Behavioral Aspects of Lighting and Occupancy Sensors in Private Offices: A Case Study of a University Office Building

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This paper examines people's behavior as it relates to lighting usage in private offices in a university office building. Sixty-three private offices were monitored at one-minute intervals for room occupancy and lighting usage over an 11-month period in 1995. Walk-through observations were also conducted, and two written surveys were administered. Four lighting control configurations were tested; two configurations used manual dual-level switching, and two configurations used automated daylighting controls. All rooms had occupancy sensors, however these were disconnected for one group of offices to provide a control group.

The results showed that people in offices with occupancy sensors were less likely to turn off the lights when they left the room. Instead they relied on the occupancy sensors to control the lights for them. They were also somewhat less likely to choose a switch setting other than full illumination from the overhead lights. Both of these findings suggest that in this kind of setting, people modify their behavior in the presence of an occupancy sensor in ways that reduce the savings potential from the device. The tendency to rely on the sensors to control the lights was estimated to reduce the savings from the occupancy sensors by about 30% in this case. Overall, the occupancy sensors were not cost effective in these individual offices from the standpoint of saving lighting energy, because people managed the lights in their offices fairly diligently. The use of blinds was also found to be a significant factor in savings from the daylighting controls.

INTRODUCTION

Background

By various accounts, lighting energy accounts for 40–50% of the total electricity used in commercial buildings (EIA 1992). It is thus no surprise that active lighting controls have been promoted as a way to manage lighting usage in offices and other commercial buildings. These controls seek to reduce lighting energy usage by turning off lights in unoccupied rooms, or by reducing light output (and lighting energy usage) in rooms that are adequately illuminated by daylight. (DOE 1993).

Although much has been written about the technological aspects of lighting and lighting controls, less is known about how people interact with the controls, as well as how this interaction affects savings from the technologies. Richman, Dittmer and Keller (1994) provide evidence that people's perceived sense of space has an important influence on light management behavior. They distinguish among ''owned,'' ''unowned,'' and ''temporarily owned'' spaces, and argue that people are more likely to manage the lights when they perceive ownership.

Until recently, it has proven difficult to measure lighting usage in relation to room occupancy. Previous efforts have employed random inspections, time-lapse photography, electric eyes in doorways and motion detectors (Rea and Jaekel 1983 and 1987; Richman, Dittmer and Keller 1994).

Scope

This paper describes some of the results from a monitoring study that looked at the use of overhead lighting in private offices in a newly constructed office building on the campus of the University of Wisconsin at Milwaukee. The project, known as the Lighting Showcase, was a collaborative among Wisconsin Electric Power Company, the State of Wisconsin Division of Facilities Development, the University of Wisconsin at Milwaukee, and Wisconsin Demand-Side Demonstrations. In July 1995, the Energy Center of Wisconsin assumed responsibility for the project.

The study was designed to test the efficacy and cost-effectiveness of occupancy sensors and two types of daylighting control systems in private offices. This paper is focused on findings from the study that are related to occupant behavior.

METHODOLOGY

The building used for the study was a new facility for the University of Wisconsin at Milwaukee School of Business

Administration. The 4-story structure has a shallow U-shape with the open part of the ''U'' facing west (Figure 1).

Sixty three individual faculty, staff, and teaching assistant offices were selected for testing from among the 117 offices on the third and fourth floors of the building. Except for five teaching assistant offices, the monitored rooms were individual offices for faculty and staff. The teaching assistant offices had two occupants each; these offices also had smaller windows.

All of the monitored offices were on the perimeter of the building. Every office has a window, which averages somewhat less than 25% of the exposed wall area. The typical office is 11 by 15 feet, with two 3-bulb (T8) fluorescent fixtures in the ceiling. A few offices have three fixtures. Light level readings taken during walk-through surveys in the spring of 1995 showed typical illumination levels at the work plane of 400 to 600 lux (with the blinds closed).

Experimental Groups

Four lighting control strategies were tested for the project. These are summarized in Table 1, and are described below. Most of the results presented in this paper are based on the analysis of data from the first two groups (i.e. those without daylighting controls).

Standard configuration. The standard lighting configuration for the building is manual dual-level switching with an occupancy sensor. Manual dual-level switching allows a person using the room to control the level of lighting with two wall switches. One switch turns on the center bulb in each fixture, and the other switch turns on the outer two bulbs. The combinations of switch positions allows an occupant in the typical two-fixture office to activate two, four, or six bulbs.

