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Authors

Jennings, Judith D
Rubinstein, Francis M
DiBartolomeo, Dennis
et al.

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**Environmental Energy
Technologies Division**

April 2000

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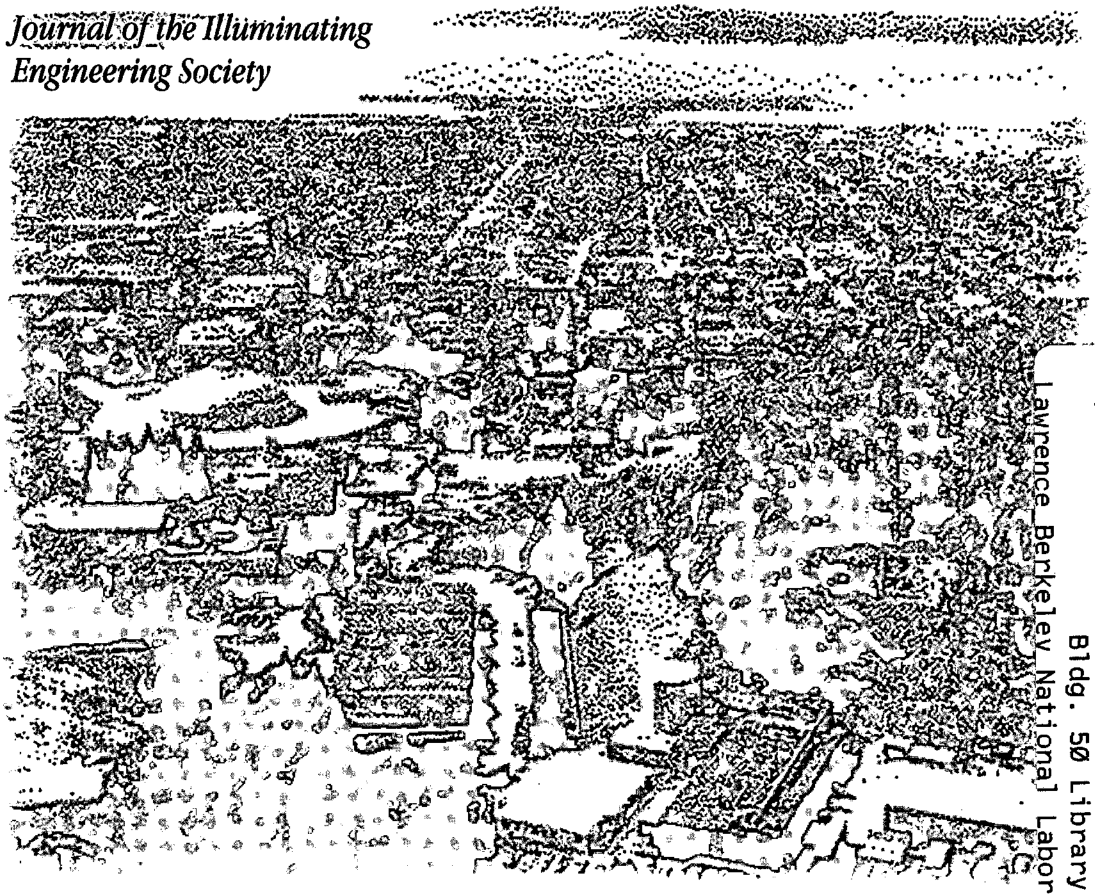

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Judith D. Jennings, Francis M. Rubinstein, Dennis DiBartolomeo
Building Technologies Department
Environmental Energy Technologies Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California, USA 94720

Steven L. Blanc
Pacific Gas & Electric Company
Customer Energy Management Dept., Research & Development Group
2303 Camino Ramon, Suite 100
San Ramon, California, USA 94583

April 2000

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Comparison of Control Options in Private Offices in an Advanced Lighting Controls Testbed

Judith D. Jennings[i], Francis M. Rubinstein[i], Dennis DiBartolomeo[i], Steven L. Blanc[ii]

ABSTRACT

In a major test of different lighting control technologies in a typical office building, we present analyses of seven months' results from five control scenarios in private offices. We compare the energy savings and effectiveness of various combinations of occupant detection, daylight dimming, and switching techniques. Comparing measured energy use with occupant sensors against baseline energy use calculated using wall switch operation only, we found that occupant sensors saved 20-26% lighting energy compared to manual switching alone. In offices where light sensor controls were installed and properly commissioned, additional savings up to 27% for a total of 46% were obtained over a seven-month period, even in an area with unusually high minimum lighting requirements. Dimming the lighting system to desired task levels (task tuning) also resulted in significant (23% additional, 43% total) energy savings in overlit areas. On the base case floor, where only bi-level switches were installed, we found significant usage of only one switch resulting in an additional 23% savings over single-level switches-an unexpected result with implications for building code requirements.

We found that the energy savings due to occupant sensing vs. dimming depended on the behavior of occupants. In offices whose occupants tended to stay at their desks all day, dimming controls saved more energy, and vice versa. The lighting requirements of occupants appear to depend on their type of work.

INTRODUCTION

Lighting controls have the potential to reduce lighting energy consumption significantly and to moderate peak demand in commercial buildings.[1,2] Lighting controls reduce lighting energy consumption by exploiting one or more strategies. The most common and, arguably, most successful lighting control strategy is occupant sensing, which employs an occupant sensor to switch lights on and off according to detected occupancy. Despite their relatively widespread use, there are surprisingly few well-documented studies in the US that demonstrate that occupant sensors actually reduce lighting energy use sustainably.[3,4,5] Daylighting is another lighting control strategy that has been investigated in a few monitored sites.[2,7] With the advent of inexpensive manual dimmers and handheld remote controls, occupant-controlled manual dimming is becoming an affordable option, and has been shown to have some energy savings potential and high occupant satisfaction rating in one installation.[4] Less common strategies such as task tuning, lumen maintenance, and load shedding have been described in the literature[1] but not investigated at real installations. The most humble of lighting control strategies, bi-level switching, has not been seriously evaluated even in those states where it is required by energy code.

Given the many ways that lighting controls can reduce lighting energy waste and potentially improve occupant satisfaction, the shortage of well-monitored installations showing the sustained benefits of different lighting control strategies is surprising, and is probably a contributor to the relatively slow adoption of lighting controls in nonresidential buildings.

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[i] Lawrence Berkeley National Laboratory

[ii] Pacific Gas and Electric Company

The lighting testbed in the Phillip Burton Federal Building in San Francisco was set up to fill many of the gaps in the understanding of savings achievable with lighting controls. Using data from a portion of the testbed, this paper focuses on the energy savings possible through use of occupancy, switching, and three types of dimming control in private offices, ranging from very simple to complex intelligent systems.

DESCRIPTION OF THE SITE

The Phillip Burton Federal Building in San Francisco is a 21-story high-rise office building constructed in 1962. It has been undergoing major renovation as part of a larger effort to modernize the building. About 85,000 net square feet (out of 180,000 gross square feet) on the 3rd, 4th, and 5th floors of the building were set aside as a testbed for examining the energy savings and cost-effectiveness of different types of lighting control systems in private offices, open daylit areas, and interior open office spaces. Each office or group of lights that are switched and controlled together is operated and monitored as a separate lighting zone, for a total of 175 zones. The three floors are entirely occupied by General Services Administration personnel, with tasks that vary widely and include administrative, architectural, real estate, legal, financial, and security personnel with a similar variety of working habits and schedules.

The 99 perimeter private office zones (all with windows) on these three floors, accounting for 18,600 square feet, are the subject of this paper. These zones range in size from 112 to 480 square feet, with an average of 188 square feet. Single-glazed windows on all facades run from 3 ft. above the floor to ceiling height (9 ft), and all are fitted with manually operated mini-blinds. The windows on the east, south, and west facades are coated with a film that absorbs approximately 50% of incident solar radiation (approximately 40% transmittance), while the north windows are uncoated (approximately 88% transmittance). Nearby buildings shade the walls at the level of the 3rd, 4th, and 5th floors during parts of the day, and reflections off those buildings occasionally add to the daylight coming through the windows. A solar data collection station, which measures global and diffuse horizontal daylight illuminance on 5-min intervals, is installed on the roof of the building.

Overhead electric lighting throughout the testbed consists primarily of 2' X 4' 18-cell 3-lamp T-8 parabolic-louver fixtures, with some 2' X 2' 2-lamp fixtures. While under-shelf task lighting is available nearly everywhere in the open parts of the testbed, perhaps only 2/3 of the private offices have task lighting of various types (fluorescent, incandescent, and halogen incandescent), some built-in (fluorescent under-shelf) and some brought in by the occupants. The most typical private office has two overhead fixtures, but as many as six fixtures are found in the largest offices. After relamping and initial lamp burn-in at the start of the testbed, the average full-light illuminance in all private office spaces was about 800 lux, with a maximum of 1300 lux and a minimum of 400 lux.

Though GSA buildings are not subject to the requirements of California's Title 24 energy code, the standard lighting control technique used throughout the Phillip Burton Federal building is bi-level switching. In this method one switch operates the center lamp in each fixture and another operates the outer lamps, resulting in three possible lighting levels despite the name "bi-level."

Plans of the experimental area are shown in Figure 1. Only the perimeter offices (shown unshaded) are discussed in the present paper. The arrows at the top of each of the three floor plans in the figure indicate where to look for each different area that we will discuss; for example, "5EP" indicates East Private daylit offices on the 5th floor. Shaded areas (described in the figure legend) will not be discussed in this paper.

METHODS

This installation, by its nature as a testbed, has a much more varied system of controls throughout its area than would be seen in an installation not subject to research. Each individual scenario that we examine,

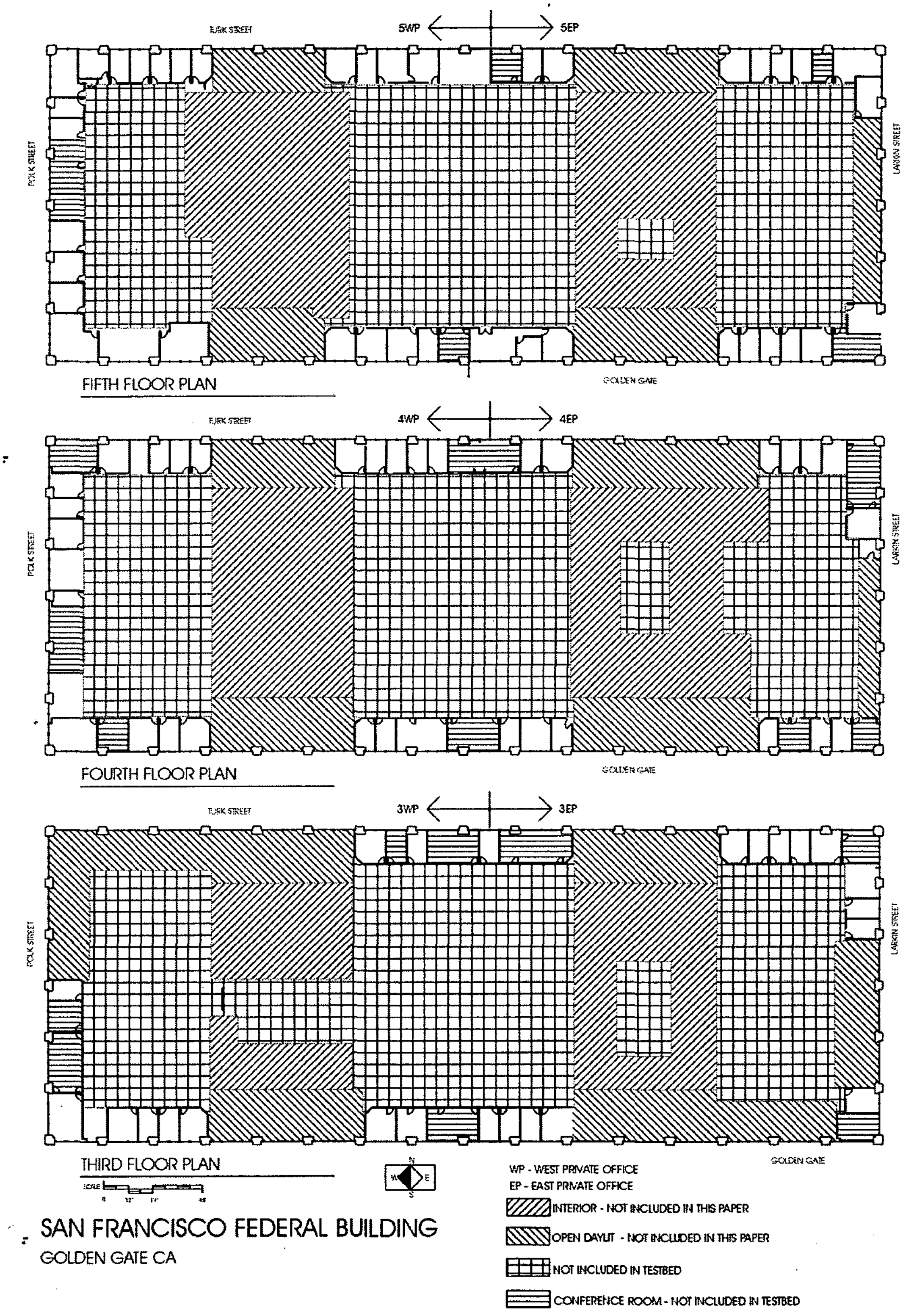

Figure 1. Floor plan of the Philip Burton Federal Building in San Francisco showing various portions of the testbed.

however, is representative of a technique that might be applied, on its own or in combination with few other control techniques, in any building. Of the thirteen separate control scenarios installed in the testbed, six are applied only to private offices, and five of these six are the focus of this paper. We will examine two primary lighting control techniques, occupant sensing and light level adjustment. Light level adjustment is further subdivided into bi-level switching, manual dimming, and two means of automatic dimming in response to daylight. Previous work[7] has detailed the results from the open daylit zones under study in the testbed and future work will describe the results from additional control scenarios.

