Sleep Health 3 (2017) 204–215

Contents lists available at ScienceDirect

Sleep Health

Journal of the National Sleep Foundation

journal homepage: sleephealthjournal.org

The impact of daytime light exposures on sleep and mood in office workers

Mariana G. Figueiro, PhD [a,*], Bryan Steverson, MA [b], Judith Heerwagen, PhD [b], Kevin Kampschroer, MA [b], Claudia M. Hunter, PhD [a], Kassandra Gonzales, MS [a], Barbara Plitnick, RN [a], Mark S. Rea, PhD [a]

[a] *Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY*
[b] *Office of Federal High-Performance Green Buildings, US General Services Administration*

ARTICLE INFO

Article history:
Received 7 November 2016
Received in revised form 9 March 2017
Accepted 15 March 2017

Keywords:
Light exposure
Circadian rhythms
Sleep
Mood
Phasor analysis

ABSTRACT

Background: By affecting the internal timing mechanisms of the brain, light regulates human physiology and behavior, perhaps most notably the sleep–wake cycle. Humans spend over 90% of their waking hours indoors, yet light in the built environment is not designed to affect circadian rhythms.
Objective: Using a device calibrated to measure light that is effective for the circadian system (circadian-effective light), collect personal light exposures in office workers and relate them to their sleep and mood.
Setting: The research was conducted in 5 buildings managed by the US General Services Administration.
Participants: This study recruited 109 participants (69 females), of whom 81 (54 females) participated in both winter and summer.
Measurements: Self-reported measures of mood and sleep, and objective measures of circadian-effective light and activity rhythms were collected for 7 consecutive days.
Results: Compared to office workers receiving low levels of circadian-effective light in the morning, receiving high levels in the morning is associated with reduced sleep onset latency (especially in winter), increased phasor magnitudes (a measure of circadian entrainment), and increased sleep quality. High levels of circadian-effective light during the entire day are also associated with increased phasor magnitudes, reduced depression, and increased sleep quality.
Conclusions: The present study is the first to measure personal light exposures in office workers using a calibrated device that measures circadian-effective light and relate those light measures to mood, stress, and sleep. The study's results underscore the importance of daytime light exposures for sleep health.

Introduction

Retinal light exposures affect human physiology and behavior by directly stimulating the brain's biological clock.[1] The daily pattern of light and dark falling on our retinas sets the timing of the biological clock, which most notably perhaps compels us to sleep at night and stay awake during the day in synchrony with Earth's 24-hour axial rotation.[2] The human circadian clock free-runs in constant darkness, generally with a period slightly greater than 24 hours. Sustained morning light is needed to advance, and therefore synchronize, the biological clock to local time on Earth.[3]

In contrast to foveal vision, on which most building lighting standards are based, the human circadian system requires high retinal exposures from short-wavelength light to be activated. Since electric lighting used in buildings is presently manufactured, designed, and specified only to meet visual requirements, the built environment may not provide a sufficient amount and the appropriate spectrum of light at the right time to stimulate the circadian system during the day. With the advent of self-luminous displays, there also may be too much light exposure during the night.[4–7] Irregular light–dark patterns or exposure to light at the wrong time may lead to circadian disruption and poor sleep quality, both of which have been associated with mood disorders, including depression, and with health risks such as diabetes, obesity, cardiovascular disease, and cancer.[8–14]

Consistent with the idea that reduced daytime light exposure might affect sleep quality and mood in office workers, Boubekri et al.[15] showed that office workers sitting close to windows, and presumably receiving higher amounts of light during the day than their colleagues in windowless offices, exhibited more activity overall and slept, on average, about 46 minutes longer at night. Office workers sitting close to windows also reported having better scores on the Pittsburgh Sleep Quality Index (PSQI) and the vitality scale of

* Corresponding author at: Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union Street, 3rd floor, Troy, NY 12180.
E-mail address: figuem@rpi.edu (M.G. Figueiro).

http://dx.doi.org/10.1016/j.sleh.2017.03.005
2352-7218/

the Medical Outcomes Study 36-item short form health survey (SF-36). A limitation of the study was that light exposures were reported in terms of photopic illuminance using devices worn on participants' wrists. Figueiro et al.[16] showed that light level measurements recorded on the wrist are not well correlated with circadian-effective light at the eye. Moreover, photopic illuminance, defined in terms of the spectral sensitivity of foveal cones, peaking at 555 nanometers (nm), misrepresents circadian-effective light because the spectral sensitivity of the human circadian system peaks at approximately 460 nm. A more appropriate measure is circadian light (CL_A), which uses a spectral sensitivity function that best matches the response by the circadian system to light, as measured by acute melatonin suppression (discussed in Light exposure and activity measurements).