Figure 1. *The University of Wisconsin at Milwaukee School of Business Administration (View from the West)*

The occupancy sensors are model DT100L Watt Stoppers. The Watt Stopper is a dual technology sensor capable of sensing both occupancy and illumination levels. The photodetectors in the sensors were not connected for these offices. The occupancy sensors also controlled the room's HVAC controls, although analysis of this aspect of the control was not part of this study.

For sensing room occupancy, the DT100L can be configured to use both sound and motion detection or either one separately. The occupancy sensors have a built-in delay before turning out the lights after the room becomes unoccupied. Upon installation, these were roughly set at 10 minutes, although subsequent analysis of the monitoring data showed that they actually ranged from 6 to 21 minutes. This period is typical of factory settings for these controls (DOE 1993; Richman, Dittmer and Keller 1994).

Control group. Offices in the control group were like those in the standard configuration group, with one important difference: although the rooms all had functional occupancy sensors, the sensors for the control group were disconnected from the lights. If occupants in these rooms left the lights on, they would stay on. Although the occupancy sensors did not control the lights in these rooms, they were functional, and were in fact used for monitoring room occupancy. Like the standard configuration, the control group rooms had manual dual-level switches.

Automated bi-level daylighting. These offices used the photo sensor in the DT100L to switch the center bulb in each fixture on or off in response to the level of daylight in the room (in addition to sensing occupancy). A single wall switch allowed the occupant to control the outer bulbs in the fixtures. The room occupant had no control over the center bulbs: whenever the photocell detected a low light level and room occupancy, the center bulbs were automatically switched on. They also stayed on after the occupant left, until the occupancy sensor timed out.

Continuous daylighting. The continuous daylighting rooms used a separate ceiling-mounted photocell and special dimmable ballasts to continuously adjust the output of the overhead lights in response to the level of daylight in the room. The ballasts allowed continuous dimming of the light from the fluorescent bulbs from 20% to 100% of full output. A single manual switch allowed an occupant to turn the lights on or off, but did not allow adjustment of the level of lighting, which was handled automatically by the photocell. These offices also had occupancy sensors.

Staff and faculty in the monitored rooms were informed that their office was a part of an experimental lighting project, and that their lights might not work the same as other offices. They were given a short description of each of the control

Table 1. *Study Groups*

Configuration	Occupancy Sensor Control?	Light Level Control	Wall Switches	Window Exposure N	E	S	W	Total Rooms
Control group	no	manual	dual-level	3	11	2	5	21
Standard configuration	yes	manual	dual-level	6	10	0	2	18
Automated bi-level	yes	center bulb automatic on/off	single switch (controls only the outer bulbs)	3	4	3	0	10
Continuous daylighting	yes	automatic dimming of all bulbs	single switch (controls all lights)	0	0	12	0	12
			TOTAL	12	25	17	7	61

strategies, but no special effort was made to inform them about how the lights in their office worked.

Data Collection

Five TF32 Dataloggers™ and associated sensors were installed in January 1995 to monitor the energy usage of the lights and the status of the occupancy sensors. This was just prior to the opening of the facility to all staff and faculty who moved over from the old Business School facility.

Two parameters were monitored for each room: occupancy status and energy use for the overhead lights. Occupancy was measured by connecting the monitoring system to a spare relay on the DT100L occupancy sensors. Energy use for the lights was recorded using a standard current transformer on the lighting circuit in each office and voltage transducers to allow true power to be measured. In addition, a photometer (Licor model LI-210SA) was mounted between the window and the blinds in an office near the center of each face of the building to measure the light striking the building. The monitoring system sampled all channels at 1.5 second intervals, and recorded the data as one-minute averages.

In addition to the data from the monitoring system, periodic walk-through surveys of all the rooms in the study were conducted. The purpose of these surveys was to gather information on illumination levels, use of task lighting, and the status of the window blinds. Attempts were made to visit each of the 63 rooms at least once a week at randomly selected times between the hours of 6:00 a.m. and 4:00 p.m. A reading of the illumination level on the work surface for each room was taken. The surveys were conducted between February and May 1995. Most offices were visited between 25 and 27 times during this period.

In May 1995, a written survey was sent to the occupants of the monitored rooms. The survey solicited information on their satisfaction with the lighting controls, as well as the degree to which they manipulated the controls and the blinds in their office. A total of 48 persons responded to the survey, representing a 76% response rate.

In January 1996, at the request of the building administration, all rooms were returned to the standard configuration.

In April 1996, a four-question postcard survey was conducted to ask occupants about their preference for lighting, and to get their opinion about the dual level switching. Thirty-eight people responded to this survey, representing a 61% response rate.