All fixtures on floors 3 and 5 were retrofitted with dimmable electronic ballasts and some means of controlling them. The bi-level switches were replaced with low-voltage electronic switches (with the appearance of an ordinary wall switch) that control all three lamps together in order to simplify the dimming scenarios. Each private office on these floors is equipped with an occupant sensor. All low-voltage switches and occupant sensors are connected to the distributed control system, so that each time the low-voltage switch is operated or the occupant sensor detects a change in occupancy a switch event is automatically logged.

The entire 4th floor of the testbed serves as a reference or "base case" floor (we avoid calling it a "control" floor for obvious reasons), with the existing non-dimmable electronic ballasts and bi-level switching.

The underpinnings of the testbed consist of a distributed control system that also acts as a data acquisition system throughout the testbed. Its minimum function is to collect trend data on energy use in each of the 175 zones in the testbed and in each whole quadrant of each of the three floors, as well as event data for each switch on the 3rd and 5th floors and every occupant sensor. The quadrant energy and demand monitoring also includes the non-testbed areas on the three floors. Switch and occupant sensor priorities are programmed in the distributed control system.

For several of the control scenarios, the distributed control system also performs various control functions itself, relying for example on input from one or more light sensors to calculate a desirable ballast dimming level from a user-determined function and then transmitting that dimming response to the ballasts over the network. Among the private office scenarios, we programmed ballast control functions available in the distributed control system for two: the task tuning scenario and the indirect closed-loop scenario described below.

Scenarios Tested

Scenario 1: Bi-Level Switching- The simplest scenario under study is the base case on the 4th floor (4EP and 4WP in Fig. 1), that uses the building standard bi-level switching. The switch state in these zones can be determined relatively accurately by monitoring energy use, because there is no dimming on the 4th floor. Occupancy is not monitored, though in hindsight it would have helped to monitor occupancy in these base case zones.

To determine whether the occupants of the 4th floor used their the bi-level switches to choose lower light levels, we analyzed the wall switch usage patterns for 30 daylit private offices. We used the measured energy data for each of the 30 offices to compute the average number of hours per day that the occupants set their lights to 1/3, 2/3 and full light levels.

Scenario 2: Occupant Sensing With Task Tuning- In the east half of the 3rd floor (3EP in Fig. 1), lighting control in private offices is a combination of task tuning and occupant sensing. Task tuning refers to the practice of adjusting the workplane light level in overlit spaces either to a recommended level or to a level that is satisfactory to the occupants. (It differs from lumen maintenance in that its intent is to provide appropriate lighting, rather than to compensate for lamp lumen depreciation over time. Areas where task tuning is employed should also be readjusted periodically for lamp lumen depreciation.) The desired level may vary depending on the task performed in the lit area.

Before the spaces were occupied (June 1996) , we used the distributed control system to tune the lights in the private offices on the east half of the 3rd floor to provide between 550 and 660 lux (50 - 60 fc). During the seven-month period of this analysis, the power to the lights was increased once to maintain the 550-660 lux light level in the space. No occupant control was provided, and the occupants were not told formally that their lights had been dimmed.

Scenario 3: Occupant Sensing with Manual Dimming- In the west half of the 3rd floor (3WP in Fig. 1), lighting control in private offices is a combination of occupant sensing and manual dimming. Here the occupants can dim their lights using slide dimmers installed in addition to low-voltage wall switches. Turning off the switch at the bottom of the slide dimmers reduces the lights to the lowest level achievable by the ballasts, leaving the lights obviously on. The occupants were not provided with instructions in the operation of the switches.

Scenario 4: Occupant Sensing with Direct Closed-Loop Light Level Control- The east half of the 5th floor (5EP in Fig. 1) is equipped with occupant sensors as usual, as well as ceiling-mounted closed-loop light sensors with a 60-degree field of view. The sensor signal is directly connected to the low-voltage control wiring of the dimmable ballasts in the room. The light sensor is mounted in the closest possible ceiling tile above the work surface. Its output is calibrated by means of a hand-held illuminance meter.

Scenario 5: Occupant Sensing with Indirect Closed-Loop Light Level Control- The west half of the 5th floor (5WP in Fig. 1) also has closed-loop light sensors, but differs from the east half in that the light sensor output is used as one input to a ballast control function in the distributed control system. The output from that function in turn controls the ballasts. The ballast control function is programmed into the system by the operator, and can be tuned to the specific needs of the occupants. Sensors are calibrated using a hand-held illuminance meter and the output is scaled using the distributed control system.

Culling the Data

In this paper we analyze in detail approximately 7 months (June 1 - December 31, 1998) of overhead lighting data in private offices on weekdays.

Our method of determining energy savings requires not only the lighting energy data but also the wall switch and occupant sensor data for each analyzed office. Therefore, we had to exclude a number of rooms from the analysis simply because not all three data streams were successfully recorded over the seven-month analysis period. Also, some GSA working groups were moved from one area to another during the test period, leaving some areas largely unoccupied. We eliminated entire zones from further consideration if substantial data (more than 150 out the 214 possible days from June through December) was missing or if our analysis of occupant sensor data showed that the zone was largely unoccupied over the test period. This first level filter removed 4 out of 25 possible private offices on the 3rd floor and 41 of 55 private offices on the 5th floor, leaving 21 zones on the 3rd floor and only 14 zones on the 5th floor. This first filter left us with 4494 zone-days for the 21 3rd floor zones and 2996 zone-days for the 14 5th floor zones.

Next, we applied a second filter to the 39 remaining offices in order to reject zone-days that we deemed to be substantially unoccupied. The second filter rejected days when either

- the total time the lights were on was less than one hour, OR

- the occupants used no overhead lights AND occupancy data showed less than 4.5 occupied hours.

The latter condition was intended to include those days where the occupant apparently worked all day without overhead lights. A total of 2058 zone-days survived the second filter (substantial occupancy) on the 3rd floor, and 1410 survived on the 5th floor. Thus, an average of 98 occupied days were considered for each of the 21 sampled offices on the 3rd floor during the period from June 1 - December 31, 1998, while an average of 101 occupied days were examined for the 14 sampled offices on the 5th floor. Most of the data set from the direct closed-loop daylighting systems on the east half of the 5th floor did not survive the filters for this seven-month period.

Thirty offices on the 4th floor survived the first filter. The second filter did not apply in the same way, because we had no occupancy data, so zone-days where no lighting was used had to be considered unoccupied and were not used in the analysis.

Occupant Sensors, Dimming, and the Moving Baseline

Occupant sensors throughout the study are commissioned to turn lights off when no occupancy has been detected for approximately 15-20 minutes. Wall switches are programmed to have priority over occupant sensors, so that if an occupant wishes his/her lights to stay off, s/he can turn the wall switch to the "off" position. However, even with the wall switch set to the "off" position, the occupant sensors continue to provide occupancy data.

Each time an occupant turns his/her wall switch on or off, the time, date and switch state (ON or OFF) are automatically recorded. Each time the occupant sensor data indicates a change in the occupancy of the space, the time, date and occupancy state (occupied or vacant) are recorded. Wall switch and occupant sensor operation times are recorded as event data with one-minute resolution. Energy data are recorded automatically every 15 minutes in each zone.

To exploit the unprecedented detail of information provided by these data, we developed a computational method to analyze the wall switch and occupancy data. With this approach, we could determine, to within the minute, when the lighting controls in each office were in one of the four possible states defined in Table 1 below.

Table 1. Lighting Use State Definitions

State	Description	Wall Switch	Occupant Sensor	Overhead Light State
0	Office vacant with light switch OFF	OFF	OFF (vacant)	OFF
1	Office occupied with light switch OFF	OFF	ON (occupied)	OFF
2	Office vacant with light switch ON	ON	OFF (vacant)	OFF
3	Office occupied with light switch ON	ON	ON (occupied)	ON

An office can only be in one state at a time, although it is common for an office to pass frequently from state to state over the course of a day. Figure 2 is a lighting energy plot from a typical monitored office. The lower trace shows actual lighting energy use, directly measured at 15-minute intervals. The superimposed upper traces show when the wall switch and occupant sensor switched the lights ON or OFF. The duration of each resultant state can also be seen in the figure. As expected, the State 2 vacancy "notches" in the occupant sensor trace align with the "power off" portions of the overhead lighting energy data. These dips in the power data reflect what we would expect based solely on the wall switch and occupancy data.

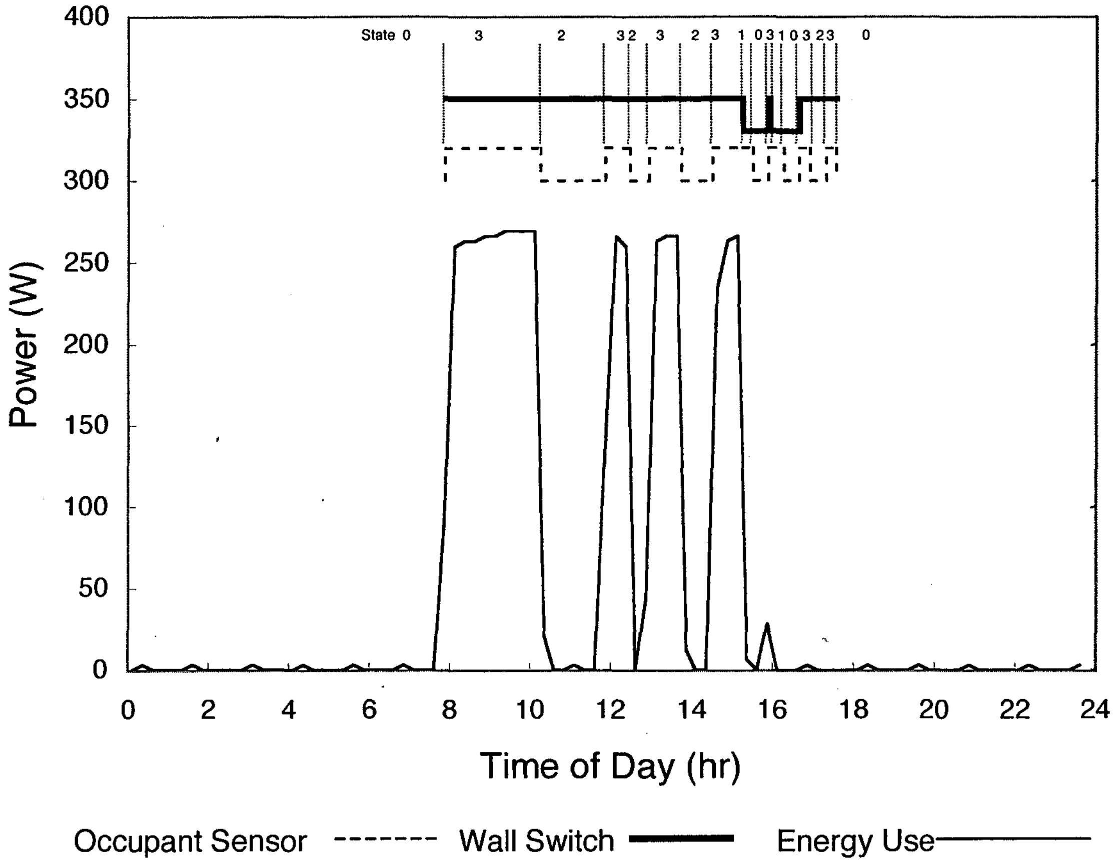

Figure 2. Lighting power, wall switch operation and occupant sensor operation as a function of time of day for a typical private office on the 3rd floor. The resultant lighting use states are marked above the graph.

