Daylight and Productivity – A Field Study

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ABSTRACT

Although it is well documented that lighting controls in combination with daylighting in offices can save up to one-half the lighting energy in commercial buildings, the positive impacts of daylight on productivity, human health and well-being may be more compelling reasons to incorporate daylight into the design of buildings.

There is growing evidence that light can impact human circadian systems and that the light intensities and spectra needed to activate the circadian system are different from those needed to activate the visual system. Lack of bright light exposure during the day may result in disruption of the circadian system and lead to feelings of depression, poor sleep quality, lethargy, and even illness.

Based on these speculations, it was hypothesized that people working in interior offices would spend less time in their offices and would be less productive than a matched group of people in windowed offices.

This study looked into the occupancy rates, amount of time subjects spent on work-related tasks, and electric lighting operation in daylighted and interior offices. The results showed no difference in occupancy, but people in windowed offices spent significantly more time (15%) on work-related tasks than people in interior offices. Regarding electric lighting operation, energy waste (lights on when office is unoccupied) in interior offices was greater (28% of the times observed) than in windowed offices (13% of the times observed). Energy savings (lights off when office is occupied) occurred only in windowed offices (18% of the times observed).

Introduction

Daylighting used in concert with existing lighting control technologies can save one-half of the energy used for lighting in offices (LRC, 1994; Rubenstein et al., 1984; Nilsson et al., 1991; Zonneveldt et al., 1998). One study (Maniccia et al., 1998) showed that people in effectively daylighted offices would not even turn on their electric lighting for most tasks. Yet, even with these compelling data on energy savings, few architects, engineers, or builders have taken steps to coordinate the use of daylighting with lighting energy savings in commercial buildings.

Two recent studies have shown that significant positive impacts of daylighting include increased retail sales (Heschong, 2001a) and higher student test scores (Heschong, 2001b). These findings have brought attention to other possible benefits resulting from the use of daylight in various spaces. However, these two studies do not present a theoretical framework for *why* daylight might affect human behavior. There is growing evidence that light can impact the human biological system through nonvisual pathways affecting circadian regulation (Stevens and Rea, 2001). Even though this hypothesis was not tested directly in this study, the literature suggests that circadian regulation might be an important underlying biophysical reason for exposing people to bright light during the day.

It is beyond the scope of this paper to review the large body of research on circadian photobiology (but see McIntyre et al., 1989; Lewy et al., 1982; Lack et al., 1983; Stevens and Rea, 2001). What seems clear, however, is that disruption of the circadian pattern of sleep (Wehr et al., 1995), alertness (Lack et al., 1993), and task performance can occur with either too much light at night or too little light during the day.

Perhaps, then, the strong preference for daylighted spaces by office workers (Hartleb and Leslie, 1991) may have a foundation in circadian regulation. To counteract circadian disruption, we hypothesized, people in interior offices may "self-medicate" themselves by spending more time out of the office visiting locations with bright light. such as those of their colleagues in windowed offices. A recent study showed that social interactions also impact circadian rhythms (Schaap and Meijer, 2001), so people in interior offices may also engage in relatively more conversations with other people, in person or on the phone, in an 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 in their offices due to illness or self-medication in bright locations. They should also spend less time on work-related tasks, instead spending more time talking to co-workers in person and to others on the telephone.

It was essential, therefore, 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 part of their primary job functions. Although it was impossible to analyze "productivity" directly, we could observe whether employees were engaged in computer tasks or performing other functions in the space. 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.

Electric lighting operation in windowed and interior (including private) offices was also observed. Combined with the occupancy data, it was possible to assess lighting energy waste (i.e., light operation in vacant offices). Based on a number of previous studies (e.g., Maniccia et al., 1998 and 1999), it was hypothesized that less lighting energy would be wasted in windowed offices than in interior offices.

Methods

Site

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

Population

Information about employee ages and salaries was not available, but the Human Resources Director provided a description of the office occupants selected for the present study. Only one executive occupied a two-person, windowed office. All other executives occupied private offices. About one-half of the occupants in private (interior) offices held executive positions and were typically older than the rest of the employees; therefore, they were excluded from the occupancy analysis, described below. These other employees were all about the same age (late 20's and early 30's) and were reported to have similar job positions and salaries. Four groups were identified, each occupying different sections of the building. The Human Resources Director, however, repeatedly assured us that there was no systematic separation of employees within groups into interior or exterior offices. Engineers were located on the west side of the building, the quality assurance and web development groups were located on the east side, and documentation personnel were located on the north side of the building.

