Saving Energy with Highly-Controlled Lighting in an Open-Plan Office

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ABSTRACT

An installation in a Federal building tested the efficacy of a highly-controlled, workstation-specific lighting retrofit. The study took place in 86 cubicles in an open office with low levels of daylight. A direct/indirect pendant luminaire with three 32 watt lamps, two DALI ballasts, and an occupancy sensor provided both task and ambient light for each cubicle. All three lamps turned on and off according to occupancy on a workstation-by-workstation basis. Field measurements demonstrated 40% lighting energy savings compared to a baseline that represents a typical Federal building retrofit; the baseline has a lighting power density of $0.83W/ft^2$ and no advanced controls. A photometric analysis found that the installation provided higher desktop light levels than the baseline did, while an occupant survey suggested that occupants preferred the lighting system to the baseline.

Disclaimer

Introduction

Lighting systems consume about 25% of US commercial building electricity (DOE 2007). Advanced lighting controls provide the most practical and economical means to dramatically reduce the energy footprint of commercial building lighting systems and make building electrical systems more responsive to the real-time price of energy (NBI 2003). However, efficient, highly-controlled lighting for open-plan offices has always been a challenge for facility designers. This work describes one emerging solution – *workstation-specific (WS) luminaires* - that offers tremendous potential advantages in terms of both energy efficiency and providing luminous conditions that reflect occupant needs in open-plan offices.

WS luminaires are designed to provide highly-efficient, customizable lighting for cubicles in open-office areas. In a typical WS system, one luminaire per workstation provides dimmable, independently controllable downward task and upward ambient light. Fixtures are typically equipped with built in occupancy sensors and/or photocells and networked together using a microcontroller that intelligently controls lights in accordance with operational requirements. Occupants can set and adjust light levels according to individual preferences.

This report describes an installation with WS luminaires at the General Service Administration's (GSA's) Philip Burton Federal Building in San Francisco and summarizes the measured energy savings, lighting conditions, and occupant responses realized in this demonstration.

Background

Studies have found that occupants prefer direct control over their lighting and select a wide range of light levels when given this control (Boyce, Eklund, & Simpson 2000; Newsham, Veitch, & Duval 2004; Veitch & Newsham 2001). This suggests that WS lighting with personal controls could provide major benefits to open-office occupants. A recent study of 86 cubicles found that shutting off task lights based on daylight, occupancy, and personal controls saved close to 70% of daytime energy compared to an uncontrolled baseline (Galasiu et al. 2007). A smaller study found 32% savings from occupancy sensors and personal controls alone (Galasiu & Newsham 2009). The choice of baseline of course has a fundamental effect on savings.

In 2007, GSA commissioned Lawrence Berkeley National Laboratories (LBNL) to run a small pilot study to identify the energy savings and cost-effectiveness of WS lighting in a typical GSA building. Researchers found that one type of WS luminaire that extinguished downward task lights in unoccupied cubicles used 53% less energy than the uncontrolled baseline while providing higher desktop light levels (Rubinstein et al. 2008).

Current Demonstration

Demonstration Area

Based on the outcome of the pilot study, GSA elected to build-out a larger demonstration area in the same building (San Francisco's Philip Burton Federal Building). WS luminaires were installed in 86 open-office cubicles in three zones, as shown in Figure 1. The building has a deep floor plan, and only the east zone receives significant levels of daylight.

Floor areas were calculated to include both the cubicles and corridors in each zone, with the exception of a few corridors lit by recessed lights. A few solitary recessed lights provide emergency lighting and were not taken into account. Corridors along the outside edges of the zones were included if they did not contain other luminaires and excluded if they did. A takeoff resulted in a total floor area of 8200ft^2, or about 95ft^2 per workstation.

Typical workstations are 7ft by 9ft in plan, with large cabinets lining the walls in varying configurations (see Figures 2 and 3). Partitions are 81" high between rows of cubicles; between cubicles partitions usually drop to 66" and/or 54" for part of their length.