Using the state definitions, we can calculate several quantities of interest to evaluating lighting operation hours (all calculations assume a wall switch):

Measured (actual) lighting ON hours = Time in state 3

Calculated lighting ON hours for wall switch only = Time in state 3 + Time in state 2

*Calculated energy use for wall switch only = (Time in state 2 + Time in state 3) * installed wattage*

The calculated energy use for wall switch only for each zone-day is used as the normalization constant for the occupant sensor and dimming energy use values (see Results).

As an indicator of occupant sensor effectiveness, state 2 is of the greatest interest since the occupant sensor can only reduce lighting hours by the length of time that the lights are in this state. We define the energy savings from an occupant sensor to be:

Daily Energy Savings (%) = Time in State 2 ÷ (Time in state 2 + Time in state 3)

Although we have no zones that use occupant sensing alone as a control technique, we can calculate the full-light energy use with occupant sensing alone:

$$\textit{Energy use with occupant sensing alone} = \textit{Time in state 3} * \textit{installed wattage}$$

Similarly, the effects of the occupant sensor data can be deconvolved roughly from the energy data to give us an estimate of the energy that would have been used over the wall switch ON hours with dimming only and no occupant sensor:

$$\textit{Energy use with dimming alone} = \textit{Measured energy use} * \frac{(\textit{Time in state 2} + \textit{Time in state 3})}{(\textit{Time in state 3})}$$

These values are computed for each day and office in the data set, effectively providing a tailored or "moving" baseline for each individual office. While cumbersome, this method provides far more accurate information about how occupancy patterns affect lighting usage than the standard method of using a fixed number of hours as an assumed daily average, though it results in lower calculated energy savings from occupant sensors. In particular, it allows one to explore how the typical variations in people's working habits affect the occupant sensor effectiveness from day to day.

The moving-baseline method for analyzing the savings from lighting controls is nothing more than a formalization of the methods that some occupant sensor manufacturers now use to demonstrate the effectiveness of these controls for specific building applications. Pigg et al.[3] and Richman et al.[5] report using a similar technique.

RESULTS

Occupant sensors

Figure 3 shows the lighting energy data for a typical office with an occupant sensor for four different days in May of 1998. The wall switch ON and OFF times and the occupancy pattern as indicated by the occupant sensor are superimposed on the same graphs, as in Figure 2.

The electric power usage for each day reflects the occupancy pattern recorded by the occupant sensor for that day, and illustrates how much energy the occupant sensor actually saves. Consider Fig. 3B, where the energy savings from occupant sensing are a modest 7% since the occupant apparently left the office only once at noon. On the other days (Fig. 3A, 3C, and 3D), the occupant was out of the office for longer times thus increasing the occupant sensor savings for these days to 28-37%. Note that the long time delay settings on the occupant sensors distort the occupancy data to an extent that varies depending on the habits of the occupant. An occupant who stays in his/her office all day will have fairly accurate occupancy readings. An occupant who comes in for one minute every 15 minutes can show a similar occupancy pattern without being present more than a few accumulated minutes during the day.

Table 2 gives statistics for offices with occupant sensors (those on the 3rd and 5th floors).

Keeping in mind the time delay settings of the occupant sensors, we further analyzed the computed state data to compare lighting usage and occupancy trends in individual offices. In Figure 4 the dots show the average measured lighting ON hours per day (both occupant sensor and switch ON) for each of the 21 offices on the 3rd floor. Superimposed on the same figure are the lighting ON hours calculated based on recorded wall switch operation only (as though there were no occupant sensors), shown as small circles. In most cases, the occupant sensor-plus-switch data show fewer lighting ON hours by about 2 hours per day than the switch data alone. Finally, the dashes on the same graph show the apparent occupied hours as

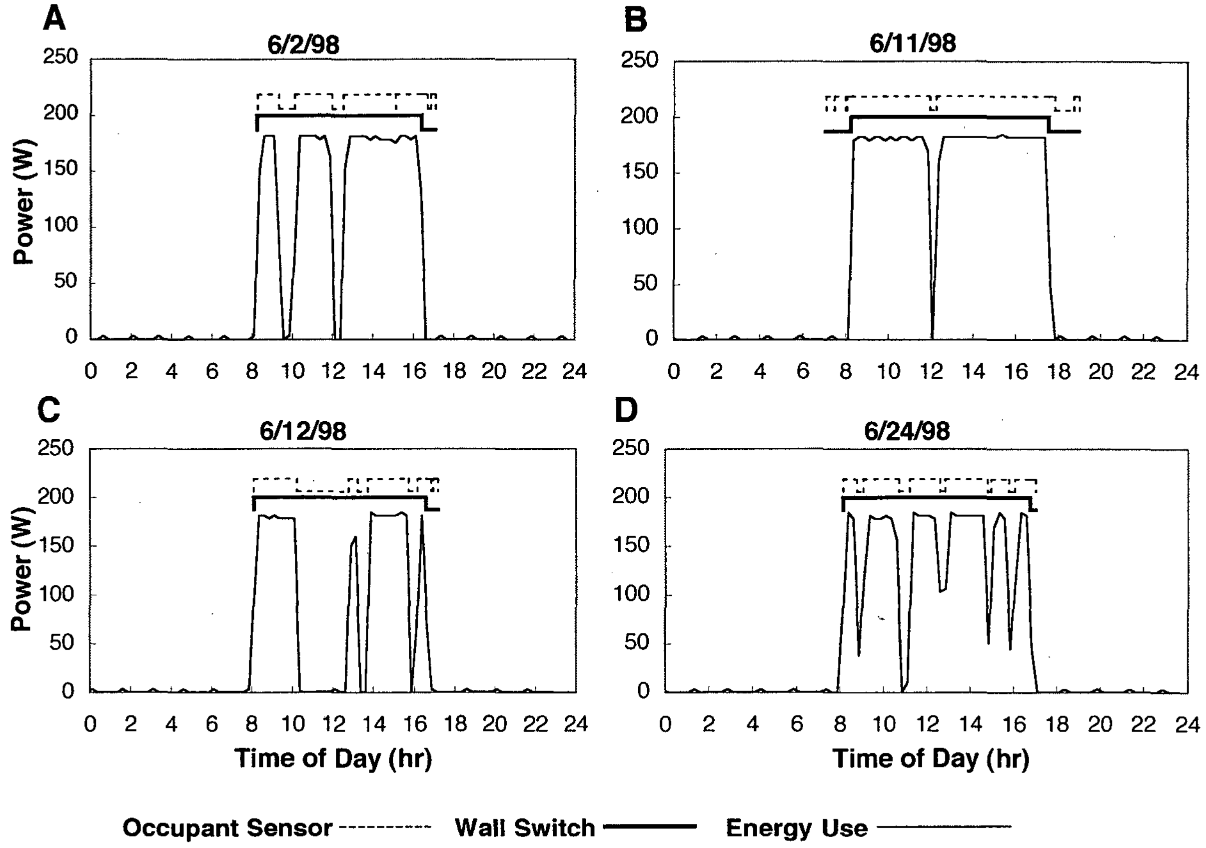

Figure 3. Lighting energy use, wall switch and occupant sensor operation as a function of time of day for one typical private office for four different weekdays in June 1998. (A) June 2, (B) June 11, (C) June 12 and (D) June 14, 1998.

recorded by the occupant sensor alone, without regard to whether the lights are on or not. Figure 5 shows similar data for each of the 14 offices on the 5th floor. Those zones where the apparent occupied hours are above the calculated (wall switch) ON hours (Fig.4: rooms 2, 3, 4, 11, 12; Fig. 5; rooms 12, 13, 14) are occupied by individuals who sometimes occupy their daylit offices without switching on the overhead lights. The average of all rooms on the floor is shown at the far right-hand side of each figure.

To develop a picture of the energy savings over the entire office sample for the seven-month period, we calculated the percentage daily energy savings for all of the offices and sorted the resulting values into 20 bins at intervals of 5% (the bins are ranges of energy savings, e.g. the 0-5% bin includes zone-days with greater than zero and less than or equal to 5% energy savings, etc. There is one extra bin (0%) to capture all those zone-days where the energy savings were exactly zero. This probability distribution of calculated energy savings values for the entire 7-month period is presented in Figure 6 for the 21 offices on the 3rd floor, and Figure 7 for the 14 offices on the 5th floor.

Figure 6 shows, for example, that on the 3rd floor there is about an 11% probability that occupant sensors will save between 10 and 15% of overhead lighting energy on a given day, and almost a 2% probability that they will save between 55 and 60%. Figures 6 and 7 imply that the energy savings from occupant sensors in a group of offices is not a single value but rather a probabilistic distribution function that reflects the fact that the actual energy savings vary from day to day and office to office.

Table 2: Third and Fifth Floor Lighting Statistics–Occupied Days

Zone	*Energy savings*			*Measured occupied hrs*		*Measured wall switch ON hrs*		*Measured Lighting ON hrs*	
	No. of days	Average (%)	Stdev (%)	Average (hr/day)	Stdev (%)	Average (hr/day)	Stdev (%)	Average (hr/day)	Stdev (%)
306	93	20.53	15.98	7.05	1.64	8.22	1.24	6.52	1.63
307	111	20.61	17.63	7.31	2.14	8.62	3.08	6.71	2.75
309	85	17.00	11.84	7.54	2.02	8.32	2.17	6.94	2.13
310	72	16.79	13.50	6.90	1.81	7.56	1.97	6.28	1.90
316	103	2.67	8.67	8.56	2.53	7.24	2.98	6.98	2.74
317	103	36.69	13.09	6.49	1.37	9.96	1.92	6.21	1.51
318	95	24.75	14.95	7.73	1.58	9.58	2.30	7.10	1.92
329	125	7.42	13.25	9.94	3.09	6.42	4.71	5.69	4.22
338	93	17.62	11.48	7.11	1.94	8.31	2.29	6.78	2.05
339	97	27.78	15.71	8.08	2.13	9.91	2.53	7.09	2.24
340	123	14.17	10.41	11.34	1.42	12.75	2.27	10.82	1.44
341	120	28.72	21.89	7.40	2.45	9.28	2.68	6.43	2.60
342	87	13.67	15.47	8.33	2.06	8.07	2.97	6.83	2.69
343	108	20.31	11.84	7.69	1.17	8.09	1.93	6.33	1.50
344	96	23.40	20.14	7.59	1.78	6.95	5.04	4.52	3.35
345	102	32.62	15.59	7.99	1.78	10.88	2.74	7.20	2.22
346	82	19.71	15.08	7.58	1.42	7.32	3.30	5.64	2.46
347	79	25.37	17.81	7.21	2.07	8.63	3.07	6.31	2.41
348	88	20.50	17.34	8.53	2.46	10.14	3.73	7.80	2.98
349	69	34.90	14.52	6.57	1.76	9.42	3.01	5.92	2.02
350	127	4.69	12.55	10.52	3.38	6.77	3.84	6.39	3.75
513	96	12.06	11.94	6.84	2.22	5.64	3.24	4.85	2.86
514	85	11.05	13.28	7.10	2.53	6.08	3.34	5.36	3.12
515	69	14.71	14.39	8.29	2.36	9.20	2.32	7.90	2.44
516	96	20.24	10.58	8.43	2.04	9.29	2.15	7.41	2.16
517	104	14.77	12.35	7.59	2.39	8.59	2.74	7.23	2.44
518	88	15.40	15.54	7.36	2.15	8.45	2.18	7.11	2.15
520	88	12.66	12.95	7.76	1.86	8.09	2.23	7.06	2.20
522	120	13.99	13.08	8.62	1.47	8.68	1.91	7.45	1.98
525	116	27.66	22.37	7.26	2.64	8.83	1.80	6.50	2.51
526	116	49.85	23.53	5.77	2.70	11.10	3.80	5.22	2.87
527	121	24.28	26.22	8.10	2.78	10.26	2.22	7.62	2.72
528	111	23.18	23.50	9.11	2.94	9.32	5.03	6.67	3.91
529	116	41.17	22.87	7.54	3.58	12.20	2.75	7.51	3.59
535	84	21.24	27.84	8.31	3.31	9.55	3.56	7.37	3.59

Note that the most likely energy savings bin (or interval) on the 3rd floor is 15-20% (Fig. 6), and by this bin method the average energy savings overall is 20%. On the 5th floor (Fig. 7), occupant behavior seems to vary from day to day more widely than on the 3rd floor. While the probability of obtaining large energy savings (e.g. >50%) is higher than for the 3rd floor, 0-5% is the most likely energy savings bin, and the average energy savings is about 23%. The average energy savings noted on both figures includes the effect of those days for which there was 0% energy savings.

