument under test to the LRS 450 Light Standard as a function of irradiance, normalized to unity at the highest irradiance level. Deviations from a linear response are within a few percent over the 3 1/2 decades of irradiance levels tested. Similar performance is expected for higher irradiance levels up to the maximum reading of the instrument, but could not be tested due to the limitation of the light source standard. Because both the photopic and blue sensor readings continue to track together when exposed to daylight radiation levels approaching 100 000 lux, it appears that saturation for the blue sensor is not occurring, since it is well-known that the silicon detector response does not saturate. Measurements of lower irradiance levels have degraded linearity due to lower signal-to-noise ratios and a greater relative dependence on specifying an accurate zero irradiance level value. Fortunately, however, this problem is insignificant for accurately measuring meaningful irradiances to the circadian system because the threshold for circadian activation is fairly high; for white light the threshold is approximately 30 lux incident on the cornea for one hour [29]. It is interesting to note that potential artifacts of the instrument's auto-ranging circuitry are not readily discernible in figure 3, even though the range-setting resistors have a tolerance of 1% and should show some discontinuity in the response as the range changes. In addition, the resistor for the most sensitive range has a value of 100 mega-ohms, which could lead to leakage current induced errors; however, this does not appear to be a major factor.

3.2. Head angle and activity measurement

A monolithic integrated circuit (IC) accelerometer (Analog Devices ADXL311) provides information on head position and movement. The two-axis accelerometer is mounted vertically and provides signals that are digitally processed to indicate head angle. Head inclination angle is provided at each logging interval with a resolution of 0.1 degree. A measure of activity is provided by the root-mean-square (RMS) value of the ac component of acceleration in the x and y directions. Activity is reported in units of milli-g RMS (i.e., a value of 1 = 1/1000 g of force) and is calculated as a moving average over a five-second period.

3.3 Data processing and logging

A microprocessor (Texas Instrument MPS430) digitizes the amplified photosensor signals, provides a time clock, performs calculations, and controls data storage and retrieval functions. The processor stores calibration data for the sensors, which are used to process the downloaded data to provide calibrated output. The processor incorporates a12-bit ADC with up to eight multiplexed inputs and an extensive library of functions to reduce power. A dual clock system enables it to go into a low-power sleep mode when not taking measurements. It also supports an RS232 serial link port that is used to issue commands to the system and retrieve data. The processor stores the digital data in an Amtel EEProm flash memory unit. This type of processor is used extensively in high-volume consumer applications, making it easily available and low cost.

3.4 Power supply

Power is supplied by an external battery providing a minimum of 3.5 volts and 30 mA of peak current to the on-board 3.3 V voltage regulator. The external battery is connected to the Daysimeter by a thin cable. For simplicity and to limit power requirements, the supply does not use a negative rail. In the interest of cost and availability, a 9-volt alkaline battery was used and provides more than one week of continuous operation when logging at a rate of 1 Hz.

3.5. System commissioning and calibration

To use the instrument, it must first be zeroed and then calibrated to a known standard. These functions are accomplished in the following fashion.

The dark calibration command sets the zero level for the digitizer. The instrument is placed in total darkness, and when the dark calibration command is issued, the processor records the dark value.

The system is then exposed to an incandescent light source (CIE Illuminant A) because of its well-characterized, continuous spectral power distribution and stable output characteristics. The processor prompts the experimenter for the numerical value (in lux) and records the ADC value. The photopic and blue signal channels are calibrated separately using the same light source and are set to provide the same numerical values for CIE Illuminant A. It should be noted that this calibration procedure is different than that used in conventional photometry, whereby the blue action spectrum would have been set to provide 683 lumens per watt at 555 nm [30]. Since the blue action spectrum has almost no sensitivity at 555 nm, it was deemed more appropriate to calibrate the blue signal to produce the same numerical values as the photopic signal for the well-characterized CIE Illuminant A. Thus, the blue channel was calibrated in relative units of blue radiation, or *b-lux*. During field use then, exposure to commonly available incandescent sources similar to the one used for calibration will provide data with equal values from the photopic and blue channels. Exposure to sources with more radiant power at short wavelengths (e.g., daylight) will cause the blue channel to display a numerically higher blue channel value than the illuminance value generated by the photopic channel.

