DAYLIGHT AND PRODUCTIVITY - A POSSIBLE LINK TO CIRCADIAN REGULATION

Mariana G. Figueiro, Lighting Research Center, Rensselaer Polytechnic Institute
Mark S. Rea, Lighting Research Center, Rensselaer Polytechnic Institute
Richard G. Stevens, University of Connecticut Health Center, Dept. of Community Medicine
Anne C. Rea, Lighting Research Center, Rensselaer Polytechnic Institute

Abstract

It has been long held that daylight positively affects worker productivity. Two recent studies reinforce this belief, but the cause-and-effect relationship between daylight and productivity has not been established. Basic research in circadian photobiology suggests that light has a very important role regulating human behavior, including the sleep-wake cycle and seasonal depression. Given these findings, it was hypothesized that during winter months in northern latitudes the absence of daylight in interior spaces might have a negative impact on worker productivity during work hours. The present pilot study compared occupancy rates and types of behavior in matched samples of office workers assigned to interior or to windowed offices during the winter of 2001. Although occupancy rates were identical, workers in windowed offices spent more time on computer tasks, less time talking on the telephone and to co-workers than matched workers in interior offices. The root cause of these findings remains unknown, but the results are consistent with the hypothesis that bright light during the day improves productivity during winter months.

Introduction

Biological systems that repeat approximately every 24 hours are called circadian rhythms. Circadian rhythms are expressed in measures of alertness, task performance, body temperature, and, of course, sleep/wake cycles. A “master clock” in the suprachiasmatic nucleus (SCN) of the brain regulates these various circadian rhythms.

Melatonin is a hormone produced by the pineal gland at night under conditions of darkness. Melatonin production is regulated by the SCN and serves as the circadian messenger to many other regulatory systems in the body. Disruption of the melatonin circadian cycle can result in poor sleep quality [1], lack of alertness [2], seasonal depression [3], immune deficiencies [4] and perhaps even an increase in malignant tumor growth [5].

Previous studies have shown that light can suppress melatonin and consistently entrain the circadian system to a 24-hour cycle. If the circadian pathway receives no external light stimulus, it will free run, i.e., it will run with a period slightly longer than 24 hours and eventually become asynchronous with the day/night cycle. Depending on the timing of the light exposure, the circadian clock can phase delay, phase advance or not be affected at all. External cues, the light/dark cycle being the most important, resets the internal clock and, thus, synchronizes it to the day by advancing the clock a little bit everyday. Because human circadian clock needs to be phase advanced every day in order to be entrained with the day/night cycle, the timing of the light exposure is very important.

Recent research has shown, however, that lighting characteristics (quantity, spectrum, distribution, timing and duration) required to achieve melatonin suppression, and thus, circadian regulation, are substantially different than the ones needed for vision. It is beyond the scope of this poster/paper to review the literature on the circadian system, but one important note is that light levels required to achieve melatonin suppression are much higher that the ones required for vision, which are the ones typically used in interior environments [6]. The visual system performs at near maximum for most visual tasks at 300 to 500 lx on the task (approximately 100 lx at the eye), but the circadian system is only marginally affected at this same light level (Figure 1) [7]. Windows may, therefore, play an important role in circadian regulation because it is not at all uncommon for light levels to exceed 300 lx at the eye in windowed environments.

Moreover, although the photoreceptors that are responsible for the circadian system are still unknown, it is already established that the spectral sensitivity of the circadian system is quite different than the spectral sensitivity of the visual system. The visual system is sensitive to wavelengths much longer than those affecting the circadian system.

This line of research led us to speculate that people working in interior offices may not have the opportunity to be exposed to illuminances greater than 100 lx at the eye during their working hours. Furthermore, in latitudes during the winter when the days are short, a person comes to and leaves from work in the darkness. This limits the opportunity for light exposure outside working hours. This prolonged “biological darkness” may therefore provide an insufficient stimulus for synchronization of a person’s circadian rhythms to the day/night cycle [8].