Another way to look at the energy savings from occupant sensors is to add up the lighting ON time by zone-day, sort the results into time-period bins on the x-axis, and plot the probability of each bin (e.g. 1 hr/zone-day, 2 hrs/zone-day, ..., 8 hrs/zone-day, ..., 24 hrs/zone-day) on the y-axis. This type of analysis is shown in Figures 8 and 9 for the 3rd floor and Figures 10 and 11 for the 5th floor. The data are normalized so that the sum of all the values equals 100% (i.e. the lights must be on for some period each day even if

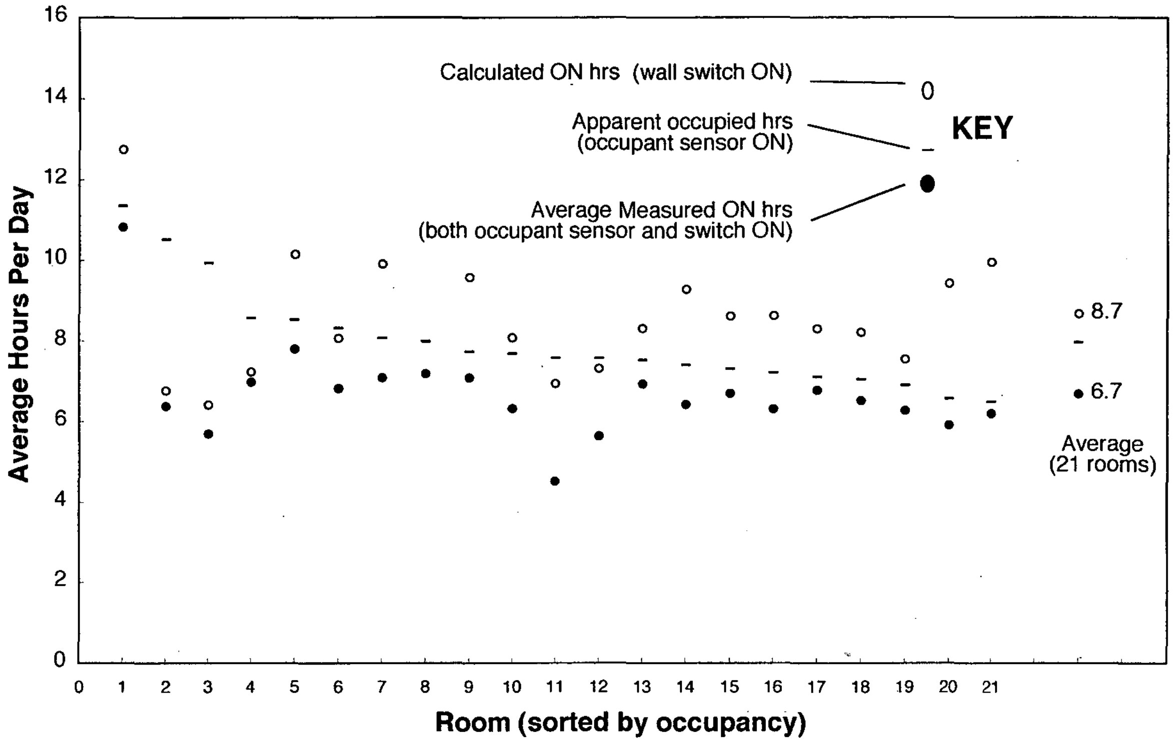

Figure 4. Average hours per day that lighting is ON as measured using occupant sensor control and as calculated based on wall switch use only for 21 offices on the 3rd floor. Data are for occupied weekdays from June

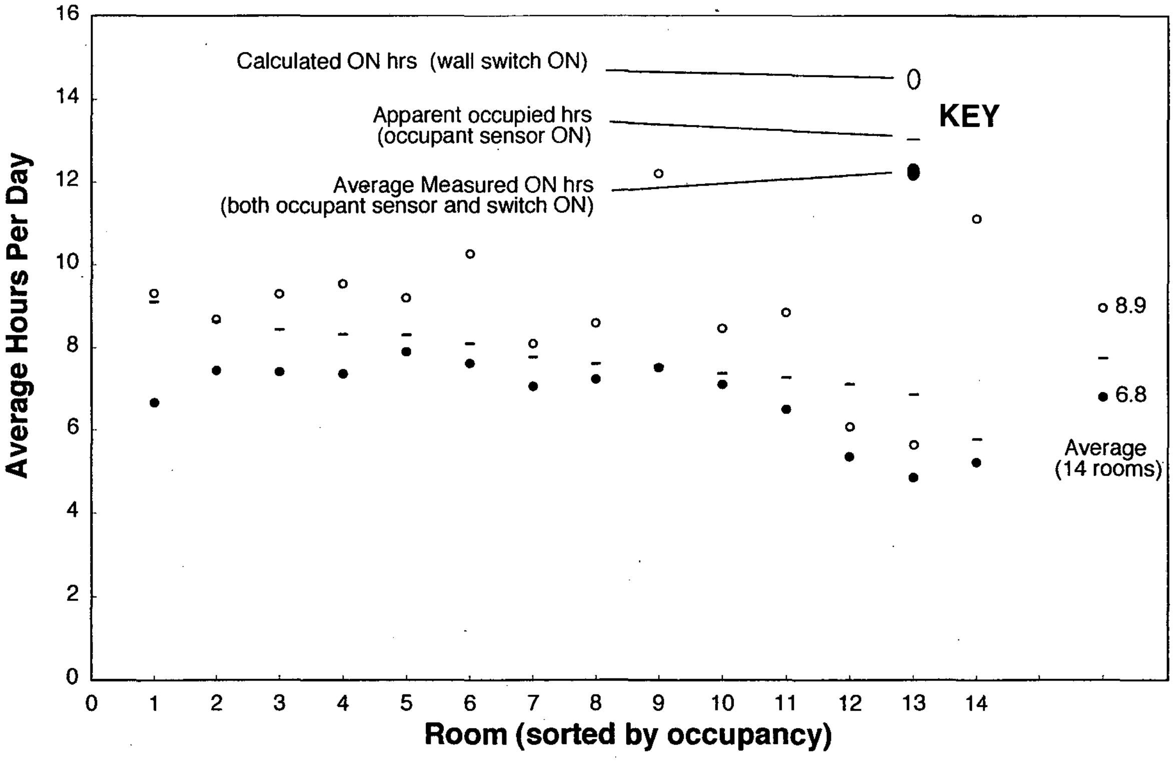

Figure 5. Average hours per day that lighting is ON as measured using occupant sensor control and as calculated based on wall switch use only for 14 offices on the 5th floor. Data are for occupied weekdays from June 1 to December 31, 1998.

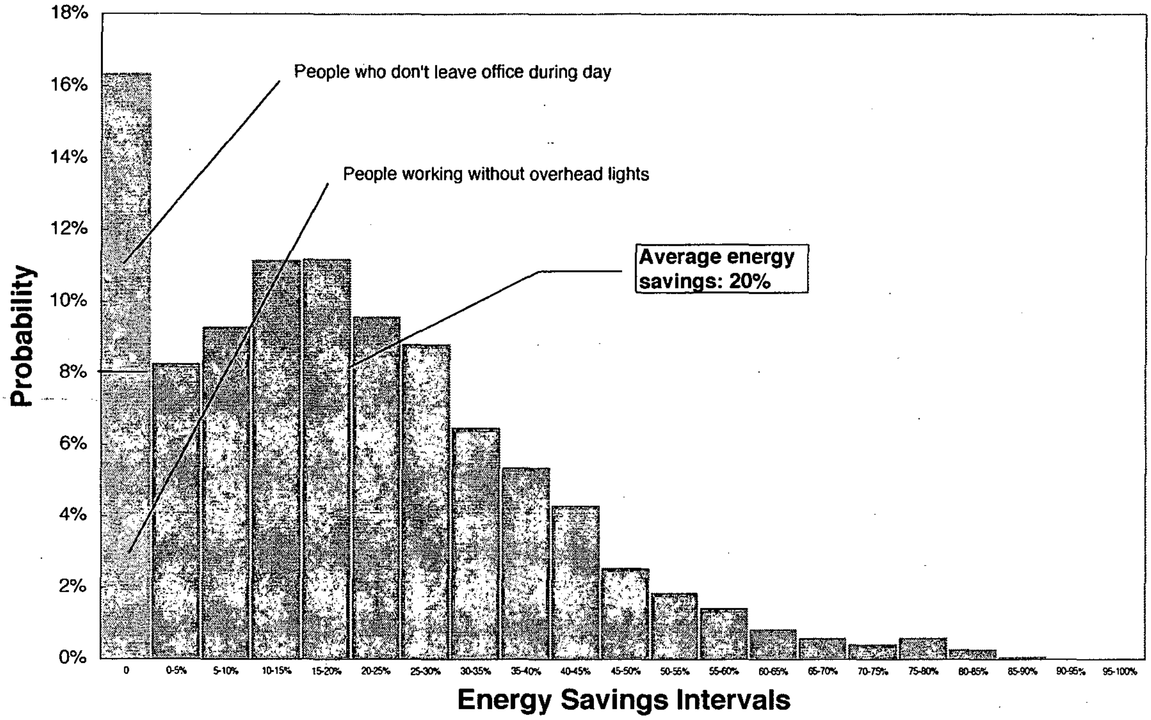

Figure 6. The energy savings from occupant sensors in 21 offices on the 3rd floor for occupied days between June 1 and December 31, 1998. The energy savings by zone-day are binned into 5% intervals with a separate

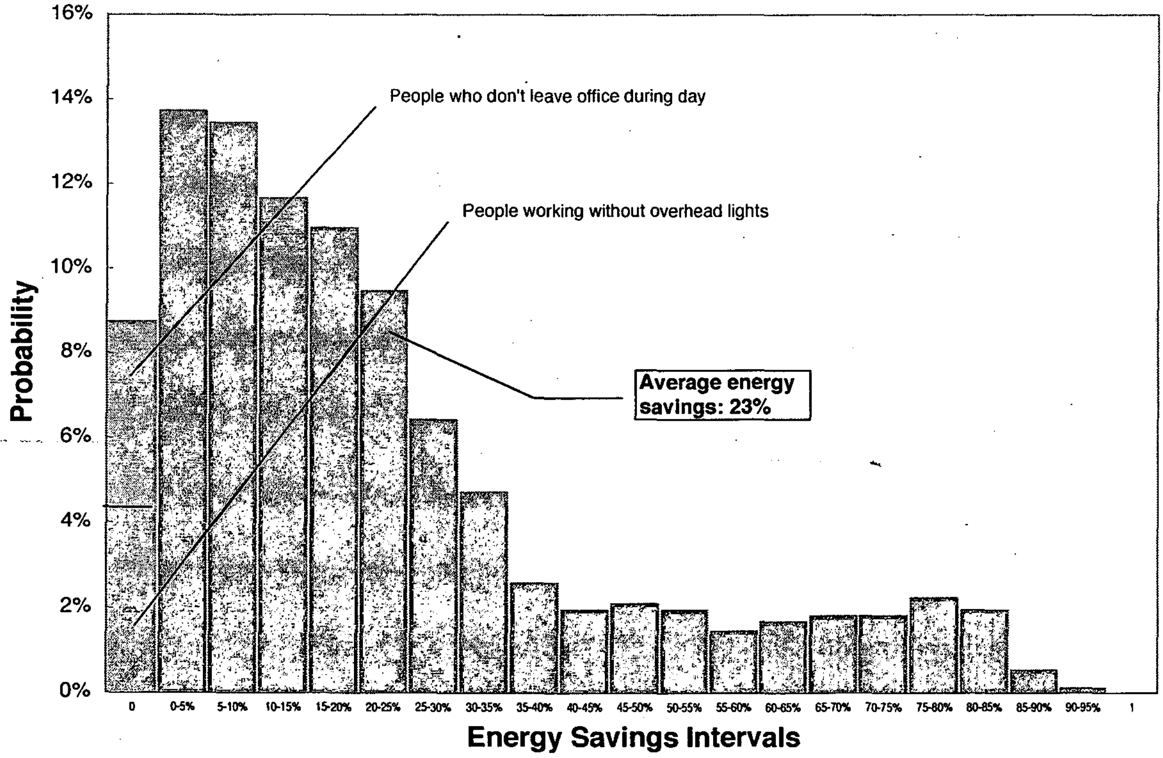

Figure 7. Daily energy savings from occupant sensors in 14 offices on the 5th floor for occupied days between June 1 and December 31, 1998. The energy savings by zone-day are binned into 5% intervals with a separate bin for days with exactly 0% energy savings.