3.6 Interface and control

The system is controlled via the RS232 serial link to the host computer. The libraries of commands used to control the system consist of “start logging,” “stop logging,” and “retrieve data.” The “start logging” command sets the data-logging rate. Typical rates are 0.1 Hz to 1 Hz. The “stop logging” command sets the system to a low-power sleep mode. The “retrieve data” command downloads the data from the flash memory to a file in the host computer. The file is a text file consisting of date and time, photopic and circadian light levels, head tilt, and activity measures.

4. Illustrative Data

To exhibit the capabilities of the Daysimeter as a practical research tool, sensor readings from two example data sets are plotted. The first data set was obtained during a laboratory experiment where a subject wore the Daysimeter for a five-hour experimental session. The second shows a less controlled situation afforded by wearing the instrument home from work in the evening.

Figure 4 shows data collected from one subject wearing the Daysimeter and performing a computer-based numerical verification task [31]. Photometric data from this subject were obtained from 05:00 to 10:00 on February 5, 2005; sunrise was at 07:03. The subject was seated at the computer screen, facing a north window. The room was illuminated throughout the experiment with fluorescent lamps having a correlated color temperature (CCT) of 3500 K. Before dawn, similar readings were recorded from both channels of the Daysimeter (approximately 150 units). Although the spectral power distribution (SPD) of a 3500 K fluorescent lamp is quite different than that of Illuminant A used to calibrate the Daysimeter, the spectral band-pass characteristics of the two detectors, in combination with this fluorescent SPD, led to quite similar readings from both channels. As daylight increased, however, distinctly different values were obtained from the two sensors. Toward the end of the experimental session, the photopic illuminance was approximately 1000 lux whereas the blue sensor recorded approximately 3000 b-lux. These data illustrate the importance of considering spectral response in quantifying the light stimulus. Also evident in the figure are several occurrences (e.g., 08:30) when the subject moved away from the window to a more interior space illuminated with fluorescent lamps, as indicated by the drop in light level to approximately 150 lux and yielding a b-lux/lux ratio near unity. From these data showing marked variations in light exposure over time due to the continual head movement of the subject, a radiation dose could be calculated by integrating the recorded values over the desired time period together with an estimate of pupil area.

Figure 5 shows values obtained by the two channels of the Daysimeter worn at the Lighting Research Center laboratory and later during a drive home at night. Even though these data were collected after sunset, changes in the recorded values of nearly three orders of magnitude are obtained. Annotations in the figure indicate what the subject was doing. Interestingly, during the period of nighttime driving, luminous events such as headlight flashes from oncoming traffic are discernable, although with a sampling rate of 0.5 Hz, the recorded signal likely underestimates the magnitude and extent of the transients. Of perhaps more significance for the circadian system are the relatively high values encountered while pumping gas at a service station. Without the Daysimeter, it would be difficult to accurately determine people's circadian radiation exposure, owing to the wide range of lighting conditions commonly encountered.

5. Conclusions

Measurement is at the core of progress in both science and commerce. Light as a specific stimulus for vision and as a commodity for sale has been well-established and readily used for nearly a century [32]. Only recently has the role of optical radiation as a stimulus for circadian regulation in all species, including humans, become better understood [1]. Even today, work is ongoing toward the development of a detailed understanding of phototransduction of optical radiation by the circadian system. Due to the very recent nature of these scientific developments, the specification and sale of optical radiation for the circadian system has yet to take place in a systematic way. Once an internationally sanctioned system of measurement of circadian radiation is established, however, products that generate and control light for the circadian system will become much more prevalent.

To assist progress in both science and commerce, a prototype device for measuring radiation for the circadian system, the Daysimeter, was designed, constructed, calibrated, and utilized in one scientific investigation with more to follow. The conceptual framework for the Daysimeter reflects the unique nature of optical radiation for the circadian system in contrast to that for the visual system. Unlike the visual system, the circadian system has a much higher threshold to optical radiation, it has a peak spectral sensitivity at much shorter wavelengths, it is indifferent to image formation, it requires longer radiation exposures for activation, and perhaps most important, it is differentially sensitive to optical radiation over the 24-hour day [12]. These fundamental differences between the visual and the circadian systems were specifically addressed in the design and development of the Daysimeter described here. Moreover, because activity patterns provide an indication of the circadian timing unique to each person, the instrument also incorporates detection and recording of head motions [23].