Figure 1. Workstation Locations

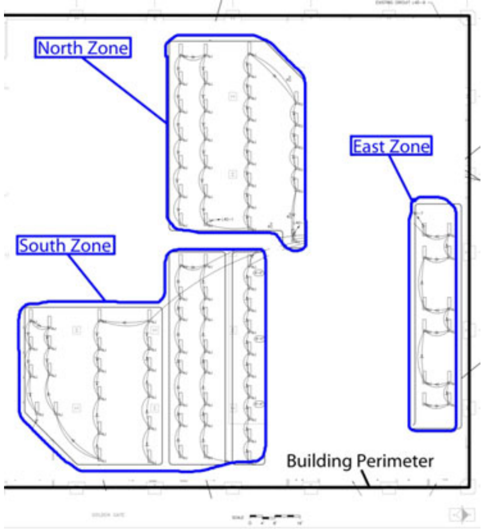


Figure 2. Cubicle Plan

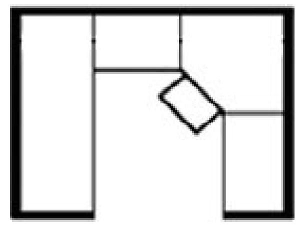


Figure 3. Cubicle Interior

Workstation-Specific Luminaires

A parabolic, direct/indirect luminaire illuminates each workstation. Each luminaire has three 32W T-8 lamps (color temperature 4100K), two controlled by a dimmable ballast for downward task lighting and one controlled by a separate dimmable ballast for upward ambient lighting. Fixtures include occupancy sensors as well as built-in photosensors, which were not activated during this study due to the low levels of available daylight. A lighting controller (Lumenergi Lighting Measurement Control System (LMCS)) records the power level commanded to each ballast at 2 minute intervals.

Out of a range of possibilities, a bold and somewhat extreme occupancy-based control strategy was selected for this study: both task and ambient lamps switch on and off according to individual cubicle occupancy as determined by the fixture-integrated occupant sensor. Lights turn on when someone enters the cubicle and fade off after the cubicle has been unoccupied for specified timeouts. Previous studies have typically left ambient lights on in unoccupied cubicles during work hours (Galasiu & Newsham 2009; Galasiu et al. 2007; Rubinstein et al. 2008).

All the ballasts were initially programmed to default settings with specified power levels and timeouts (at default, luminaires operate at 92W and have a 20 minute timeout at 92W and a 10 minute timeout at 61W before fading off). At the end of the study, approximately 80% of the workstations still used default settings. Adjustments generally increased or decreased power levels or increased timeouts.

Default settings remained prevalent largely because occupants had only indirect control over their overhead lighting. To adjust light levels and timeouts, they had to request changes, which were implemented by a third party. GSA intends to add personal controls in the future and in subsequent WS installations. Previous studies suggest that adding personal controls will both reduce energy use and increase occupant satisfaction (Boyce, Eklund, & Simpson 2000; Galasiu & Newsham 2009; Galasiu et al. 2007; Veitch & Newsham 2001).

Additional Light Use

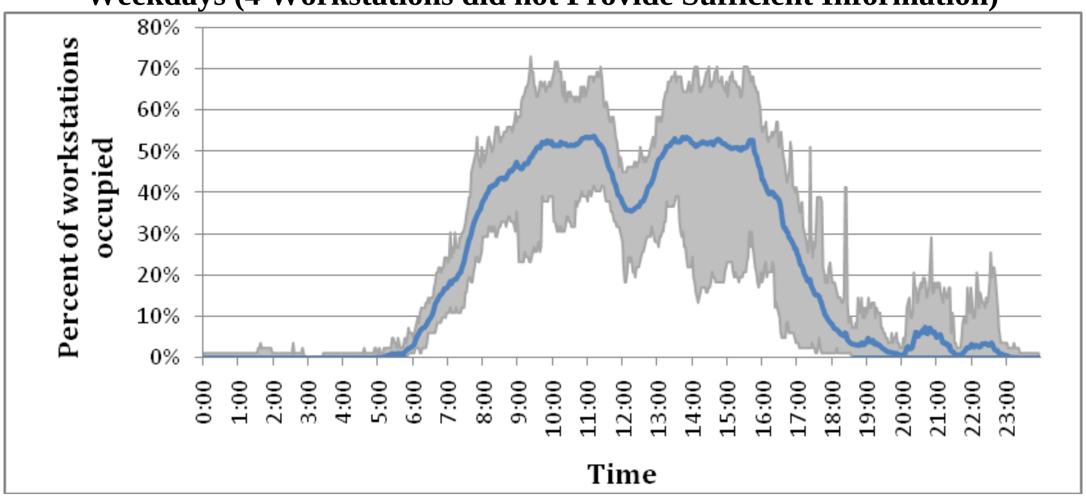
Two factors increased light use in the WS study area beyond that specified by the control settings described above. First, the ambient lamps in 11 workstations were set to turn on from 7 to 10 p.m. every weeknight, followed by their usual timeouts. Second, three luminaires had significant performance issues that resulted in lamps staying on far longer than intended.