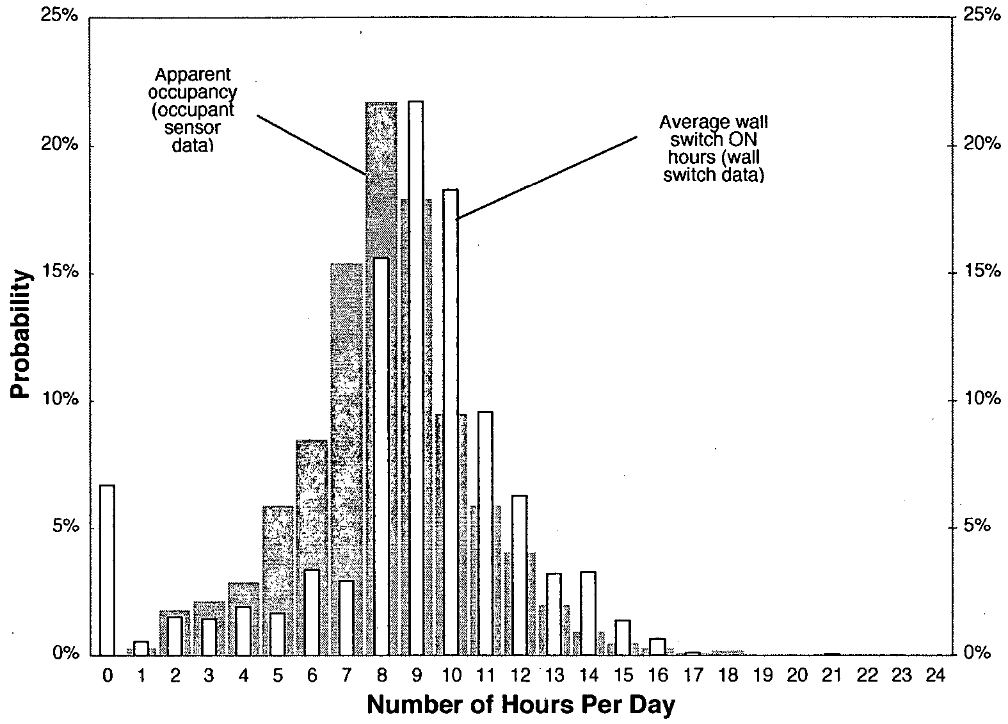

Figure 8. Average lighting ON hours per day (calculated from the wall switch data) for 21 offices on the 3rd floor for occupied days between June 1 and December 31, 1998. Apparent occupancy (occupant sensor data) for the same data set is shown with gray bars. The apparent occupancy includes the occupant sensor time

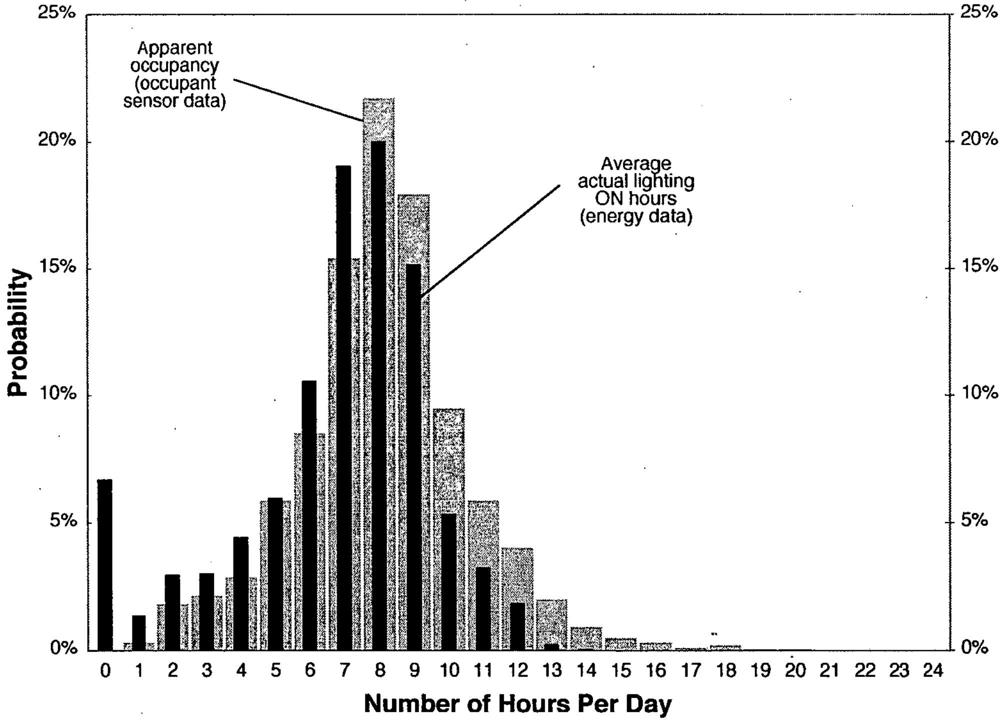

Figure 9. Average lighting ON hours per day for the 21 3rd floor offices (both light switch and occupant sensor ON) for occupied days between June 1 and December 31, 1998. Apparent occupancy (occupant sensor data) for the same data set is shown with gray bars. The apparent occupancy includes the occupant sensor time

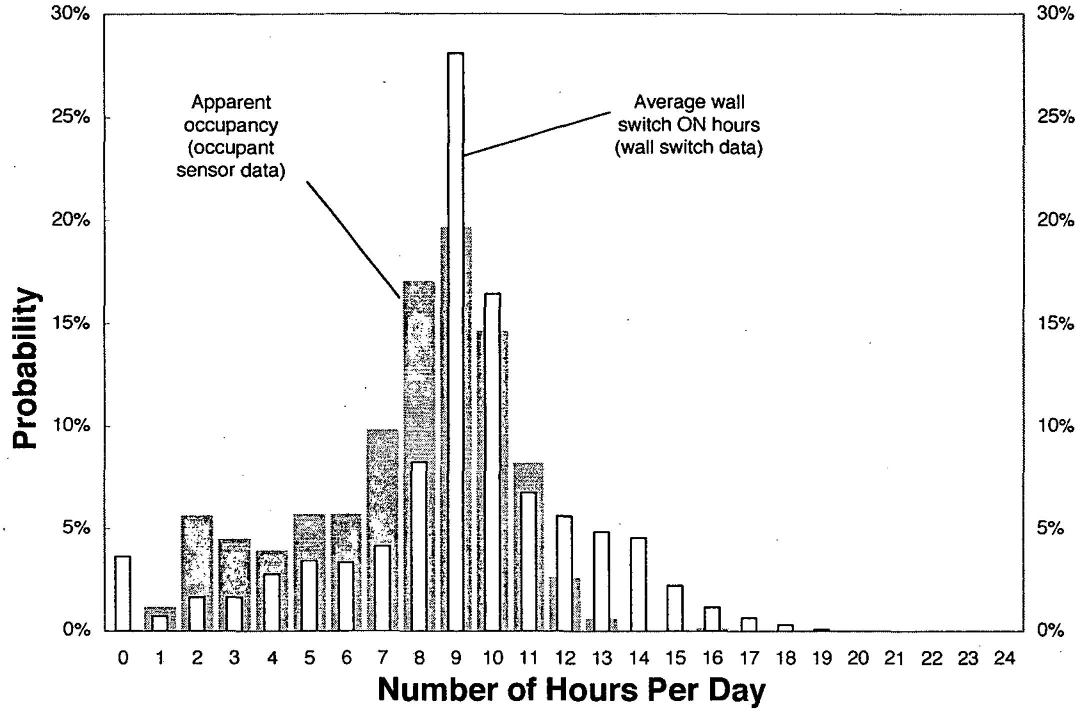

Figure 10. Average lighting ON hours per day (calculated from the wall switch data) for 14 5th floor offices for occupied days between June 1 and December 31, 1998. Apparent occupancy (occupant sensor data) for the same data set is shown with gray bars. The apparent occupancy includes the occupant sensor time delays and

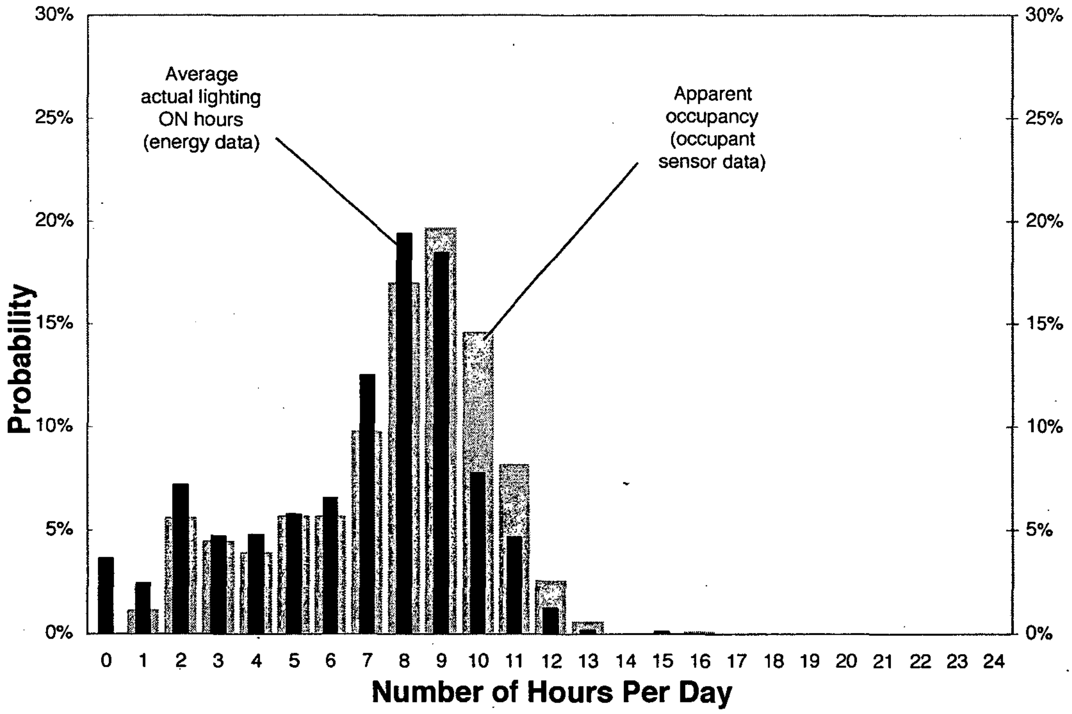

Figure 11. Average lighting ON hours per day for the 14 5th floor offices (both occupant sensor and switch ON) for occupied days between June 1 and December 31, 1998. Apparent occupancy (occupant sensor data) for the same data set is shown with gray bars. The apparent occupancy includes the occupant sensor time delays and therefore overestimates actual occupancy.

this period is zero). In all four of these figures the apparent occupancy (occupant sensor bin data) appears as gray bars behind the lighting ON hours data. The white bars in Figs. 8 and 10 represent lighting ON hours calculated from the wall switch data alone. Note that in the absence of the occupant sensor, the lights are likely to be on for 9-10 hours per day, and are often on as long as 12 hours. Furthermore, the peak of this profile is shifted to the right of the peak of the occupancy profile, which occurs at 8-9 hours day. With the hours of operation reduced by the occupant sensor (black bars in Figs. 9 and 11), lighting ON hours peak at only 7-8 hours per day. This is perhaps the clearest evidence that the occupant sensors reduced hours of lighting operation effectively, causing the lighting schedule to align better with actual occupancy.