Perhaps, then, the strong preferences for daylighted spaces by office workers [9] may have a foundation in circadian regulation. We hypothesized that during winter months people in interior offices may “self medicate” themselves by spending more time out of the office visiting locations with bright light like those experienced by their colleagues in windowed offices. A recent study showed that social interactions also impact circadian rhythms [10], so the same people in interior offices may also engage in relatively more conversations with other people, in person or on the phone, in a presumably unconscious attempt to synchronize their circadian systems with the day/night cycle.

These speculations led to the hypothesis that people in interior offices would be less productive than a matched group of people in windowed offices during winter months when access to daylight is minimized. Operationally, it was reasoned that people in interior offices should spend less time on work-related tasks by spending more time talking to co-workers in person and to others on the telephone.

To test this hypothesis, it was essential to find a work environment with both interior and windowed offices housing employees assigned to the same work-related tasks. Moreover, it was important to identify a business where “productivity” could be easily assessed. We were very fortunate to identify a modern office building with a relatively large number of interior and windowed offices (81) housing relatively young employees performing computer-related tasks as their primary job function. Although it was impossible to analyze “productivity” directly, we could observe whether employees were engaged in computer tasks or performing other functions in their spaces. Therefore, we were able to study matched samples of employees housed in interior and in windowed offices who performed the same or similar computer tasks.

Methods

Site

The study was conducted at a software development company located in upstate New York. One hundred twenty desk spaces distributed in 81 offices were selected for the study: thirty-five windowed offices with 2 desk spaces each, totaling 70 desk spaces; twenty-five interior offices with 2 desk spaces each, totaling 50 desk spaces; and twenty-one private (interior) offices with 1 desk space each, totaling 21 desk spaces.

Population

Information about employee ages and salaries was not made available, but the Human Resources Director provided a description of the office occupants selected for the present study. Executives occupied private (interior) offices and were typically older than the rest of the employees; therefore, private offices were excluded from the analyses. All other employees were about the same age (late 20's and early 30's) and had similar job positions and salaries. The Human Resources Director repeatedly assured us that there were no criteria used to separate non-executive employees into interior or exterior offices.

Lighting Conditions

A variety of lighting systems were used throughout the 60 non-executive offices. Every office had two 2' x 4' recessed fluorescent light fixtures (troffers) with small-cell parabolic louvers (luminaire efficiency ≅ 30%), each containing three 32-W fluorescent lamps. Wall switches located inside the office near the door controlled both fluorescent lamp luminaires. In 73 desk spaces (61% of the offices), wall sconces, halogen torchieres, table lamps, desk lamps, or undercabinet lighting were used in addition to the overhead lighting. Forty-five interior desk spaces (90%) had task and/or supplementary lights, while only 28 windowed desk spaces (40%) had them.

All the shared offices were approximately 10 feet by 16 feet (3.3 meters by 5.3 meters) with two desk spaces; one desk was near the door and the other desk was at the back. In windowed offices, the back desk position was near the window. It was not practical to do an extensive documentation of the highly variable illuminances in all rooms, at all occupant locations, at all times of day, and for all nine weeks of the study. Moreover, these measurements would not be unambiguously linked to actual retinal exposures of light of the occupants, not only because the spatial sensitivity of illuminance meters do not exactly represent the spatial distribution of light entering the eye [11] but also because the spectral sensitivity of these instruments do not represent the spectral sensitivity of the circadian system [12,13,14]. It was only practical and useful to make several spot measurements of the illuminances (one morning in March) in the exterior and interior offices to gain a general sense of light levels in the two types of offices.