This rapidly evolving understanding of the circadian system led us to hypothesize that in buildings where daylight was a major design consideration, people would be exposed to lighting conditions that were sufficient to reliably entrain the circadian system to local time on Earth, especially in summer months. Specifically, we hypothesized that workers receiving morning circadian stimulus (CS) of ≤0.1, an exposure level needed for reliable measurements of nocturnal melatonin suppression in the laboratory,[17] would be less synchronized to the natural day–night cycle than those experiencing morning CS ≥0.3. As a corollary, we further hypothesized that those receiving morning CS ≥0.3 would exhibit better sleep quality and mood than those receiving morning CS ≤0.1.

To test these 2 hypotheses, participants were recruited from 5 different buildings managed by the General Services Administration (GSA), the largest landlord in the United States (US). GSA selected the buildings. Four of the buildings were selected because daylight considerations were incorporated in their original design (GSA Central Office, Washington, DC) or during extensive renovations undertaken between 2009 and 2013 (Edith Green–Wendell Wyatt Federal Building, Portland, OR; Federal Center South Building 1202, Seattle, WA; and Wayne N. Aspinall Federal Building and U.S. Courthouse, Grand Junction, CO). The fifth building (GSA Regional Office Building, Washington, DC), where daylight was not a major design consideration and many participants had little or no access to daylight, was selected as an experimental control. The selection was based on the notion that occupants in buildings with abundant daylight availability would be exposed to high levels of CS during work. Unfortunately, as we had usable data for only 5 participants in winter and 10 participants in summer from the non-daylit building, we do not have sufficient data to provide comparisons between participants from that building and the other 4 buildings.

Participants and methods

Participants

The study included 109 participants (69 females), of whom 81 (54 females) participated in both summer and winter (Table 1). One participant did not indicate their sex in the personal data. The total number of measurements obtained from these participants in both buildings for both seasons was 191 (124 from females); of those, 87 (58 from females) measurements were collected in summer and 104 (66 from females) were collected in winter. (Due to issues related to participant compliance and/or and the absence of useable data, the numbers of participants noted for the analyses reported in Results vary from the totals listed here.) All participants were federal employees from the 5 federal buildings selected for the study. All participants were employed as office workers; to a limited amount, some participants in the Seattle and Portland buildings conducted fieldwork. No exclusion criteria were applied in the selection of participants, as the study did not include a lighting intervention.

Generally, the participants in all 5 buildings received the Illuminating Engineering Society's recommended levels[18] (ie, approximately 30 footcandles [300 lux]) of horizontal illuminance at their desk spaces, although those from the Grand Junction and Portland facilities sometimes experienced lower levels during winter. Data collection in all 5 buildings was conducted between 2014 and 2016, and the analyses reported herein were conducted in the spring and summer of 2016.

Light exposure and activity measurements

Circadian light and circadian stimulus

Using published action spectrum data for acute melatonin suppression, Rea et al. proposed a mathematical model of human circadian phototransduction.[19,20] This model is also based on fundamental knowledge of retinal neurophysiology and neuroanatomy, including the operating characteristics of circadian phototransduction (converting light into electrical signals), from response threshold to saturation.[19,21] The intrinsically photosensitive retinal ganglion cells (ipRGCs) are the central elements in the phototransduction model, consistent with electrophysiological and genetic knockout studies.[22–27] The model also reflects neural input from the outer plexiform layer of the retina, consistent with studies showing that signals from rods and cones provide photic information to the ipRGCs.[21]

Using this phototransduction model, the spectral irradiance at the cornea is first converted into CL_A, reflecting the spectral sensitivity of the circadian system, and then, second, transformed into the CS, reflecting the absolute sensitivity of the circadian system. Thus, CS is a measure of the *effectiveness* of the retinal light stimulus for the human circadian system from threshold (CS = 0.1) to saturation (CS = 0.7).[28,29] Fig. 1 shows the modeled spectral sensitivity of the human circadian system at one light level (300 scotopic lux at the cornea) needed to determine CL_A at that light level, and Fig. 2 shows the absolute sensitivity of the human circadian system plotted as a function of CL_A. For reference, corresponding values for photopic illuminance, CL_A, and CS for common light sources (incandescent and daylight) are shown in Fig. 2.

Table 1
Total number of measurements by building and season

GSA building, location	Summer	Winter	Both	Total per building
GSA Central Office, Washington, DC	31 (16)	43 (22)	31 (16)	74 (38)
Edith Green–Wendell Wyatt Federal Building, Portland, OR	18 (13)	18 (13)	18 (13)	36 (26)
Federal Center South Building 1202, Seattle, WA	20 (15)	26 (17)	19 (14)	46 (32)
Wayne N. Aspinall Federal Building and U.S. Courthouse, Grand Junction, CO	7 (7)	11 (10)	7 (7)	18 (17)
GSA Regional Office Building, Washington, DC	11 (7)	6 (4)	6 (4)	17 (11)
Total number of measurements	87 (58)	104 (66)	81 (54)	191 (124)

Note: Number of measurements in females indicated in parentheses.