It is important to note that the cleaning crews in the building are well trained to turn off lights consistently as they make their rounds through the building at night. In some cases, such as an occupant leaving his/her door locked with the light switch on, the occupant sensor is indeed responsible for the overnight savings. We had no means to keep track of locked rooms and did not include such hours in the analysis.

LIGHT LEVEL ADJUSTMENT-SWITCHING

Bi-level Switching

Figure 12 gives the results of the analysis of the bi-level switching on the base case floor for seven months (June - December 1998). Note that while 19 occupants (63%) use mostly full lighting (all three lamps), 4 (13%) used mostly 2/3 lighting (outer two lamps) and 7 (23%) tend to use only 1/3 (inner lamp). Furthermore, the data indicate that these light levels are chosen consistently for each room, demonstrating that a significant fraction of the occupants in this sample use the bi-level switches consistently to choose less-than-full lighting. Even those occupants who usually use full lighting occasionally use only one switch for the entire day. The inset in Figure 12 shows the percentage of total lighting hours in this sample at each light level. 45% of the lighting zone-hours were at less than full lighting, with 28% at only 1/3 lighting.

We found that the lights were on (at any light level) for an average of 8.4 hr/day, with full lighting averaging 4.7 hours, 2/3 lighting averaging 1.4 hours and 1/3 lighting averaging 2.3 hr/day. A T-test on the lighting ON hours for floors 3 and 5 versus floor 4 showed that even in the absence of occupant sensors the average daily lighting hours for the 4th (base case) floor are not significantly different from the wall switch ON hours for the 3rd floor (8.4 hr/day) and 5th floor (8.9 hr/day). In other words, from this data the occupants' switching behavior appears not to be affected significantly by the presence of occupant sensors. However, the actual measured lighting ON hours per day (both light switch and occupant sensor ON) are significantly lower for the 3rd and 5th floors (6.7 and 6.8 hr/day). As mentioned earlier, the cleaning crew is diligent about turning off lights on all three floors at night.

The overall savings attributable to bi-level switching over the 7-month period amounted to about 23% on a zone-hourly basis if we assume that lights on at any level would translate to lights on at full power in the absence of bi-level switching. The statistics for the 4th floor data are presented in Table 3 below.

Light Level Adjustment-Manual and Automatic Daylight Dimming

The above analysis of occupancy data ignored the additional energy-saving effects of dimming. Figure 13 consists of graphs of occupancy, wall switch, and energy data for four representative perimeter offices, one in each of the four dimming modes (task tuning, manual dimming, direct closed-loop daylighting, indirect closed-loop daylighting). The shape of the each energy curve in Figure 13 is characteristic of the type of dimming control technique that is used in that area. All four examples have the same installed wattage.

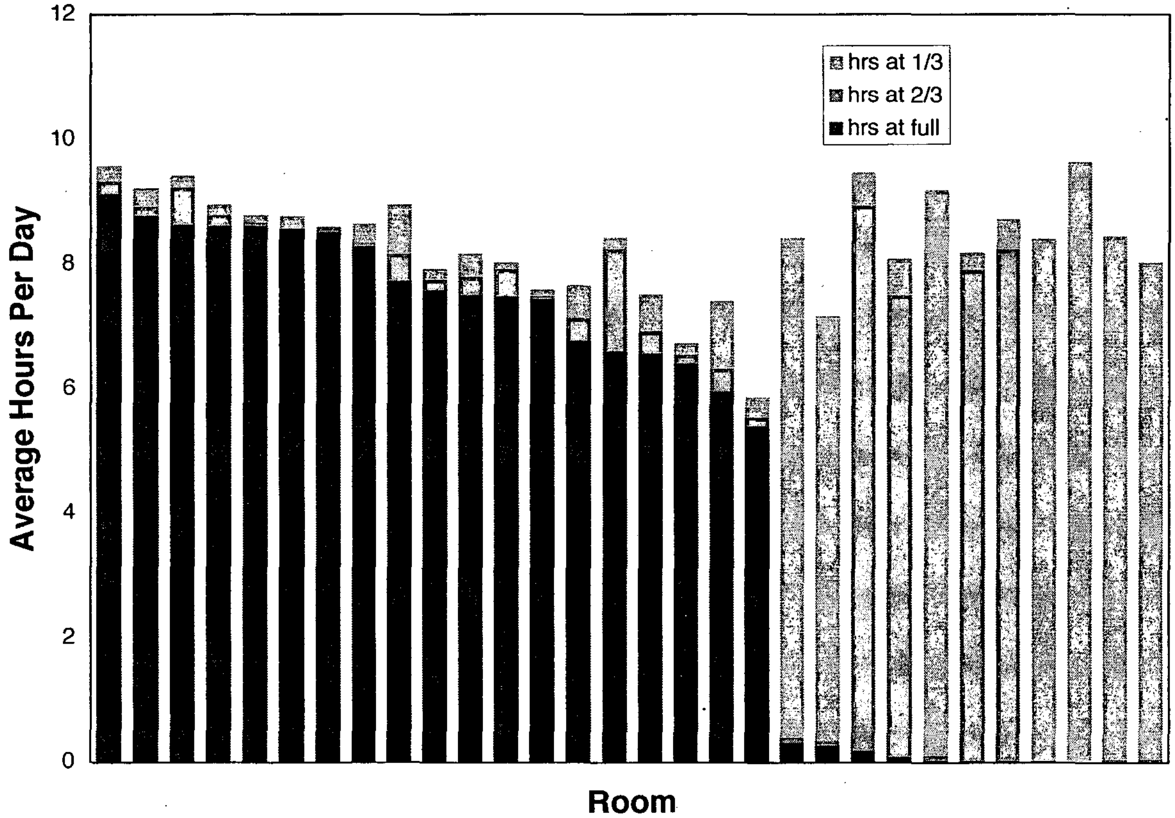

Figure 12. Average hours per day at 1/3, 2/3 or full light levels for 30 private daylit offices on the 4th floor. Data are for 2527 occupied office-days between June 1 and December 31, 1998, sorted by full-light hours.

Varying degrees of occupant sensor activity, passing clouds, or shadows/reflections from neighboring buildings show up as spikes in the energy data, but it is the shape of the underlying curve that is of interest. For the task tuning example (Fig. 13A) the energy curve is lower than on the manual dimming example (Fig. 13B) because that manual dimmer was set to full light. But both curves are essentially flat while the lights are on, because there is no dynamic dimming taking place during the day. In the direct closed-loop daylighting example (Fig. 13C), the energy curve is basically sinusoidal, with the energy use from the electric lights changing in direct response to varying amounts of daylight coming into the space. The low point of the curve for this dimming technique is purely a function of the amount of available daylight, limited only by the ballast minimum output (~20% power).

The indirect closed-loop daylighting example, Figure 13D, has a flat area at the bottom of the energy curve, indicating that the minimum programmed light output was reached and further dimming was prevented. (For this last example, the minimum was set rather high because of the occupant's visual needs. Other possible variations on the dimming protocol are possible by modifying the dimming algorithm in the distributed control system). The ability to control and set the minimum light level is an example of the flexibility of the distributed control system. Had the light sensor been wired directly to the ballasts' low-voltage control leads, the minimum light level would be determined solely by the ballast characteristics as in 13C.

Table 3: Fourth Floor Lighting Statistics—Occupied Days

Zone	*No. of days*	*Hours at Full Light*		*Hours at 2/3 Light*		*Hours at 1/3 Light*		*Hours Lights Off*	
		Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	Average	StdDev.
409	95	9.13	2.05	0.19	0.49	0.25	0.50	14.16	2.07
410	86	7.51	1.62	0.30	0.97	0.37	0.63	15.55	1.29
412	103	8.63	3.28	0.61	1.92	0.18	0.41	14.31	2.66
413	115	0.27	1.00	0.08	0.33	6.83	2.70	16.55	2.54
414	75	6.78	3.04	0.37	1.51	0.51	1.12	16.08	2.58
415	41	7.45	2.18	0.05	0.22	0.10	0.30	16.14	2.15
419	94	0.00	0.00	0.04	0.19	8.41	1.75	15.29	1.68
420	120	0.19	1.02	8.75	3.01	0.53	1.27	14.26	2.31
421	98	8.61	2.26	0.06	0.24	0.11	0.32	14.95	2.22
422	84	0.09	0.39	7.42	1.83	0.58	0.98	15.64	1.58
423	106	8.57	1.59	0.01	0.10	0.19	0.92	14.96	1.24
424	102	7.73	1.69	0.43	0.57	0.79	0.62	14.77	1.95
425	54	7.49	2.77	0.44	1.90	0.11	0.32	15.69	2.69
426	34	0.32	1.36	0.08	0.27	8.02	2.40	15.31	1.40
427	97	0.03	0.16	7.88	1.85	0.28	0.89	15.54	1.55
428	106	0.02	0.14	0.01	0.07	8.38	2.14	15.33	2.14
429	108	8.62	2.16	0.17	0.42	0.16	0.39	14.79	2.09
430	119	6.42	2.75	0.13	0.33	0.18	0.41	16.99	2.69
439	101	0.00	0.00	0.05	0.21	7.99	1.72	15.70	1.66
440	39	8.29	5.21	0.05	0.22	0.31	0.61	15.08	5.05
441	79	8.52	1.52	0.06	0.25	0.03	0.16	15.12	1.40
442	82	6.61	3.03	1.65	2.89	0.17	0.38	15.30	1.54
443	63	7.58	2.92	0.17	0.46	0.17	0.38	15.79	2.79
444	77	0.04	0.19	0.06	0.57	9.08	2.58	14.55	2.31
445	72	0.02	0.15	8.23	2.53	0.47	1.21	15.01	2.14
446	31	5.42	3.53	0.13	0.34	0.32	0.65	17.86	3.17
448	88	6.57	3.10	0.36	1.26	0.58	1.75	16.22	2.85
450	74	8.77	3.59	0.15	0.43	0.30	0.57	14.52	3.51
451	100	0.01	0.10	0.00	0.00	9.64	1.54	14.09	1.51
452	84	5.97	3.81	0.36	1.31	1.08	2.22	16.33	3.25
Total	2527	4.69	4.37	1.40	3.10	2.32	3.71	15.32	2.42

Figure 13D is particularly interesting in that it also shows the superimposed effect of daylight dimming and occupant sensing on the electric lighting power usage. Graphs showing the successful integration of daylighting and occupant sensing in private offices have not been reported elsewhere. This figure provides evidence that advanced lighting control techniques that combine several control strategies simultaneously can work well in private offices.

Figures 14, 15, and 16 show the average energy use in individual offices under three of the four dimming scenarios, derived as described in Methods. The offices (zones) in each graph are ordered by measured energy use. The normalization constant in these figures is the calculated full-light energy use for the wall-switch ON hours in each office as described in Methods. The first column for each office shows the energy use that would have occurred with the occupant sensor as the only control method. The second column shows the energy use with dimming alone, and the third column shows the actual measured energy use with both occupant sensing and dimming (a wall switch is present in all three scenarios). Note that the savings from occupant sensing and from dimming are not independent, and thus are not additive.