Data Processing

Data from February 1 through December 31, 1995 were used for the analyses presented here. Overall, the data recovery rate during this time period was 91.5%. Most of the lost data occurred between the hours of 6 p.m. and midnight, and coincided with the daily upload of data from the five data loggers at the site to a central computer system. The only significant period of lost data was a two-week period in November, when one of the data loggers (which monitored 14 offices) went off-line.

Data processing included adjusting the occupancy data to remove the delay period after the person had left the room but before the sensor had timed out. This was done using individual delay periods determined for each sensor. It should be noted that the occupancy sensor delay meant that we could not detect a person leaving the room for less than the delay period. For example, if the occupant of a room with a sensor set for a ten-minute delay left for only five minutes and then returned, it would not be detectable in the occupancy data.

Some data were dropped from the analysis. First, data from rooms with extended periods without any evidence of occupancy were dropped. This resulted in the complete elimination of one room, and dropping about half the data for another room. The least occupied room retained for analysis had about 100 hours of occupancy over the 11-month monitoring period.

Second, a few rooms showed spurious occupancy data that resulted from the occupancy sensor registering movement other than that of a person in the room. In one case, this turned out to be the result of a small flag near the sensor that occasionally was stirred by air currents. In another case, the occupant sometimes left a fan running overnight. The room with the flag was dropped, and a total of six months of data from three additional offices were dropped for this reason.

Finally, one person in the control group apparently did not realize that the occupancy sensor in her office did not control the lights. She approached a member of the project team and asked why her lights didn't turn off on their own. When informed of the situation, she began turning out the lights manually. Data for February and March were eliminated for this room. There was no indication that any of the other people in the offices were similarly confused about how their lights worked, and the survey results generally suggested that people in the study paid little attention to how the lighting controls in their office worked.

RESULTS

In this paper, we focus on the behavioral aspects of lighting usage revealed by the study. In particular we examine:

- propensity to turn out the lights when leaving the office
- illumination preference with dual-level switching
- time spent in offices with lights off
- blind management

Table 2 lists some basic occupancy and lighting characteristics over the period of interest to help put the case study in context, and Figure 2 shows the average occupancy and lighting profiles for the four groups on weekdays. In general people in the control group were in their offices somewhat more than people in the other groups: this group had proportionally more staff members and fewer faculty than the other groups. Where appropriate, we adjusted the results for this difference.

Propensity to Turn Out the Lights When Leaving

Collecting occupancy and lighting data at one-minute intervals allowed a detailed examination of how often—and under what conditions—people turn the lights off when leaving their offices. We found that the length of the subsequent absence and the presence of an occupancy sensor were both strongly related to the propensity to turn out the lights when leaving the office, as Figure 3 shows.

As one might expect, people were less likely to turn their lights off when they left for a few minutes than when leaving for an extended period. It was very rare for someone without occupancy sensor control to leave the lights on for a long period of time when the room was empty.

Perhaps the most interesting finding is that people who worked in offices with occupancy sensors (the standard configuration) were only about half as likely to turn out the lights when they left compared to those without occupancy sensor control (the control group). The observed difference between these groups is both practically and statistically significant (at a 95% confidence level) for all but the very shortest time period.[1] For subsequent absences of four hours or more, the difference between the groups is statistically significant at better than a 99% level.

This observed difference is consistent with what would be observed if some people—knowing that the occupancy sensor will automatically shut the lights off after ten minutes—choose not to turn the lights out manually. Indeed, we asked on the written survey whether the presence of advanced lighting technologies caused the person to use their lights differently than they traditionally use room lighting. Of the 17 respondents who said yes—and provided an explanation—12 responded to the effect that they didn't bother to turn the lights on and off anymore.

Analysis at the individual room level indicated that the occupants of four of the 18 rooms with occupancy sensor control turned out the lights manually less than 5% of the time when leaving for an extended period. On the other hand, people in seven of these 18 offices still manually turned off the lights more than 90% of the time when they left for an