Occupancy sensors that triggered in unoccupied cubicles contributed to increasing energy use as well, though this effect could not be quantified since false triggering was not identifiable in the data. Several sensors were observed to trigger when someone walked by in the hallway.

Occupancy

The LMCS system records each ballast's status every two minutes. Since occupants cannot manually override controls, subtracting out timeouts translates these records directly into occupancy levels, presented in Figure 4. These results depend on the sensors working correctly and only capture unoccupied periods of time that last long enough for the lights to drop below their operating power (typically 20 minutes).

Figure 4. Mean, Maximum, and Minimum Occupancy Levels for 82 Workstations over 32 Weekdays (4 Workstations did not Provide Sufficient Information)



Occupancy levels are fairly low. Average occupancy peaks below 55%, and the peak daily occupancy averages roughly 63%. Twenty-two of the 82 workstations have less than three hours of occupied time on at least half the days studied. Occupancy patterns also vary significantly day to day. Relatively low and highly variable occupancy levels are an ideal environment for WS luminaires, which capitalize on individual absences.

Baseline Case

The baseline case, called "GSA retrofit" and installed on another floor in the same building, conforms to the current GSA lighting standard and is typical of GSA retrofits in the past five years. Energy use for GSA retrofit was calculated rather than measured. Layout, daylight levels, surface materials, and type of work performed are largely identical in the two areas. Occupants in both areas work for GSA.

In the GSA retrofit system, pendant-mounted, direct/indirect luminaires with ON-OFF switching controls at the room level only and a one-lamp cross section are installed in continuous rows, with 8ft spacing between rows. Luminaires have 32 watt T-8 lamps and GE Ultramax normal ballasts, with an input power of 53 watts per 8ft length of luminaire. Lights are assumed to stay on for 16 hours each day. These long lighting hours were verified by direct circuit monitoring during the 2007 pilot study and make the office an ideal place to save energy with WS luminaires. GSA retrofit has a calculated lighting power density (LPD) of 0.83W/ft^2 and a daily energy use of 13.25W-h/ft^2/day. It provides relatively low desktop light levels.

Undercabinet Lights

Energy numbers throughout this report refer to overhead lighting only and exclude undercabinet and desktop task lights for both systems. In addition to overhead fixtures, each workstation contains up to three built-in undercabinet lamps, with an average installed power per workstation of about 40W. Energy use by undercabinet lights and table lamps could not be measured due to outdated plug load circuit diagrams, but informal observation suggested that a substantial minority of occupants keep these lights turned on for long periods of time.

In order to make overall comparisons valid, we have ignored undercabinet light use patterns and assumed that undercabinet light use does not very significantly between WS and GSA retrofit occupants. We believe this approach is conservative for the WS system, as GSA retrofit provides lower illuminance levels and occupants with lower light levels are expected to use additional task lights more frequently.

Energy Analysis

Methodology

The central processor records each ballast's status every two minutes in the form of an input command that corresponds to a DALI number. The system then uses a lookup table to convert the ballast command into the estimated power draw of the ballast. To create the lookup table, LBNL performed bench-top measurements on the installed fixture configuration at a variety of input levels. The resulting estimated installed LPD for the WS system is 118 watts/workstation (1.23W/ft^2), default is 92 watts/workstation (0.97W/ft^2), and standby is 4.5 watts/workstation (0.05 W/ft^2). The occupancy sensors must draw power at all times, preventing standby power from dropping to zero.

After eliminating weekends, holidays, and incomplete or missing data, 32 workdays in August, September, December, and January made up the final data set. Estimated power was summed over the ballasts in all 86 workstations to obtain the total power draw.