Of course the most remarkable feature of the illuminance measurements were their wide variation. Horizontal illuminances were measured by placing the illuminance meter on the work plane, near the computer. Illuminances at the eye (vertical orientation) were measured by placing the illuminance meter at a position approximating that of the eyes of a person sitting at the desk, facing the computer. Light levels in interior offices, both near the door and at the back, ranged from 10 to 603 lx on the desk and 11 to 367 lx at the eye. Light levels in windowed offices were more variable due to ever-changing sky conditions and the various positions of the mesh shades. (The positions of the mesh shades were not analyzed in this study). In windowed offices illuminances on the desks near the window ranged from 41 to 2390 lx; near the door values ranged from 71 to 434 lx. Illuminances at the eye for desk spaces near the window were between 73 to 1105 lx; near the door values ranged from 15 to 175 lx. Vertical illuminances near windows were often above 2500 lx, so depending upon the direction of gaze, illuminances at the eye could have been quite high for all occupants of windowed offices. These spot measurements were consistent with those recommended for offices by the IESNA for interior offices (300 – 500 lx) and those reported by Benton (1986) [15] for exterior offices (1500 – 2600 lx).

Additional illuminance measurements were made after the study was completed to determine the relative importance of light emitted from computer screens. In a laboratory setting, illuminances measured at the plane of the eye at 18 inches and at 12 inches were 60 and 100 lx, respectively. Thus, the occupants were exposed to light levels slightly higher than those documented in the literature and from our spot measurements.

Data Collection

Due to lower costs and higher practicality, a systematic sampling technique for both light operation and occupancy was used in this study. Sampling is a practical and proven method for estimating characteristics of a large population. Rea and Jaekel (1983, 1987) [16, 17] found very high correlations (R>0.98) between detailed (e.g., continuous video monitoring) and sampling techniques. Periodic visits to spaces in buildings have been used previously to obtain occupancy and light operation data (Maniccia et al., 1999).

A temporary employee was hired during the 9-week period of the study (from January 8th to March 15th 2001) to walk through the building and document occupancy (yes or no), occupant task (computer, paperwork, talking, phone, or "other"), and electric light operation (on or off) for all light sources. This temporary employee was not aware of the goals of the study. The observation form was filled out 5 times a day (starting at 8:00 am, at 10:00 am, at 12:00 pm, at 2:00 pm, and at 4:00 pm). Two hundred twenty-five observation periods were planned (5 times/ day x 5 days/week x 9 weeks), but due to one holiday (Martin Luther King, Jr. Day, January 15th) and the temporary employee's illness, eight observational periods were not available, thus, a total of 217 observation periods of 120 desk spaces were used.

Results

Occupancy

Two separate analyses were performed on the data. The first analysis assessed patterns of light operation and occupancy in windowed, interior, and private (interior) offices. The results of the first analysis have been published elsewhere [18]. The second analysis focused on different tasks performed in non-executive windowed and in interior offices. Interior and windowed offices were occupied 56% and 60% of the time, respectively. Although 60% of the time shared windowed offices were occupied and 56% of the time shared interior offices were occupied, this represents occupancy for entire offices, not individual desk spaces. Occupancy was 41% at windowed desk spaces and 40% at interior desk spaces (Figure 2). Neither difference in occupancy rates (offices or desk spaces) was statistically significant.

Tasks Performed

Behavior patterns were quite different in windowed and interior offices, however. The percentages of people who performed different tasks *when they were in the office*, such as working on the computer, doing paperwork, talking to people, talking on the telephone, and other tasks, were determined. People in windowed desk spaces spent significantly more time working on the computer (t_7, $p<0.001$) and significantly less time talking to people (t_7, $p<0.003$) or talking on the telephone (t_7, $p<10^{-7}$) than people in interior offices. Paperwork and the "other" categories were not significantly different (Figure 2). Therefore, our hypothesis that workers in windowed offices would spend more time working in their computers than their colleagues in interior offices was supported.

Discussion

This small study was designed to test the general hypothesis that people in interior offices would be less productive than a matched group of people in windowed offices during winter months when access to daylight is minimized. This hypothesis was based upon the growing evidence that light exposure to retinal nonvisual pathways is an important regulator of circadian functions [19]. Operationally, it was reasoned that people in interior offices should spend less time on work-related tasks by spending more time talking to co-workers in person and to others on the telephone.