Table 2. *Average Occupancy and Lighting Characteristics, by Study Group*

		Control Group	Standard Config.	Automated Bi-level Daylighting	Continuous Daylighting	Overall
Avg. hours of room occupancy per day	*weekdays*	3.76	3.10	3.06	3.42	3.39
	weekends	0.33	0.65	0.58	0.78	0.55
	overall	2.77	2.40	2.34	2.66	2.57
Avg. occupancy events per day (≥5 min. on days with at least one occupancy)	*weekdays*	2.9	3.6	3.2	3.0	3.2
	weekends	1.4	2.7	2.2	2.4	2.3
	overall	2.8	3.5	3.1	2.9	3.1
Avg. length of each occupancy event (minutes) (≥5 min.)	*weekdays*	98.7	58.3	74.2	85.6	78.3
	weekends	104.5	48.3	90.8	82.5	70.5
	overall	98.9	57.4	75.2	85.3	77.8
Avg. hours of lighting use per day	*weekdays*	4.42	3.27	3.39	3.26	3.69
	weekends	0.46	0.56	0.60	0.46	0.51
	overall	3.28	2.49	2.58	2.45	2.77
Avg. lighting Watts		76.6	95.5	73.9	89.0	80.7

extended period. The aggregate effect of this behavior is that the lights were turned off manually about 50% of the time by people in offices with occupancy sensor control. In contrast, people in all but one of the 21 control group offices turned the lights off manually at least 90% of the time when leaving for four hours or more. During the entire 11-month monitoring period, there were only three instances where someone in the control group left the lights on overnight.

If it is true that some people tended to rely on occupancy sensors to turn their lights on and off for them, there is an energy downside from this behavior; namely, the lights remain on for the length of the sensor delay period. (Of course this is measured against the savings that the sensors achieve by turning out the lights when the occupant normally would not have turned them off manually.) By virtue of the experimental setup for this study, we were able to estimate the magnitude of this behavioral effect on the lighting savings from the occupancy sensors, given the 10-minute average delay period for the offices in the study. We found that for this study the hours of lighting energy saved by the sensors is about 30% less when the behavioral change is taken into account than it would be if people's behavior did not change in the face of the controls. We discuss how we arrived at this figure below.

We were able to quantify the net savings (in hours per year) from the occupancy sensors by comparing the time that the lights were actually on while the room was unoccupied for the control group and for the standard configuration rooms. The control group tells us how much the lights are left on in offices without occupancy sensor control, and the standard configuration group tells us how much the lights are left on in unoccupied rooms that have sensors. The difference between the two can be taken as the net impact of the control.[2] Extra lighting usage from the delay period after people leave the room without bothering to turn off the lights will be reflected in this estimate. We found that this calculation yielded average annual savings of 164 hours from the occupancy sensors, or about 14% of the average 1,200 hours of lighting used by the control group.

To estimate how much the occupancy sensors would save if people did not alter their behavior in the presence of the controls, we took advantage of the fact that the control group had functional occupancy sensors that did not control the lights. By simply adding up the times when the lights were on but the monitoring data showed that the sensor had timed out, we could calculate the number of hours of lighting usage that would have been saved if these sensors had been connected to the lights. Because the sensors did not actually control the lights, people would not in all probability alter their behavior in the presence of the controls. Therefore the savings estimate from this method would exclude any behavioral adaptation to the occupancy sensors. When applied to the control group offices, this calculation yielded an estimate of average savings of 234 hours annually per office (19.5% of total lighting use).

Figure 2. Average Occupancy and Lighting Usage Profiles by Time of Day and Study Group