Periodic direct power measurements on a circuit with 29 WS luminaires exceeded power estimates associated with the data acquisition system, though the difference dropped significantly during maintenance work after the study period. We hypothesize that certain lamps stayed on at low levels even when recorded as turned off; the control system's structure makes this scenario a possibility. While verifying power estimates is highly desirable, onsite observations have led us to believe that our bench-top measurements accurately reflect the installed system. This study can therefore be seen as an extrapolation from recorded ballast commands to the power levels that would have been associated with those commands, had they been carried out correctly.

Results

Estimated LPD over the 32 days studied is presented in Figures 5 and 6. Even though the installed LPD is 1.23W/ft^2 and the default is 0.97W/ft^2, the actual LPD is much lower throughout the day. The average LPD peaks at approximately 0.66W/ft^2, peak LPD averages 0.72W/ft^2, and the average LPD during working hours (6am-6pm) is 0.52W/ft^2. Security and custodial rounds, in which very short occupancy periods turn lights on for specified timeouts (typically 30 minutes), cause power density spikes in the evening. The average daily lighting energy density is 7.92W-h/ft^2/day, which corresponds to 40% savings compared to GSA retrofit.

Figure 5. Lighting Power Density Over 32 Weekdays (Bold Line is the Mean, Shaded Areas Extend One Standard Deviation in Each Direction)

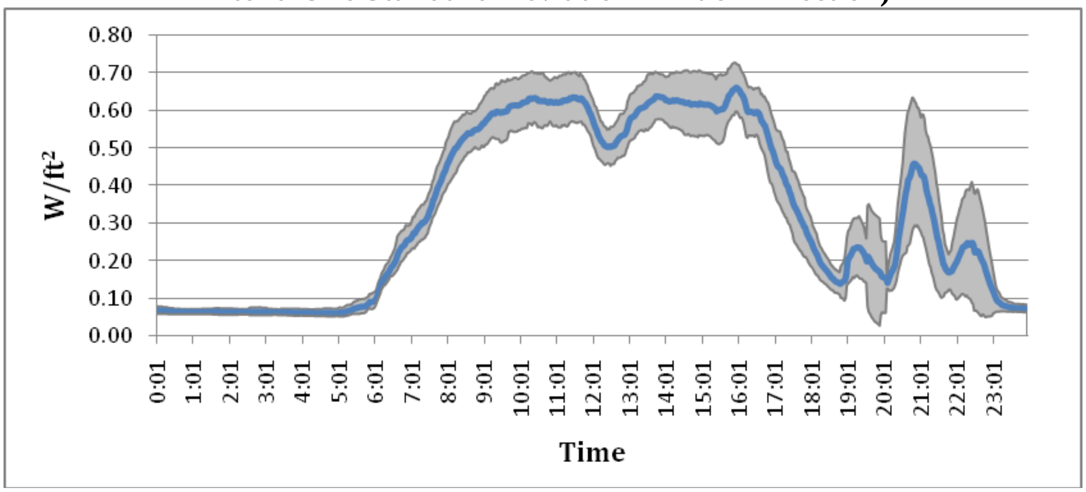
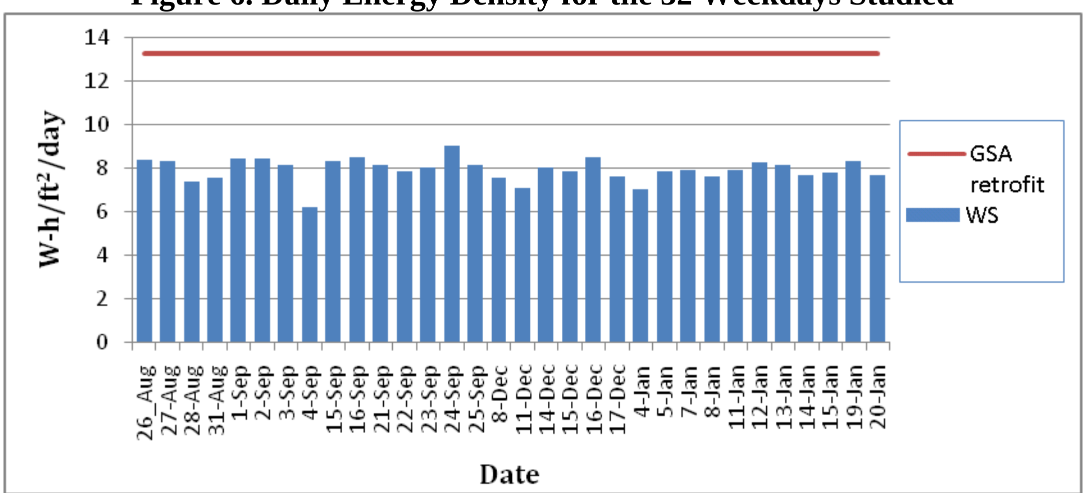