Even though this study was not designed to directly test the link between circadian regulation and productivity, these results, combined with the extensive literature on circadian regulation, indicate that daylight may affect productivity in commercial buildings during winter months. It is well established that light is one of the strongest stimuli to synchronize the circadian system to a 24-hour day/night cycle. During winter months in northern latitudes, workers in interior offices are highly likely to go to and return from work in the dark, and their circadian system may not receive enough light at the right time. Moreover, the circadian system needs higher light levels and/or longer exposure times to be activated than the visual system (Figure 1) and, in many cases, light levels found in typical interior commercial buildings are not achieved by the electric lighting alone. Indeed, these workers may be in "biological darkness" during working days in the winter, which means that their internal clock may not be synchronized to the day/night cycle. Social interactions can also impact circadian rhythms[10], and may explain why workers in interior offices spent more time on the phone and talking to their workmates.

If these inferences are correct, then the link between daylight and productivity will disappear in the summer. In the summer, workers will have the opportunity to be exposed to daylight in the morning and evening while driving to and from work. These light exposures at these times should be enough to ensure circadian entrainment, even in interior offices.

Before one can generalize these results, however, it is necessary to develop more confidence in the basic question. Namely, does bright light enhance productivity through activation of the circadian system? To provide a satisfactory answer to this question it is necessary to validate the findings of this and other studies suggesting that daylighting (or, more correctly, bright light during the day, can enhance productivity). It will be necessary to conduct additional laboratory and field studies to test the reliability and consistency of the results presented here and to test the hypothesized mechanisms by which these effects are manifested. Specifically, it is important to stay within the theoretical framework emerging from laboratory studies of circadian photobiology and within the framework of soundly designed and conducted field studies. There is certainly a lot more to learn before these results can be considered as a firm foundation for architectural practice. Nevertheless, we should all be optimistic that a concentrated line of research could lead to a new approach to building practice; one based upon the impact of bright light on circadian physiology.

Acknowledgements

The authors would like to acknowledge the New York State Energy Research and Development Authority (NYSERDA) (through the Energy

Center of Wisconsin) for supporting this study. Brian Fuller, Russ Leslie, Lenda Lyman, Janani Ramanth, Ramesh Raghavan, Swapna Sundaran, and Mike Wacholder are also acknowledged for their help in the project.