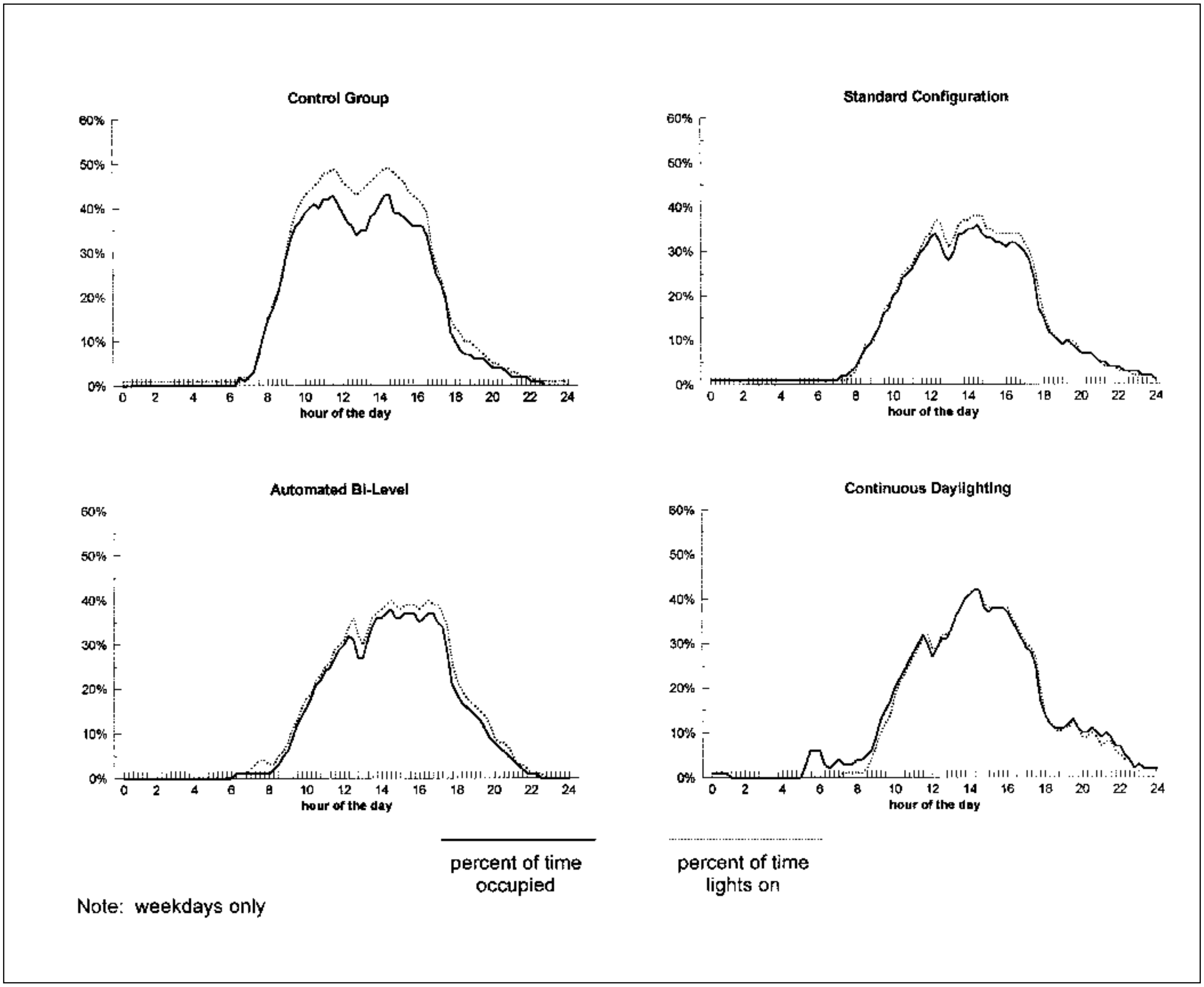
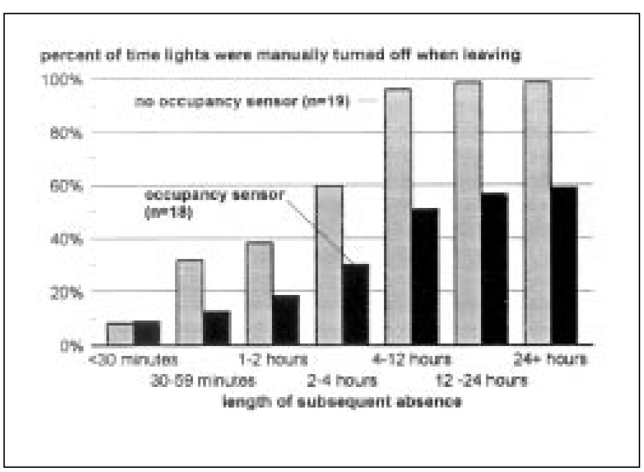


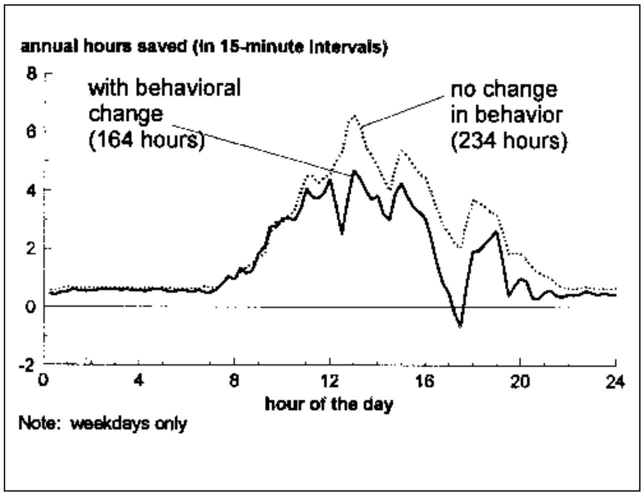
Figure 3. Likelihood of Turning off the Lights When Leaving the Room, by Length of Subsequent Absence



The difference between the two estimates—one of which includes behavioral adaptation, and one of which excludes this effect—is therefore an estimate of the magnitude of the behavioral component. This works out to be $234 - 164 = 70$ hours per year, or 30% of the estimated savings if there was no behavioral adaptation. When we repeated these calculations by time of day, we found that the effect was largest late in the afternoon, suggesting most of the behavioral effect occurs when people leave for the day (Figure 4).