Figure 6. Daily Energy Density for the 32 Weekdays Studied



Average daily and annual energy use and savings compared to the baseline are presented in Table 1. Annual energy use is calculated assuming the office remains unoccupied on weekends, a fairly realistic assumption that gives lower bound energy estimates but is conservative with respect to GSA retrofit; since GSA retrofit does not draw power when lights are turned off, the WS system saves a lower percentage of total energy annually than daily.

Table 1. Daily and Annual Energy Density and Percent Savings

Case	Average daily energy density (W-h/ft^2/day)	Percent savings from GSA retrofit	Average annual energy density (kWh/ft^2/yr)	Percent savings from GSA retrofit
WS	7.92	40%	2.18	37%
GSA retrofit	13.2	N/A	3.44	N/A

Discussion

This study demonstrates that highly-controlled lighting in an open office can achieve large energy savings compared to a retrofit alternative without advanced controls. Even though the WS system had a much higher installed LPD than GSA retrofit, it took advantage of individual occupancy patterns and achieved 40% daily energy savings. Savings arose both from dimming lights and from turning lights off in unoccupied cubicles.

Workstation density, lighting system details, and operating hours clearly influenced these findings. This study calls attention to a handful of additional factors that affect the relative success of a WS lighting system.

Occupancy patterns have a large effect on the energy savings associated with WS lighting in an open office. Lower occupancy and more varied occupancy increase the benefits of a WS system. Extremely high occupancy offices have little to benefit from individual occupancy sensors, while extremely low occupancy offices could achieve much higher savings than those found here. It is strongly recommended that decision-makers study occupancy patterns when deciding if WS lighting is the best approach to a given office environment.

WS lighting takes advantage of each individual departure, which makes the length and power level of timeouts extremely important. Over the days studied, an average 31% of the time the lights spent on occurred in unoccupied cubicles. The large energy density spike each day around 9pm (see Figure 5) occurred because a custodian entered each cubicle very briefly, triggering a 30 minute timeout each time. Additional savings could be achieved with shorter timeouts, lower power levels during timeouts, and/or more innovative scheduling.

The factors that make WS lighting successful also increase the importance of standby power. Since luminaires spend a large percentage of time off, even low standby power makes a significant contribution to overall energy use. Further, to implement WS lighting, each luminaire needs its own occupancy sensor, which increases power and prevents fixtures from dropping to zero power when turned off. In this installation, a standby power of 4.5 watts/cubicle accounted for almost 10% of total weekday energy use. Standby power has an even greater effect on weekends. Systems that attain very low standby power levels and those that innovate to shut off power in certain situations will see energy savings in addition to those presented here.

In the current WS installation, occupants have only very indirect control over their overhead lighting. They can request light level and timeout changes, but cannot adjust light levels manually or override the control system. Studies have found that providing personal controls decreases energy use significantly (Galasiu et al. 2007; Galasiu & Newsham 2009).