References

1. Wehr T, Schwartz P, turner E, Feldman-Naim S, Drake C, Rosenthal N. 1995. Bimodal patterns of human melatonin secretion consistent with two-oscillator model of regulation. *Neuroscience Letters* 194 (1995) 105-108.
2. Lack L, Wright H. 1993. The effect of evening bright light in delaying the circadian rhythms and lengthening the sleep of early morning awakening insomniacs. *Sleep* 16(5):436-443.
3. Lewy AJ, Kern HA, Rosenthal NE, Wher TA. 1982. Bright artificial light treatment of a manic-depressive patient with seasonal mood cycle. *American Journal of Psychiatry* 139(11):1496-1498.
4. Maestroni, GJ: "Melatonin and the immune system". The Pineal Gland and Cancer, eds. Bartsch, C, Bartsch, H, Cardinali, DP, Hrushesky, WJM, Mecke, D., pp. 384-394, Springer-Verlag, Berlin, 2001.
5. Blask D, Sauer L, Dauchy R, Holowachuk E, Ruhoff M, Kopff H. 1999. Melatonin Inhibition of Cancer Growth in Vivo Involves Suppression of Tumor Fatty acid Metabolism via Melatonin Receptor-mediated Signal Transduction Events. *Cancer Research* 59:4793-4701.
6. Rea, MS. 2000. Lighting Handbook: Reference and Application, 9th edition. New York: Illuminating Engineering Society of North America.
7. McIntyre IM, Norman TR, Burrows GD, Armstrong SM. 1989. Human melatonin suppression by light is intensity dependent. *J. Pineal Research* 6:149-156.11.
8. Middleton B, Stone B, Arendt J. 2002. Human circadian phase in 12:12 h, 200: < 8 lux and 1000: < 8 lux light-dark cycles, without scheduled sleep or activity. Neuroscience Letters. In press.
9. Hartleb Puleo, S.B. and R.P. Leslie. 1991. Some effects of sequential experience of windows on human response. *Journal of the IES* 20(1):91-99.
10. Schaap J and Meijer J. 2001. Opposing effects of behavioural activity and light on neurons of the suprachiasmatic nucleus. *European Journal of Neuroscience* 13:1955-1962.
11. Van Derlofske J, Bierman A, Rea MS, Ramanath J, Bullough JD. 2002. *Design and optimization of a retinal flux density meter.* Measurement Science and Technology 13(6): 821-828.
12. Brainard GC, Hanifin JP, Greeson JM, Byrne B, Glickman G, Gerner E, Rollag MD. Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. *Journal of Neuroscience* 2001; 21(16): 6405-6412.
13. Thapan K, Arendt J, Skene DJ. An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans. *Journal of Physiology* 2001; 535(Pt. 1): 261-267.
14. Rea MS, Bullough JD, Figueiro MG. 2002. Phototransduction for human melatonin suppression. *J. Pineal Res.*, 32:209 – 213.
15. Benton C, Warren M, Selkowitz S, Jewell J. 1986. Lighting System Performance in an Innovative Daylighted Structure: an Instrumented Study. 1986 International Daylighting Conference Proceedings, 4-7 November 1986. Long Beach, California, USA.

16. Rea MS and Jaekel RR. 1983. Lighting Energy Conservation: Simple Analytic Methods with Time-lapse Photography. *Lighting Research and Technology* 15(2):77-82.
17. Rea MS and Jaekel RR. 1987. Monitoring occupancy and light operation. *Lighting Research and Technology* 19(2):45-49.
18. Figueiro MG, Rea MS, Rea AC, Stevens RG. 2002. Daylight and Productivity – A Field Study. Conference Proceedings of the American Council for an Energy-efficient Economy (ACEEE) Summer Study. Asilomar, CA.
19. Stevens RG and Rea MS. 2001. Light in the built environment: potential role of circadian disruption and breast cancer. *Cancer Causes and Control* 12: 279-297.