It is noteworthy that we found no similar behavioral effect when people *entered* the room. The data showed that 95% of the time people turned the lights on within a minute of entering the room, and there was no statistically significant difference between those with and without occupancy sensor control.

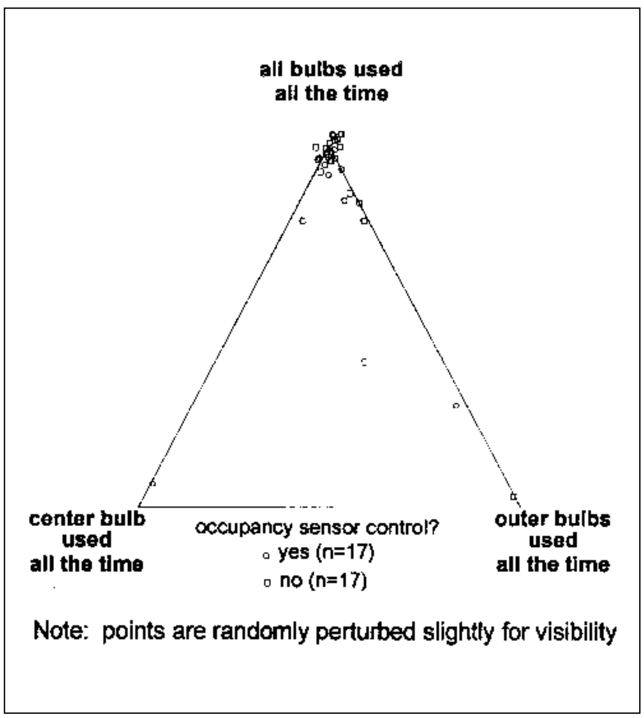
Figure 4. Average Occupancy Sensor Savings by Time of Day, Showing Behavioral Effect



Illumination Preference with Dual-Level Switching

Offices in the standard configuration and the control group had dual-level wall switches that could be used to manually select one, two, or all three bulbs per fixture for illumination. Analysis of the lighting electricity data showed that most people turned on all of the overhead lights most of the time (Figure 5). Of the 34 offices with adequate data and

Figure 5. Illumination Preference for Rooms with Dual-Level Switching



occupancy for this analysis, only four chose anything other than full illumination more than 15% of the time. The occupant in one office clearly preferred a single bulb, occupants in two other offices showed a preference for two bulbs, and one office showed no clear preference, but used all three settings at times.

We also found that there was a statistically significant difference in illumination preference between people in rooms with occupancy sensor control and those without: people in offices in which the occupancy sensor controlled the lights were more likely to use full illumination. We found that in aggregate, occupants in offices without occupancy sensors used full illumination 89% of the time that the lights were on, compared to 95% of the time for offices with occupancy sensors. A randomization test on group assignment (Noreen 1989) showed that this difference was statistically significant at about a 90% confidence level ($p = 0.088$).

To some degree, the four idiosyncratic offices that clearly preferred something other than full illumination distort the difference between the two groups. Nonetheless, excluding these offices from the analysis still reveals statistically significant—albeit smaller—difference. When the four anomalous offices are excluded, people in offices without occupancy sensor control used full illumination 95.3% of the time, compared to 98.2% for occupants of rooms with occupancy sensor control. This difference is also statistically significant ($p = .087$).

It is plausible that people who routinely rely on the occupancy sensor to turn their lights on and off do not manipulate the wall switches as much, and are thus less likely to choose a switch setting other than full illumination. If true, this represents another behavioral impact on the savings from the occupancy sensors, since full illumination requires more electricity than having only some of the bulbs on at any given time. We found that the lights in rooms with occupancy sensors used 11% more power (85.5 Watts per fixture on average) than offices without occupancy sensor control (76.6 Watts). If we remove the idiosyncratic rooms, the difference drops to about 3%. Though it seems small, a 3% increase in the average wattage drawn by the lights takes away about 18% of the 164 hours of lighting energy use that are saved by the sensors (based on 1,000 hours of lighting use per year at an average of 160 Watts per office). At an 11% difference, the effect would reduce the lighting savings from occupancy sensors in these offices by two-thirds.