Photometric Analysis

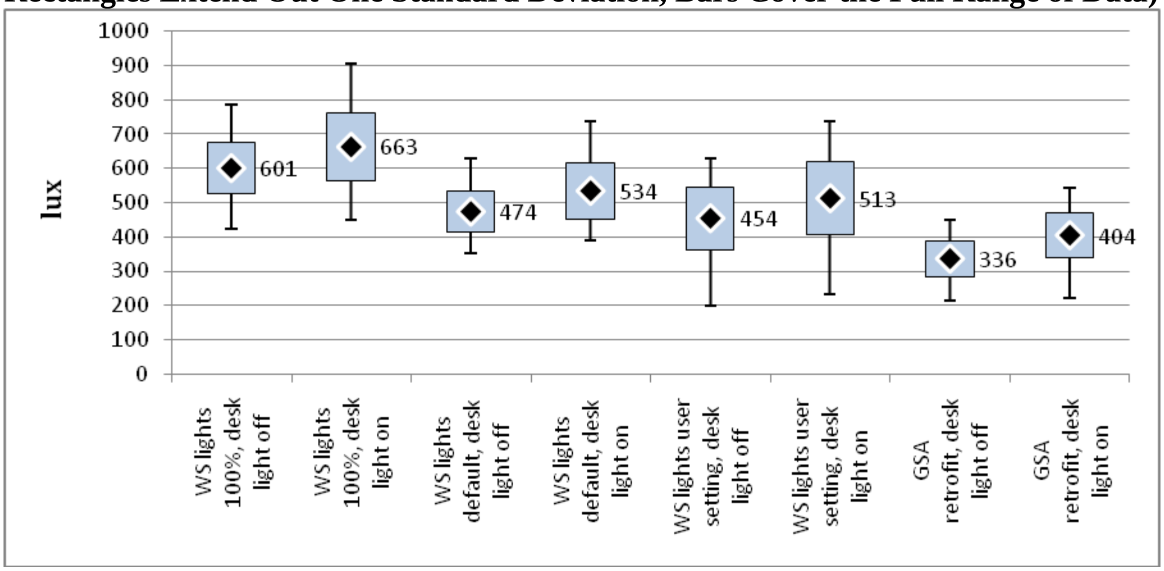
Methodology

Twenty-seven workstations with WS luminaires and 20 GSA retrofit workstations were surveyed with a handheld illuminance meter at the front corners of the middle section of the desk. WS measurements were taken with overhead lights set to both full power and currently used levels. Twenty-one of the 27 WS cubicles monitored use default light settings. In both cases, measurements were taken with the principal undercabinet light both on and off. Objects on the desks and in the workstations were not moved, and measurements were made without anyone seated at the desk. These measurements are conservative compared to those made in empty cubicles, at the center of cubicles, and in areas with low partitions.

Results

Illuminance results are compiled in Figure 7. The low illuminances in the "user setting" category come from workstations with lights intentionally set below default levels.

Figure 7. Illuminance Measurements (Black Diamonds and Values Give the Mean, Blue Rectangles Extend Out One Standard Deviation, Bars Cover the Full Range of Data)



Discussion

The WS system provides consistently higher light levels than GSA retrofit. Except where occupants requested lower light levels, all WS measurements exceeded 350 lux, while 60% of GSA retrofit measurements without a desk light fell below 350 lux. Though the two systems' design details undoubtedly affected these results, the broad lesson stands: WS luminaires provide a viable way to achieve large energy savings without sacrificing workspace lighting conditions.

Studies have shown that personal preferences for workspace light levels vary widely (Boyce, Eklund, & Simpson 2000; Veitch & Newsham 2001). WS lighting offers the significant benefit that occupants can adjust individual workstation light levels and work under their preferred lighting conditions even in a large open office. In a well-commissioned installation, providing WS lighting will not only save energy, but will allow occupants to improve their lighting conditions.

Nevertheless, two main concerns remain about light conditions in a WS system that this report does not directly evaluate. First, locating luminaires only above workstations has left the corridors between rows of cubicles fairly dark. Second, the installed system leaves a blotchy ceiling pattern, shown in Figure 8. If desired, these concerns could be ameliorated by providing additional corridor lighting and/or dimming rather than turning off ambient lights during work hours. These changes would of course increase energy use.

Figure 8. View of the Ceiling with Nearby Luminaires Turned Off

Occupant Survey

Methodology

An occupant survey designed by researchers at the Pacific Northwest National Laboratory was administered in late February and early March. The survey was based on the work of the Light Right Consortium project and had input from researchers at the National Research Council of Canada and the Lighting Research Center. It contained 38 multi-point rating and multiple choice type questions as well as space for comments. Invitations were sent to 153 people, and 91 clicked on the link to take the survey, making the overall response rate 59%.

Survey respondents were divided based on the photograph they selected to characterize their workspace lighting. Only the 48 occupants who selected WS lighting and the 12 occupants who selected lighting representative of GSA retrofit are included here. Both systems are present only in very similar open-office areas.