Lighting Conditions

A variety of lighting systems were used in the facility. 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 each office near the door controlled both fluorescent lamp luminaires. In 71 desk spaces (50% 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 (63% of that group) had task and/or supplementary lights, while only 26 windowed desk spaces (37%) had them.

All offices with two desk spaces had one desk near the door and one desk at the back and were approximately 10 feet by 16 feet in size. In windowed offices, the back desk position was near the window. Light levels were measured once at the end of the study (during a morning in March) using a calibrated illuminance meter. Horizontal and vertical illuminances were measured with only the overhead light on because this was the only lighting system common to all offices. 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 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.

Data Collection

Sampling is a practical and proven method for estimating characteristics of a large population. Rea and Jaekel (1983, 1987) found very high correlations (r>0.98) between detailed (e.g., continuous video monitoring) and sampling techniques. Periodic visits to a space provided an accurate method for obtaining occupancy and light operation data (Maniccia et al., 1999). Due to lower costs and higher practicality, a systematic sampling technique for both light operation and occupancy was used in this study.

The LRC hired a temporary employee during the 9-week period of the study (from January 8th to March 15th) to walk through the building and document occupancy (yes or no), occupant task (computer, paperwork, talking, on the 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 per 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 141 desk spaces were used for all data analyses. All 141 desk spaces were included in the analysis for electric lighting operation, but because executive offices were excluded, a total of 120 desk spaces were used for the analysis for occupancy and occupant tasks. The number of observation periods was the same for all data analyses.

Results

Data Analysis

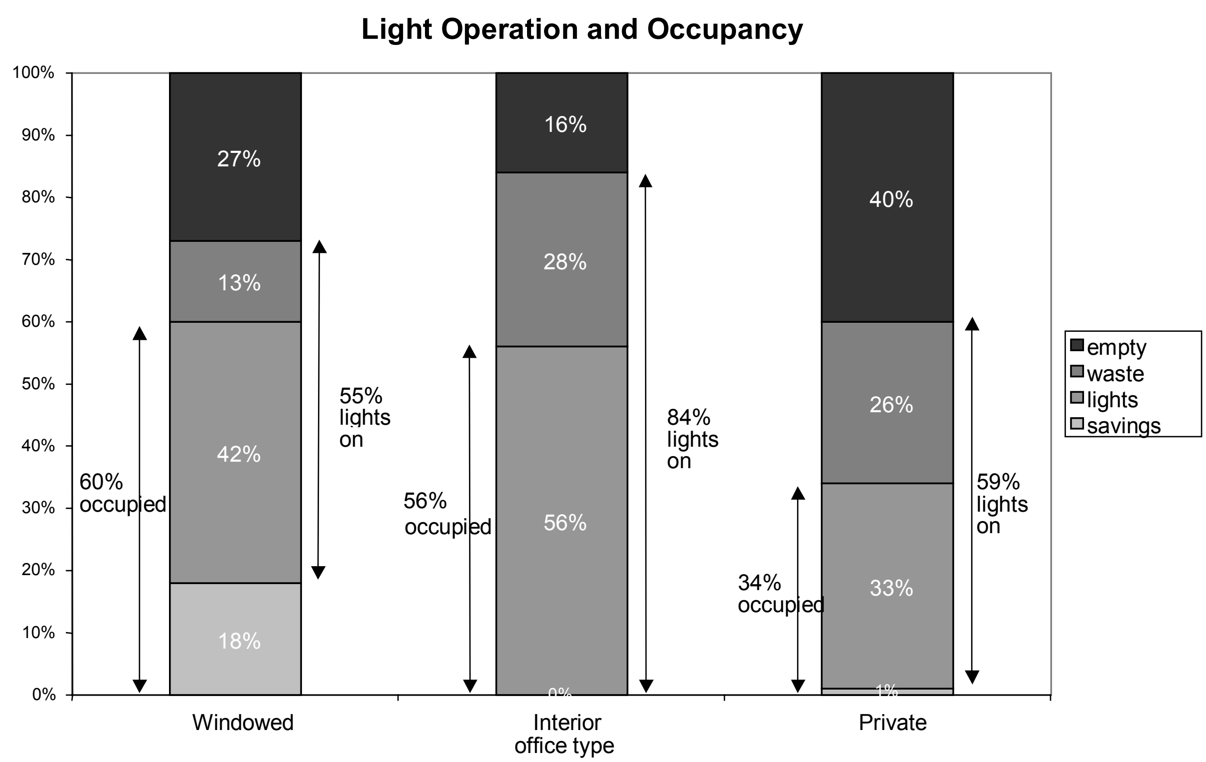
Two separate analyses were performed on the data. The first analysis assessed patterns of light operation and occupancy in windowed, interior, and private (interior) offices. The second analysis focused on different tasks performed in windowed and in interior offices. Private offices were excluded from this latter analysis because they represented a separate population with different behavior pattern.