The evidence from the monitoring data seems to contradict what people told us in the survey. When asked ''what is your preferred lighting level in your office during a typical day?'' only 48% of the respondents said that they preferred to have all of the overhead lights on, while 42% stated that they preferred two or four of the six overhead lights on (7%

responded that they preferred no lights, and 3% did not respond). Moreover, when asked whether they preferred to have two switches that allowed them to adjust the amount of light in the office or a single switch to turn the lights on and off, two-thirds said they preferred to have two switches, compared to 16% who preferred a single switch (the remaining 18% said they were indifferent). It may be that while people do not often exercise their ability to adjust the light in the office, they value the ability to do so.

Time Spent in the Office With the Lights Off

By virtue of the monitoring scheme, we were able to calculate the amount of time that people spent in their offices with the lights off. When pooled across 60 rooms with adequate data, this turned out to be 10% of the total time spent in the offices (this analysis was restricted to occupancy periods of at least 15 minutes). There was a wide variation across individual rooms, ranging from less than 0.1% to 87%. The 87% figure comes from one of the least occupied offices, however, with only about 120 hours of occupancy over the 11-month monitoring period. None of the other occupants spent more than about 40% of the time in the office with the overhead lights off, and half spent less than 5% of the time in the office with the lights off.

The walk-through inspections gathered over 400 work-plane illuminance readings from offices that had the blinds open and the lights off (the offices were not necessarily occupied at the time). The measurements showed a mean illuminance of 387 lux, a median of 313, with 90% of the readings ranging between about 50 and 900 lux.

The amount of time spent in offices with the lights off does not appear to be correlated with the presence of task lighting. Of the 9 offices that we observed (in February 1996) to have task lighting, 3 were among those whose occupants spent the most amount of time in their office with the lights off, but another 3 were in offices that spent the least time in the office with the lights off. The remaining three were in the middle. There was no statistically significant association between the presence of task lighting and the time spent in the room with the lights off.

Analyzing by group and face of the building is problematic, because the number of rooms quickly becomes small, and the offices selected for study were not uniformly spaced around the building. Nonetheless, the data did not reveal any large differences in the amount of time spent in offices with the lights off by lighting control strategy or direction. South-facing offices had the highest percent of time with the lights off (13.6%), and offices in the continuous dimming group (which were all south facing) had the highest average of the four groups (15.0%), but the differences by direction and study group were statistically insignificant for the most part.

Blind Management

The random walk-through inspections showed that people in 36% of the offices never adjusted their blinds between February and May 1995. This is consistent with self-reports of blind management from the written survey, in which 30% of respondents said they never change the position of the blinds. Nearly all of the people who did not adjust their blinds kept them open. Survey respondents who said they did change their blind positions were roughly equally divided among those who said they changed the blinds once a day or more frequently, those who changed them one to four times a week, and those who changed them two or three times a month or less.

Rea (1984) found that blinds settings were significantly different depending on the direction the window faced. The results from the walk-through surveys in this study confirm this finding. Offices on the south face of the building were the most likely to have the blinds completely shut (14% of the time) and the least likely to have them completely open (55%). Offices on the north side of the building were the least likely to have the blinds closed ($<$1% of the time) and the most likely to have them completely open (83%). Offices that faced east or west were intermediate between these extremes. The differences were highly significant (chi-square $p = 0.000$).

These results are consistent with blind manipulation to reduce daylight in the rooms, and reflect what people said on the surveys: of the 70% of respondents to the survey who said they do adjust their blinds, 43% said they do so to reduce the direct light coming into the room, and 37% said that they do so to reduce glare on their computer screen.

The *frequency* with which people adjust their blinds did not appear to be a function of exposure direction. We cross-tabulated exposure direction against three levels of blind management activity from the walk-through surveys (no changes, change in blind position for 25% or less of inspections, and changes for more than 25% of inspections). While we found that people with south facing windows were the most likely to be very active blind managers, and people with north facing windows were most likely to never adjust the blinds, the differences were not statistically significant ($p = 0.239$, using Fisher's exact test).