The small sample size for GSA retrofit should be taken into account when evaluating these results, which also depend upon occupants having selected the correct lighting system. We were not able to establish the statistical significance of the observed differences in occupant response, so results should be treated as qualitative.

Results

Selected survey results are presented below in Figures 9-11. Percentages are calculated out of the number of occupants who responded to a given question, and may not add to 100% due to rounding.

Figure 9. Responses to Questions about the Overall Quality of the Lighting System

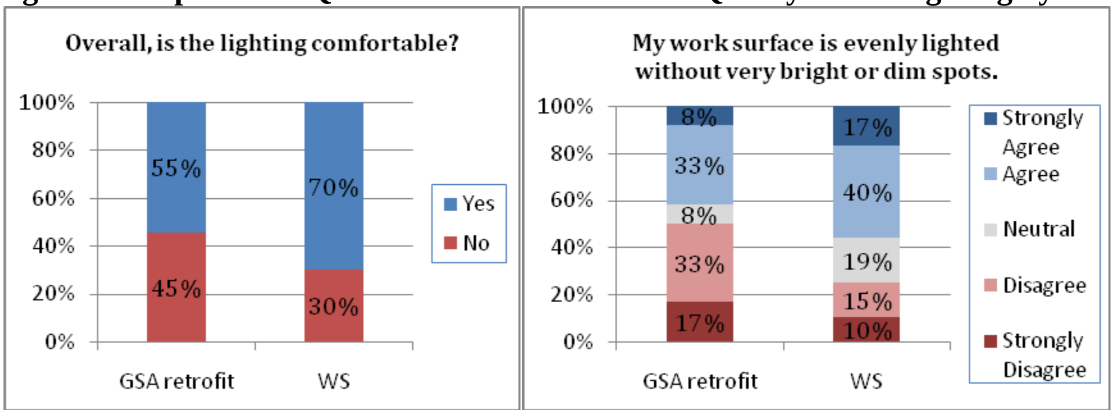


Figure 10. Responses to the Question, "How Often do You Experience Any of the Following Conditions When in your Personal Workspace During an Average Day?"

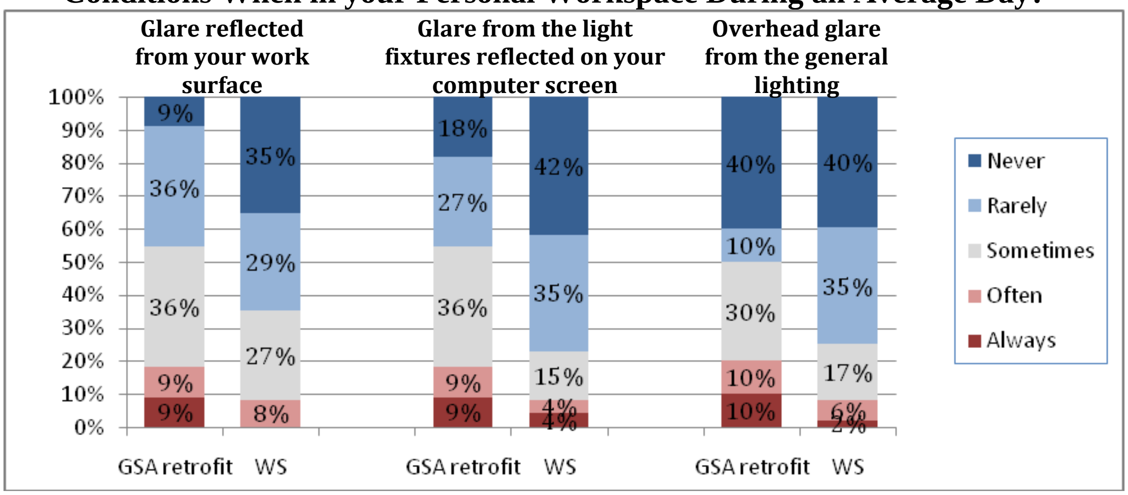
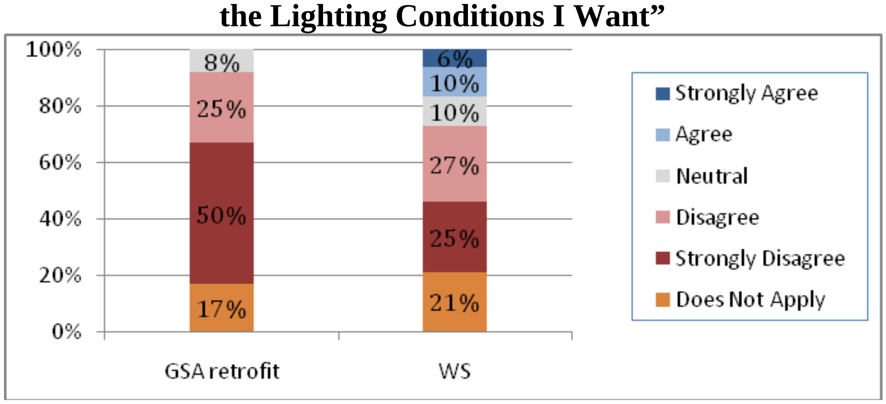