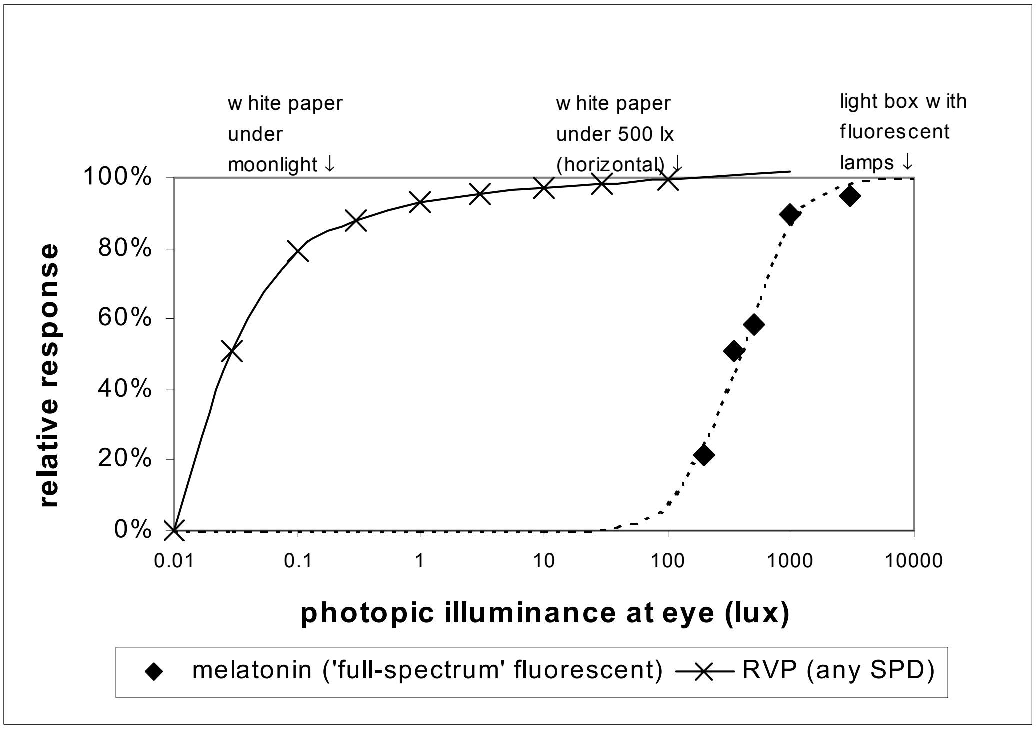
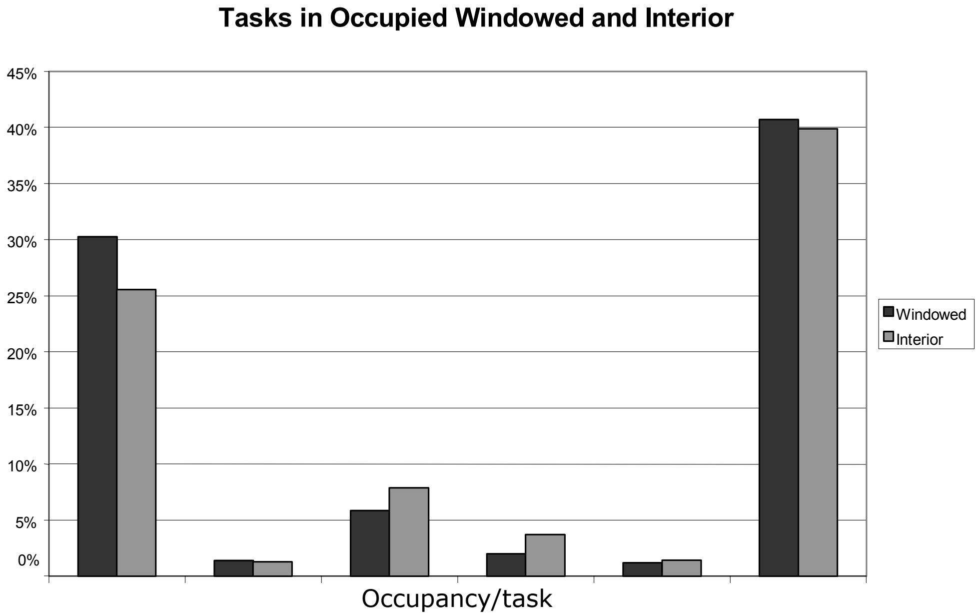


Figure 1. Relative visual performance for high contrast reading material and relative melatonin suppression by light, as a function of illuminance at the eye. For the ordinate, 0% represents the minimum (threshold) response and 100% represents the maximum (saturated) response. Data are scaled to have values between 0% and 100%; for the conditions used to measure melatonin suppression, maximum suppression was around 70%.

Figure 2. Tasks in occupied windowed and interior desk spaces (excluding private).



Desk spaces		Computer*	Paperwork	Talking*	Telephone*	Other	% Occupancy
Windowed	**Average**	30%	1.4%	5.8%	2.0%	1.2%	41%
	Std Dev	1.0%	0.2%	0.7%	0.4%	0.4%	1.1%
Interior	**Average**	26%	1.3%	7.9%	3.7%	1.4%	40%
	Std Dev	2.3%	0.3%	1.3%	0.3%	0.4%	2.9%
	p-value	0.0006	NS	0.0028	10^{-7}	NS	NS

* Statistically significant ($p<0.05$)