The use of the blinds was almost certainly a factor for some of the rooms with continuous daylighting. We found that only half of the 12 rooms that had continuous daylighting controls showed any evidence of dimming during the 11 months of monitoring. The walk-through surveys indicated that occupants in three of the six rooms in which the lights never dimmed kept their blinds closed nearly all the time. It is notable that all of the offices in the continuous daylighting group were along the south face of the building. The blind management data suggest that considerably more savings would have been obtained if the daylighting controls had been installed in rooms on a different face of the building. This is similar to findings for a daylighting retrofit study in an office building in Madison, Wisconsin (Reed et al. 1995).

CONCLUSIONS

The impact of lighting controls is notoriously difficult to pin down, since it depends on many factors that are often site specific. The university and faculty and staff offices that were the subject of this study have their own idiosyncrasies that need to be considered before the results can be generalized to other locations. Nonetheless, this study offers some lessons about the use of occupancy sensors in private offices.

One lesson is that although occupancy sensors are often recommended for private offices on the grounds that they are sporadically occupied (e.g., Dankert 1990; DOE, 1993; Crisp and Henderson 1982), the data from this study suggest that this argument does not fully account for the responsibility that occupants of private offices take in managing their lights manually. In this case, the controls, which typically cost $50 or more, saved about a dollar of electricity annually. Although the relatively low occupancy rate for this group of university faculty (who are often away at other places on campus) may partially account for the low savings, even doubling the lighting usage and savings would not suffice to cost justify the controls in this setting. (although HVAC savings from the controls—which we did not examine here—may alter the equation considerably).

Moreover, it appears that people will change their behavior in ways that reduce the savings potential from the controls. The presence of an occupancy sensor in these individual offices was associated with a statistically significant difference in the propensity to turn out the lights when leaving the room, as well as a decrease in the likelihood that the occupant would choose a light level setting other than full illumination. If people do in fact adapt their lighting usage behavior in the presence of an occupancy sensor, there are at least three implications for potential occupancy sensor installations.

First, the results here appear to confirm previous research that indicates that people's sense of personal versus public space may have an important influence on the savings from occupancy sensors (e.g. Dankert, 1990; Richman, Dittmer and Keller 1994). For private offices like the ones in this study, the occupants almost never left the lights on for an extended period of absence. In contrast, an infrequently visited public space, such as a bathroom or a conference room, is not the territory of any single individual. These spaces may be more likely to show good savings from an occupancy sensor, since people will probably feel less personal responsibility for controlling the lights.

Second, behavioral changes in the face of lighting controls have implications for monitoring protocols that assess the potential for savings from occupancy sensors by using portable occupancy sensors and light loggers to count the wasted hours of lighting usage (i.e. hours when the lights are one but the room is unoccupied). If the behavioral adaptations that we found here hold true for other sites, then such a protocol will likely over-estimate the savings potential from the sensors, because it will not capture how people change the way they use the lights when the control is present. Had such a protocol been applied to this location, it would have overestimated the energy savings from occupancy sensors by at least 30%.

Third, the delay interval for an occupancy sensor is clearly an important parameter in determining the savings from these devices. Richman, Dittmer, and Keller (1994) show how the delay interval has a considerable impact on the savings from occupancy sensors when there are no changes in occupant behavior. If the people tend to rely on the controls to switch the lights off for them when they otherwise would have manually switched off the lights, the delay period becomes even more important, because the delay period then adds wasted-light time that would not have occurred in the absence of the sensors.

To maximize energy savings, one would be inclined to set the delay period as short as possible. However, a shorter delay period increases the likelihood that the lights will turn off when someone is in the room but not moving very often. Even with the average 10 minute delay period for the offices in this study, the single most frequent complaint about the lighting was that the lights would turn off while someone was in the room. This has as much to do with sensor type and placement as it does with delay periods, but more research is needed to determine what people accept as a delay interval.

On the subject of the daylighting controls, the findings from the study reinforce the idea that the effectiveness of daylighting controls can be substantially reduced when occupants close their blinds to reduce glare through the windows, and that this is most likely to occur on the south face of the building.

ENDNOTES

1. This was based on a randomization test (Noreen, 1989) formed by randomly shuffling the data with respect

to the study group 5,000 times to create an empirical distribution of the null hypothesis that the test statistic is unrelated to whether or not an occupancy sensor is present. Other hypothesis tests reported here were similarly performed.

2. In practice, the calculation was more complicated, because the two groups had somewhat different occupancy schedules. To get around this confounding factor, we calculated lighting usage during unoccupied periods as a percent of unoccupied time. We then applied the difference in the percents to the amount of time that rooms in the control group were unoccupied. To account for time-dependent factors, we did this calculation separately by month, weekday/weekend and time of day. None of these adjustments had a large effect on the savings estimates, however.

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