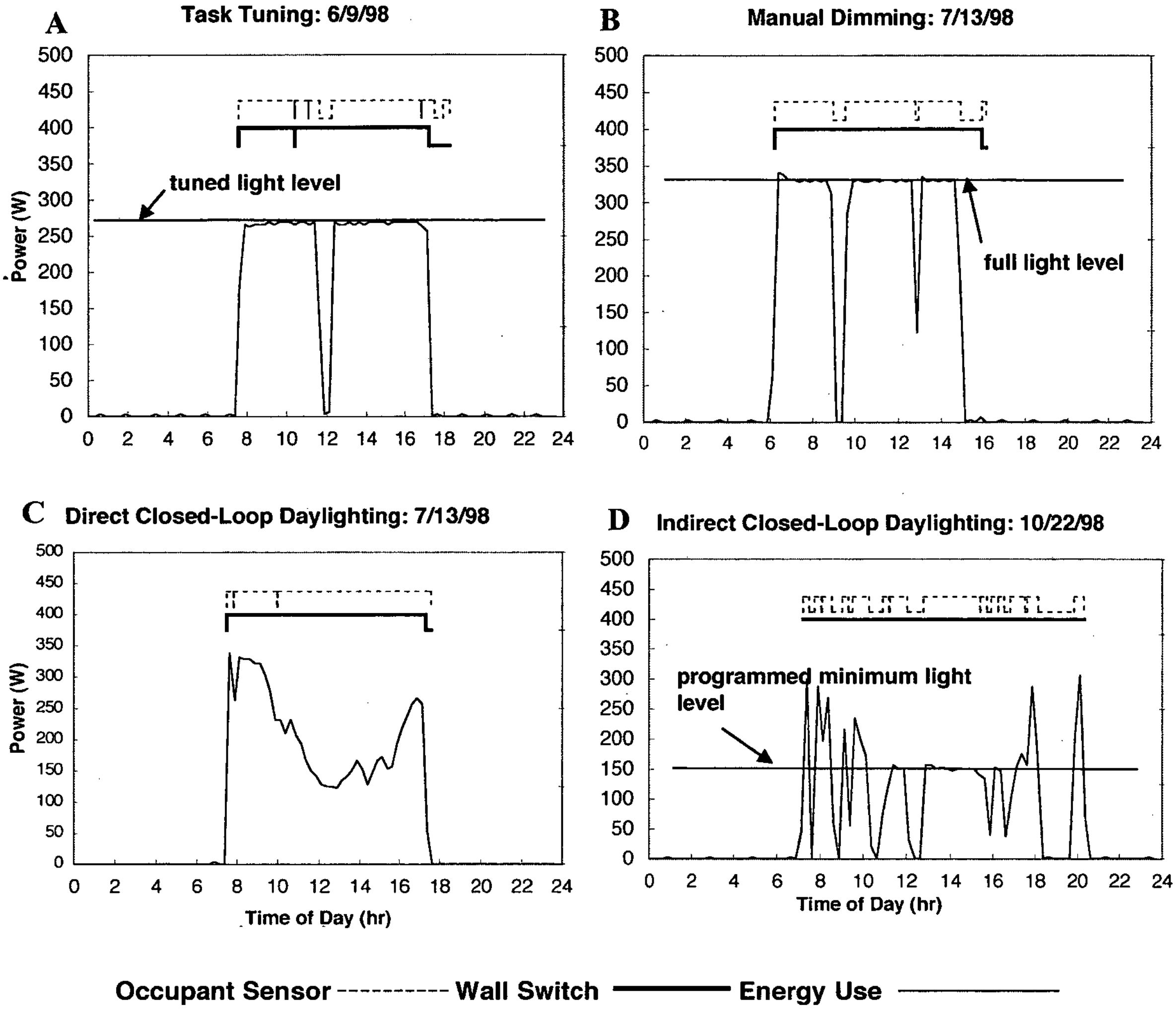

Figure 13. Lighting power, wall switch data and occupant sensor activity as a function of time of day for four same-sized offices using four different dimming scenarios. (A) shows task tuning for a day in June, (B) shows no reduction in lighting power for an undimmed room (equipped with manual slide dimmer) in June, (C) shows change in lighting power as a function of daylight during the middle of a day in July, (D) shows a pre-programmed minimum lighting level and the effect of both daylight dimming and occupant sensor activity on

In Figure 14 (Task Tuning) the dimming level was set by the research team at the start of the study, thus the height of the second column reflects room geometry and installed lighting level rather than daylight availability or occupant behavior. The difference between the first and third columns ("os only" vs. "os + dimming") is a measure of the energy savings achieved by dimming in the presence of occupant sensors.

These three graphs illustrate the fact that the actual energy savings from controls depend largely on how individuals use their offices. The heights of the columns indicate the relative importance of each control technique to energy savings in the offices in our sample. For example, in offices where occupancy is low (low "os only" column), the occupant sensor is the most important factor in energy savings. For offices where occupancy is particularly high (high "os only" column), the dimming, regardless of method, has the greatest influence on energy use.

For comparison purposes, the energy use due to each of the three control strategies plus bi-level switching is presented in Table 4. The third column of Table 4, "OS + Dimming (actual)," gives the average fraction of full-light energy used by each dimming scenario studied, derived from the measured energy use data.

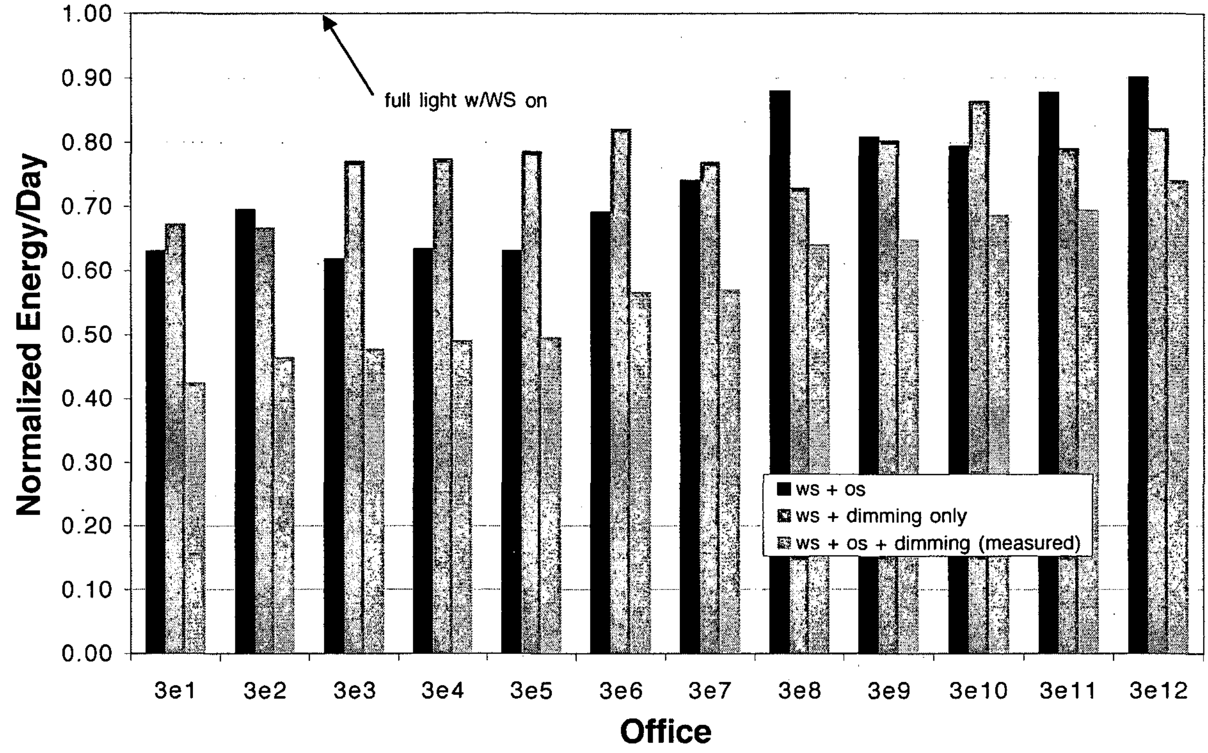

Figure 14. Task Tuning: Average normalized lighting energy use for 12 private offices using task tuning for occupied weekdays for the period June-December 1998 (3rd floor East). 2nd column reflects room geometry.

Note in the last column of Table 4 that the design light level is not the same for the different dimming methods. The design light level has a significant effect on the energy savings achieved, so it is important to take it into consideration when comparing the numbers in the rest of the table. Had the design light level in the 5th floor west been the same as the much lower target in in the 3rd floor east, the savings in the 5th floor west would have been considerably greater.

The effect of the higher design light level in the 5th floor west can also be seen in Figure 13. In Figure 13C, the low point of the energy curve is not limited by a preset minimum light level as is the low plateau of the energy curve in the Figure 13D. (The two charts can only be compared for the shape of the curve, because their data were recorded on different days.)

Task Tuning

In the Phillip Burton Federal Building, we were able to achieve very significant energy savings simply by tuning the lighting level. Table 4 shows that, used alone, occupant sensing would have saved about 26% (1.0 - 0.74 = 0.26) in the task tuning area and dimming alone would have saved 23%. Together (occupant sensing with dimming), the savings were 43%. Figure 13A and 13B compare the effect of task tuning in one office to an undimmed office in the manual dimming area. Had the building used a more appropriate light level in the original lighting design, such a large savings due to task tuning alone would not have been possible. However, it is fairly common practice to locate 2X4 parabolic troffers in a uniform 8' grid in open areas and in a symmetric pattern in private office ceilings to minimize design effort and to accommodate the changing needs of typical offices. Savings from task tuning would be possible in many office spaces if the ballasts were dimmable.

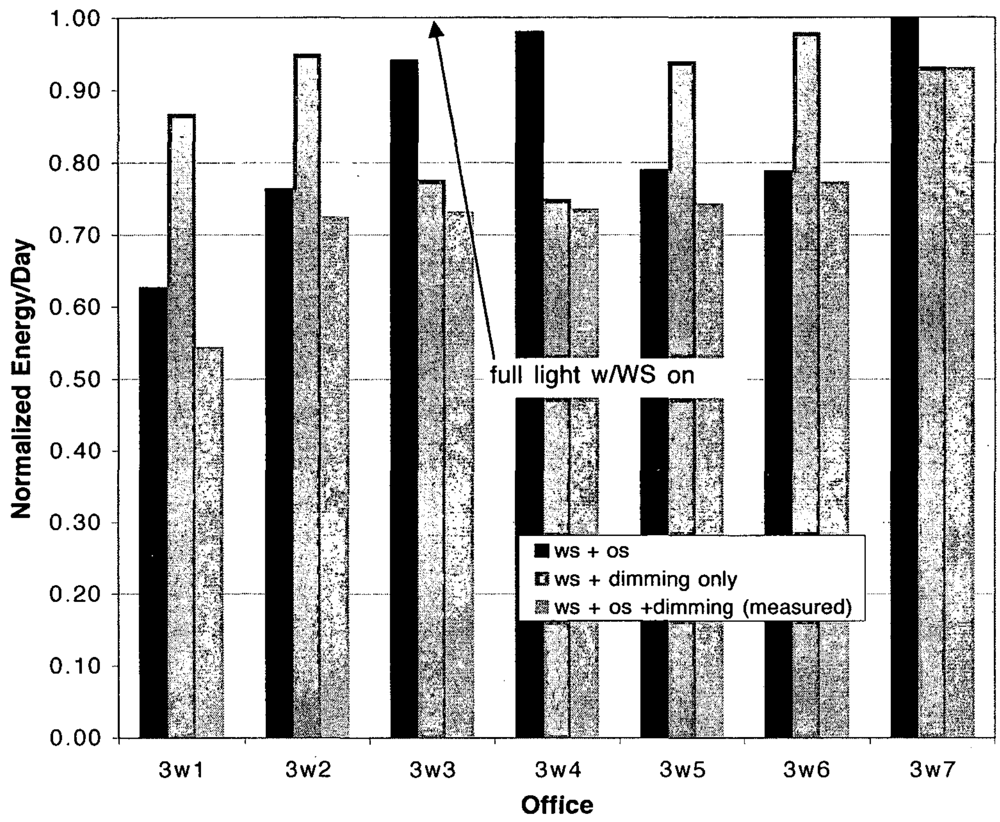

Figure 15. Manual Slide Dimmers. Average normalized lighting energy use for 6 private offices using manual slide dimmers for occupied weekdays for the period June-December 1998 (3rd floor West). 2nd column

Table 4. Energy Use Comparison Using Different Control Strategies

Light Level Adjustment Method	*OS Only*	*Light Level Control Only*	*OS + Dimming (Actual)*	*Design Light Level*
Task Tuning (3 east)	0.74	0.77	0.57	50fc (550lux)
Manual Dimming (3 west)	0.77	0.91	0.71	n/a
Automatic Daylight Dimming (5 west)	0.75	0.73	0.54	75fc (825lux)
Bi-Level Switching	n/a	0.77 (actual)	n/a	n/a

Manual Dimming

For the area equipped with manual dimmers, Table 4 indicates savings of 9% by dimming alone and 29% by occupant sensing with dimming based on measured daily energy use and lighting ON hours. These savings due to dimming may reflect artifacts such as characteristics of the dimmers or variations in usage of the switch/dimmer combination. The 15-minute data show that almost all apparent dimming is either between 90 and 100% of full power, or between 0 and 10% of full power. Such numbers could be due to users sliding their dimmers all the way up or down, and missing the endpoints of the slider, rather than using their wall switches. The small amount of data that falls between 10% and 80% of full power appears to be due to lights turned off at a random point during a 15-minute interval. We are continuing to analyze this data.