By combining data-logging functions with sensors specifically designed to measure the optical stimulus to the circadian system, all in a conveniently small and inexpensive package, the Daysimeter is a useful tool for experiments and clinical trials both in and out of a laboratory setting. The Daysimeter measures illuminance at the eye over the range from 1 lux to more than 100 000 lux and spectrally weighted blue radiation at the eye over a similar dynamic range, enabling measurements both indoors and outdoors over the complete range of meaningful irradiances to the circadian system. With a data storage capacity of 120 000 readings and sampling rates up to 1 Hz, the Daysimeter can provide a detailed record of circadian-effective radiation exposure, capturing both the short bursts of high intensity radiation as people move about in the modern environment, as well as the more gradual changes in ambient radiation levels from sunrise to sunset.

Without question, scientific details of circadian phototransduction will continue to emerge and improvements to the prototype Daysimeter described here will continue. It seems also likely that, in the near term, a few products will be manufactured and sold to affect human circadian regulation. Jet lag is a clear example of circadian disruption that can be ameliorated with light treatment [33]. Seasonal depression and sleep disorders also appear to have some foundation in circadian disruption, and these too have been shown to be positively affected by light treatment [2–4, 34]. Increased productivity for workers on the night-shift has also been shown following light treatment [35, 36]. There is also concern that circadian disruption leads to a greater incidence of breast and prostate cancers [8–11, 37, 38]. All of these important applications require more than scientific case studies with qualitative descriptions of light for the circadian system or quantitative descriptions of light based on instruments calibrated in terms of the photopic luminous efficiency function. In short, a system of measurement of optical radiation for the circadian system is essential for scientific and commercial progress in these applications.

The prototype device described here is a step in that direction, but it will ultimately require international consensus on a new system of circadian stimulus measurement before practical solutions to circadian disruption can be broadly adopted. Moving toward more precise and accurate measurements of circadian stimuli requires an iterative process, or bootstrapping approach, where instruments such as the Daysimeter, with its preliminarily defined units of optical radiation (b-lux), are needed to conduct the research from which more precise definitions of circadian-effective radiation can be determined.

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Figure 1

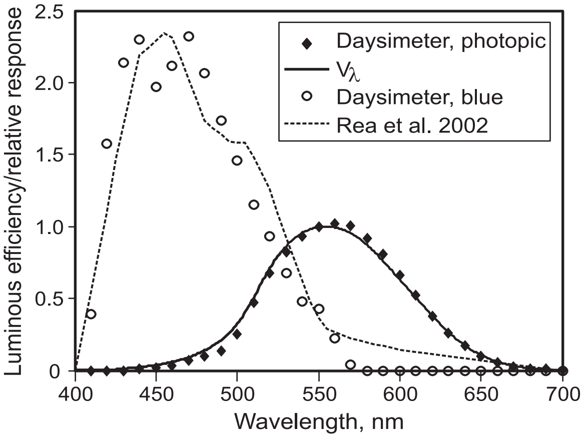

Figure 1. Shown as solid and dashed lines are the photopic luminous efficiency function (V_λ) and a spectral response of the human circadian system reported by Rea *et al* [18], respectively, normalized for equal output when integrated over wavelength with CIE Illuminant A as a light source. The corresponding measured spectral responses of the prototype Daysimeter instrument are shown with symbols.