The first analysis estimated wasted lighting energy during the nine weeks for windowed, interior, and private offices. The analysis of wasted lighting energy did not discriminate between lighting systems or the number of occupants in an office. If any lighting system, ceiling or supplementary, was in use, the office was considered illuminated. If one or more occupants were in the office, it was considered occupied.

Light Operation and Occupancy

Figure 1 shows four categories of lighting energy use based on the observations of light operation and occupancy; energy waste, energy savings, lights on while the office was occupied, and empty. Following Rea and Jaekel (1983, 1987), energy waste was defined as light operation while the office was unoccupied. Energy savings was defined as lights off while the space was occupied. Empty means lights were off while the office was unoccupied. Although it is conceivable that lighting energy use is not proportional to light operation because various lighting systems could be differentially controlled, this seems unlikely because occupants consistently used a "preferred" lighting system, including available daylight, whenever they were in the office.

Figure 1. Light Operation and Occupancy for Windowed, Interior and Private (Interior) Offices



In windowed offices, lighting energy was saved 18% of the time, while in the interior, including private, offices energy was saved less than 1% of the time. Energy was wasted 28% of the time in interior offices and 26% of the time in private offices, while energy was wasted in windowed offices only 13% of the time.

Occupant behaviors were very different in private offices than in shared offices. Private offices were occupied only 34% of the time, while interior and windowed offices were occupied 56% and 60% of the time, respectively.

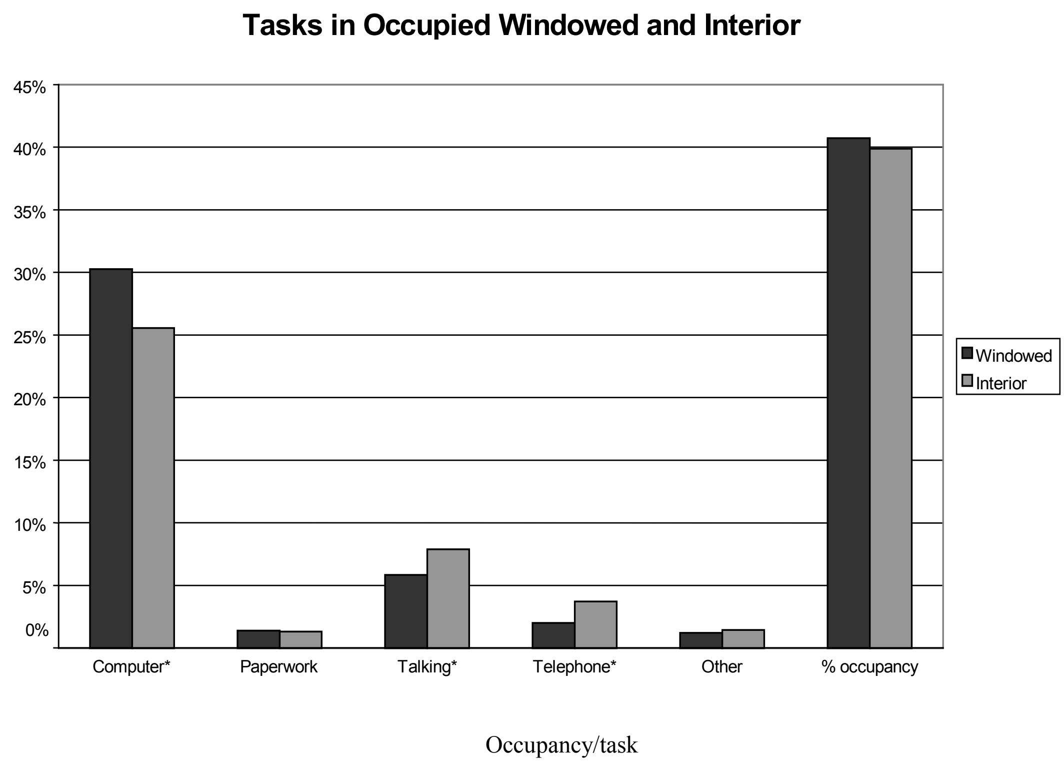
In terms of electric lighting operation, interior and windowed offices showed different effects. While windowed offices had lights on 55% of the time, interior offices had lights on 84% of the time. Private offices had lights on 59% of the time.