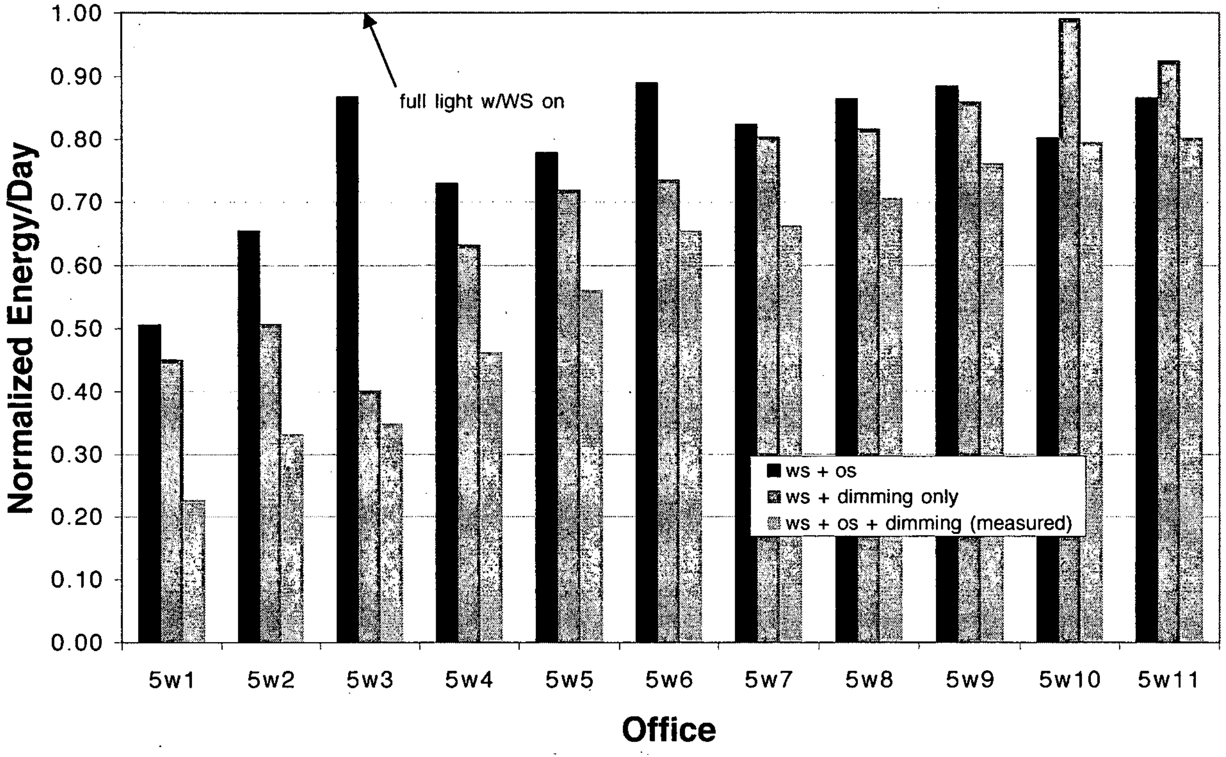

Figure 16. Automatic Daylight Dimming. Average normalized lighting energy use for 10 private offices using automatic daylighting for occupied weekdays for the period June-December 1998 (5th floor East). 2nd col-

Under somewhat different circumstances (offices both with and without windows, a different baseline assumption, more types of dimmers, and more extensive interaction with occupants), Maniccia et al.[4] found 6% savings due to manual dimmers when the manual dimmers were located on desktops as well as on the wall. It may be that people would have used their manual dimmers differently in the present study had it been possible to adjust the light levels from their desks, either by desk-mounted dimmers as in the Maniccia study or by hand-held remote dimmers. (Hand-held remote dimmers are installed in a sample of zones in the testbed, but their use is not covered in this paper.)

Daylighting

In the automatic daylighting area dimming appears to save a little more than occupant sensing (27% from dimming alone vs. 25% from occupant sensing alone). Together, occupant sensing plus dimming save 46%. It is important to emphasize that these numbers are strongly affected by the design light level given in Table 4. The savings would be significantly greater in the daylit areas had the design light level been as low as that in the task tuning area.

DISCUSSION

Our results indicate that occupant sensors save an average of 23-26% of lighting energy on occupied days in private offices at this installation. These savings were determined relative to a moving baseline that reflects an accurate calculation of what the lighting hours would have been had the lights been operated only by the wall switch. Because occupancy varies from day to day, the energy savings due to occupant sensing on a given day can easily range from 0 - 40% or more. On average the occupant sensor reduced the lighting ON hours from about 9 hours per day to about 7 hours per day.

The frequent occurrence of days with 0% energy savings in the occupant sensor analysis deserves more comment. There are two circumstances that can cause such results. By examining the data from individual days, it is clear the preponderance of days with 0% savings occur when the occupant apparently does not leave during the day for periods longer than the occupant sensor delay, so that the occupant sensor does not switch off the lights. About 10% of days on the 3rd floor and about 6% of days on the 5th floor fit this category. In addition, occupants will occasionally work the entire day without using overhead lights at all. Days in this category have no energy savings (from either occupant sensing or light level reduction) simply because the occupant would not have used any energy regardless of the control system. This seems to occur 4-7% of the time. People have been observed working in daylit offices (offices with windows) without overhead lights,[3,4] and informal comments by the occupants in this study indicate that they do work sometimes without their overhead electric lights.

Although the occupants can, and usually do, switch off the lights manually when leaving at the end of the day, the occupant sensor will switch the lights off 15-20 minutes afterward should they forget. We cannot refute or confirm the claim[3] that people working without occupant sensors tend to be more frugal about turning lights off when leaving their offices for long time periods than people with occupant sensors. However, based on our observations of the switching patterns of the base case floor, it does not appear that the occupants of this building turn off their overhead lights when leaving the office for short time periods during the day.

The use of bi-level switching by the occupants of the base case floor was unexpected and has not been reported elsewhere. Pigg et al.[3] reported very little use of bi-level switching in their installation. It is reasonable to assume that the presence of daylight in these offices had an influence on which of the four (off, 1/3, 2/3, on) possible light levels was selected by the occupants. However, an initial examination of the data revealed no correlation of the data with the orientation of the offices.

By comparison with the bi-level switching results the use of manual dimmers seems surprisingly small. Both control strategies allow user control of light levels, and their position in the room is similar. Wall-mounted dimmers may be less convenient to use than bi-level switches or dimmers located on the desktop.[4] It may be easier to choose a single switch than to adjust a dimmer to a particular position. We can also speculate that manual dimming and switching results might have been affected by the presence or absence of task lighting. Preliminary results from a survey in progress indicate that there may be such an effect.

Arguably the most convenient of the dimming options, automatic daylighting shows the largest savings compared with task tuning and manual dimming even with a much higher design light level. Clearly the savings from this method would have been much greater had the design light level been the same as for the 3rd floor offices. On the other hand, the programmable output in these offices allowed us to tune the output to the specific lighting needs of the occupants in this area, an added user benefit that should not be overlooked (see "Office Culture" below).

What affects a user's ability to make the most effective use of controls? Wyon[11] informs us that "bringing the user back into the loop is far more important for health, comfort, and productivity than optimising uniform conditions to accord with group average requirements." To make effective use of their controls he proposes that users need three essential elements: information, insight, and influence. "They must understand the way the building works and the consequences of their actions, so they must be given Insight. They must learn to use the control delegated to them, [for which] they must be given Information. Only when they have both Insight and Information can they be given Influence." In this testbed the users were given Influence in the form of the controls themselves only in the areas with manual dimming and bi-level switching controls; both Insight and Information were significantly lacking in all areas. In hindsight, had the occupants been given more information and insight into the lighting controls from the start, the results from the manual dimming controls might have been more significant. More users might have used their controls had they been introduced to the ways in which they could adjust their lighting environment, not only by using controls, but also by experimenting with the positions of their blinds.

Workers who stay in their offices all day long stand to benefit the most from dimming strategies, while those who come in and out of their offices frequently obtain the greatest energy savings from occupant sensors. On the whole, dimming can add significantly to the savings achieved by occupant sensing, saving up to a conservative 26% even without occupant sensing and up to 46% with occupant sensing. As noted above, manual dimming using wall dimmers provided little significant savings in our sample. We have yet to determine whether or not better instructions in their use would have affected this result.

We have observed that some occupants of our testbed tend to work regular hours, while others keep very unpredictable hours based on their project deadlines or case load. Also, many occupants of private offices do not spend a lot of time in their offices, and our casual observation is that the tendency to be out of the office seems to relate to the type of work that they do.

The two automatic daylighting systems we examined differed primarily in the ability to program the response of the ballasts through a remote system. Depending on the needs of the building occupants, the programmable system could save more or less energy than the directly controlled system. It is more intellectually challenging to set up the programmable system, as well as being more costly in wiring and commissioning, but it has additional benefits that mitigate the extra expense to some extent. For example, the ability to adjust the lighting levels from a remote location in response to an occupant's request can save building maintenance staff considerable time in responding to complaints.

Office culture

Working groups in GSA, as in most organizations, tend to be clustered in one part of the building or another. This arrangement facilitates communication between team members, but concentrates islands of occupant behavioral patterns according to the particular type of tasks performed. We have noticed, for example, that in the part of the building where the GSA attorneys sit, the lighting level must be set higher than in other parts of the testbed. When in their offices, attorneys work long hours reading documents that are in fine print, have been faxed, or are simply old and deteriorated. In contrast, graphic designers use computers and prefer lower light levels to keep glare at a minimum. Some types of job require the occupant to be out of the office frequently, while others require more desk time. These differences make it difficult to compare different areas of the test bed against each other. The use of the moving baseline we have described has largely eliminated this difficulty with respect to occupancy, but the differences in light level requirement are more difficult to analyze. Because this is a working building, we chose to accommodate the needs of the building occupants by giving them the light levels they required, which varied according to the type of work they were doing, rather than adhering to a rigid experimental protocol.

The building management and support personnel have a significant effect on the way the occupants use their lighting controls. In the Phillip Burton building, the building manager at the time of the startup of the experiment had been very active in encouraging his staff and the building occupants to shut off their lights when they leave an area. In addition, there are posters around the building encouraging GSA workers to conserve. As a result, the savings from occupant sensing may be somewhat lower than would be seen in other buildings.

CONCLUSION

In a major test of different lighting control technologies in a typical office building, we compared the energy savings and effectiveness of various control techniques in private offices. Using a rigorous analytical method that compared measured energy use in offices with occupant sensors versus baseline use calculated using wall switch operation only, we found that occupant sensors saved 20-26% lighting energy compared to (single-level) manual switching alone. These savings occur because of intermittent vacancies throughout the day. In offices where automatic daylight dimming controls were installed and properly commissioned, additional savings of 21% were obtained over a seven-month period, even in an area with unusually high minimum lighting requirements. Dimming the lighting system to desired task levels (task tuning) also resulted in significant (17% additional) energy savings in overlit areas. On the base case floor, where only bi-level switches were installed, we found significant usage of only one switch resulting in a 23% savings over single-level switching- an unexpected result with implications for building code requirements.

We found that the energy savings due to occupant sensing vs. dimming depended on the behavior of occupants. In offices whose occupants tended to stay at their desks all day, dimming controls saved more energy, and vice versa. The lighting requirements of occupants appear to to be related to their type of work.

In summary, including the effects of switching, occupant sensing, and light-level reduction controls, the four scenarios for which we had significant data yielded 23% savings for bi-level switching alone, 43% savings due to occupant sensing with task tuning, 29% savings from occupant sensing with manual dimming, and 46% savings from occupant sensing with automatic daylighting controls. The savings from automatic daylighting are limited for this study by the high light levels required by the occupants of the particular office areas studied.

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ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720

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