Figure 2

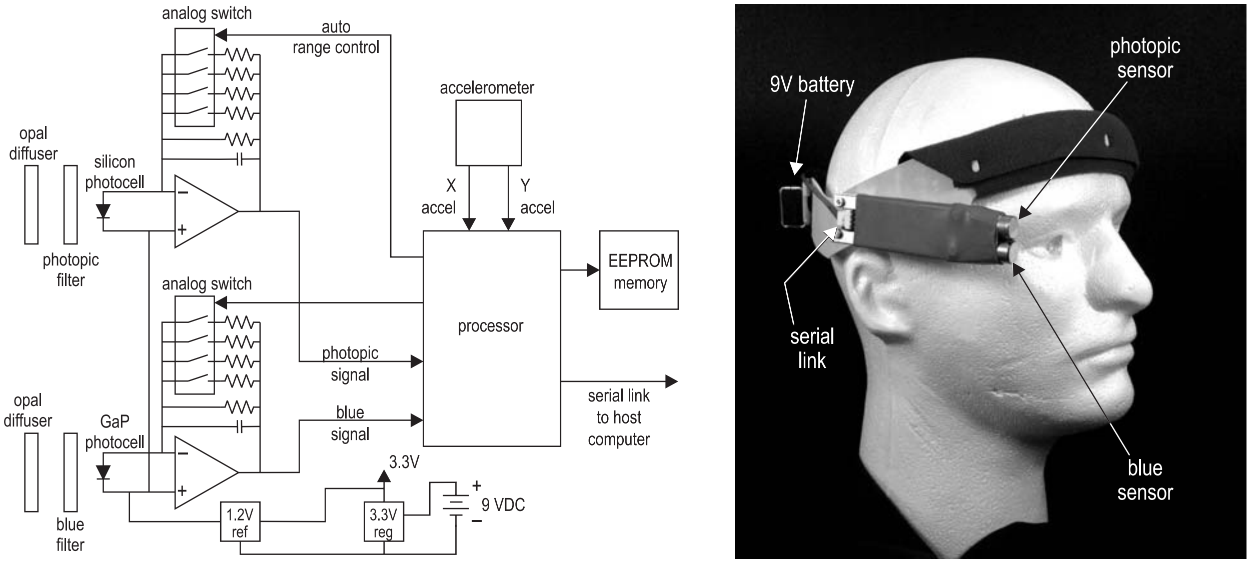

Figure 2. Schematic and photograph of the prototype Daysimeter.

Figure 3

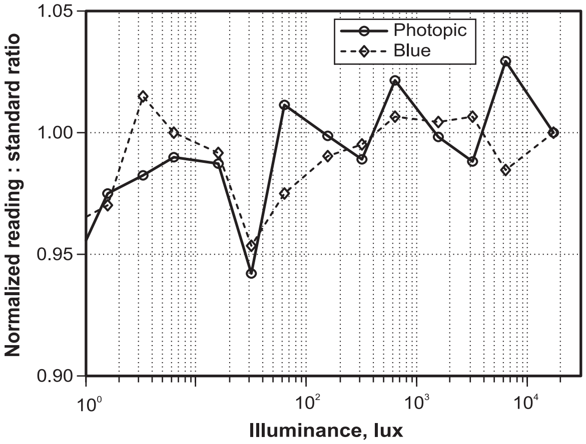

Figure 3. Results of linearity verification for one instrument. Plotted is the ratio of the instrument under test to the LRS 450 Light Standard as a function of light level, normalized to unity at the highest light level for both the photopic and blue channels.

Figure 4

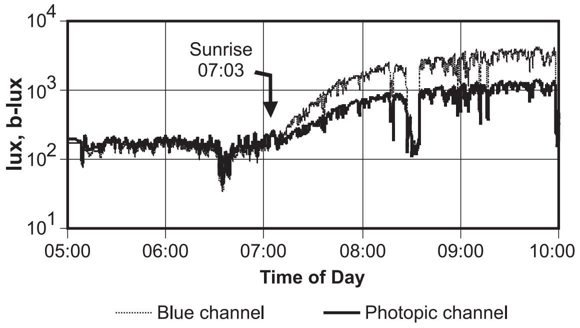

Figure 4. Daysimeter data showing the recording of the photopic and blue sensors when worn by a subject during a five-hour experimental session while seated in an electrically illuminated room next to a north-facing window. Local time is indicated on the abscissa, as is the occurrence of sunrise. Values on the ordinate are in units of photopic lux and b-lux. Breaks taken away from the window are evident by light level drops in both channels.

Figure 5

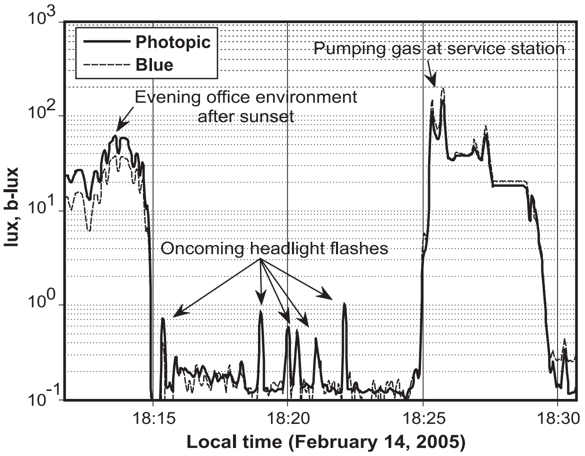

Figure 5. Daysimeter data showing the recording of the photopic and blue sensors when worn at the office and then for the drive home at night. Local time is displayed on the abscissa, and the ordinate is in units of photopic lux and b-lux. Annotations on the graph provide a description of some of the lighting conditions experienced by the subject.