It is also important to note that 50% of all desk spaces had supplementary light fixtures, but 63% of these desk spaces were found in the interior offices. Not only did the interior desk spaces have lights on more often than windowed desk spaces, interior desk spaces had both overhead and supplementary light fixtures on 19% more often than windowed desk spaces. Interior desk spaces with supplementary lighting had these light sources on 20% more often than windowed desk spaces with supplementary lighting.

Tasks Performed

Figure 2 compares occupancy and the tasks performed by people at windowed and interior desk spaces. The private desk spaces were excluded from this analysis because, as stated previously, the private offices represented a separate population with different behavior patterns and tasks, whereas the interior and windowed offices were comparable in that they both had two desk spaces and their occupants held similar jobs. Although 60% of the time windowed offices were occupied and 56% of the time interior offices were occupied (Figure 1), this represents occupancy for entire offices, not individual desk spaces. Occupancy was about 41% at windowed desk spaces and 40% at interior desk spaces. Neither difference in occupancy rates was statistically significant.

Figure 2. Tasks in Occupied Windowed and Interior Desk Spaces (Excluding Private Offices)



Offices		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	0.000629	NS	0.002773	0.000000	NS	NS

* Difference is statistically significant ($p<0.05$)

Behavior patterns, however, were quite different in windowed and interior offices. 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 for each of the twenty-five observations performed each week for occupied windowed and interior desk spaces. People in windowed offices 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 (see Figure 2).

Discussion

Electric lighting energy use, based upon observations of light operation and occupancy, was different for the three types of office spaces. All three office types wasted lighting energy (lights on in unoccupied spaces); relative to the time the spaces were occupied, private (interior) offices wasted the most lighting energy and daylighted spaces wasted the least. Earlier studies (e.g., Maniccia, et al. 1998 and 1999) have shown that daylighted spaces are associated with less wasted lighting energy than interior spaces. Often occupants work in daylighted spaces without turning their lights on. This behavior was also observed in the present study. In general then, daylight appears to be very important for lighting energy savings, as long as window treatments provide control for direct sunlight (Rea et al., 1998).

Even so, there were many opportunities to improve lighting energy savings in both interior and windowed offices. Inefficient, ad hoc lighting systems were used throughout the building. By eliminating the inefficient ceiling luminaires (except those on the emergency lighting circuits) and by replacing the inefficient supplementary and task electric lighting with more energy efficient ones, the lighting electrical load in interior offices could be reduced by 30% to 70%. By installing occupancy sensors (LRC 1992), the time the lighting would be operated could be reduced by 25%. The combined energy savings for interior offices would be between 40% and 80%. Windowed offices have less potential for energy savings than interior offices because the connected lighting load and the times the lights are on were both lower. Still, combined energy savings of approximately 25% could be realized in these windowed offices by following these recommendations.

Implementing the recommended energy saving strategies in the interior offices were estimated to save approximately $35 per office per year, an impressive amount, but this would require an estimated investment of approximately $300 per office. (These estimates ignore the interaction between electric lighting and energy costs associated with heating ventilating and air conditioning (Treado and Kusuda, 1980).) Clearly, these simple lighting energy saving strategies are not enticing investments to alter the existing lighting.

Enhanced productivity of employees may, however, provide a more complete view of daylighting economics. Considering that up to 92% of the building operation cost goes to paying the salaries and benefits of its occupants (Erwine and Heschong, 2000), a small increase in productivity can be a significant incentive for investment. It was shown in this study that the time occupants worked on their computers in a windowed office was approximately 15% longer than the time spent by comparable occupants in an interior office (see Figure 2). Assuming the average salary and benefits for these employees was $70,000 per year, and that the time on the computer was, in fact, leading to greater productivity, then daylighted offices would offer a potential benefit over interior offices of approximately $10,000 per occupant per year. Of course, this simple argument ignores the differential costs of constructing and operating building spaces with and without windows. Moreover, a complete analysis of costs and benefits should also consider the alternative to daylight, installing and operating substantially more electric lighting to provide high light levels.

Such considerations add significantly to the complexity of the economic arguments, but before one can justify more precise and comprehensive economic arguments 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). For example, it is not really known whether more time on the computer means greater productivity for the occupants. Although great care was taken to collect data from a homogenous population, it is not certain whether the occupants in the interior and windowed offices were, in fact, identical. It is expected, but not known, that the effects seen here would disappear in the summer months when people have more access to bright light during non-working hours. In short, before we, or anyone, can say that daylight enhances 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.

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