Figure 11. Responses to the Question, "The Lighting Control System Allows Me to Create the Lighting Conditions I Want"



When asked to select all desired changes to their overhead lighting system from a list of options, the largest number of occupants (60% for WS and 55% for GSA retrofit) chose the ability to control light levels with a dimmer or switch. GSA retrofit occupants were more likely to want the location and look of lighting fixtures changed and to want an additional task light. WS occupants were more likely to want a window view and better access to daylight.

Six WS occupants and five GSA retrofit occupants provided additional comments about their lighting system. WS occupants expressed dissatisfaction with light distribution in the office as a whole and complained of sensors that turned lights off in occupied workstations. GSA retrofit occupants expressed interest in more light and more control over their lights.

Discussion

Overall, occupants with WS lighting appear more satisfied than occupants with GSA retrofit lighting. They are more likely to find their lighting system comfortable and evenly distributed, less likely to experience glare associated with the lighting system, and less likely to want an additional task light. These trends suggest that the WS system successfully provides more desirable workstation illumination than GSA retrofit.

The survey did not explicitly address occupant reactions to the overall office lighting. Two free response comments from WS occupants critiqued the dark hallways and the experience of working surrounded by dark workstations. These responses suggest the existence of dissatisfaction with the overall WS lighting that the survey did not expose. Future projects could improve overall office lighting by providing additional corridor lighting and/or leaving uplights turned on to a low level during work hours.

Occupants with both systems clearly want more and better control over their lighting conditions, which confirms the findings of previous studies (Boyce, Eklund, & Simpson 2000; Veitch & Newsham 2001). Only 16% of the WS occupants and none of the GSA retrofit occupants agreed that the controls allowed them to create the lighting conditions they wanted. Further, majorities of both groups indicated that they wanted personal control over workspace light levels. Although this trend highlights a significant limitation of the WS system as currently implemented, it supports the use of WS lighting over lighting without advanced controls in general, since WS systems typically give occupants direct control over their lighting conditions.

Conclusion

Workstation-specific lighting has the potential to achieve large energy savings in an open office without reducing the quality of workspace lighting conditions. This study documented a WS system that achieved 40% energy savings compared to an uncontrolled retrofit alternative while providing higher desktop light levels and improving occupant satisfaction.

Although not yet implemented in this installation, personal taste and controls can be elegantly accommodated in a WS lighting system. Occupants can set and adjust light levels as they see fit, working under a wide range of preferred conditions even in an open-office setting. Personal controls can simultaneously increase energy savings and improve occupant satisfaction.

The installation discussed here demonstrates one of many possible approaches to WS lighting. Lowering standby losses, providing personal controls, incorporating daylighting, improving commissioning, and reducing timeouts could further increase energy savings. Providing additional corridor lighting and leaving ambient lights on during work hours in order to improve overall office lighting conditions will have the opposite effect. Workstation density, layout, occupancy patterns, and the specifics of the installed ballasts, sensors, lamps, and fixtures will change the equation as well.

As the demand to save energy increases, WS lighting offers a viable way to achieve large energy savings while improving workspace lighting and increasing occupant control, even in an open office. By focusing light when and where it is needed, a WS system can respond to individual absences and personal preferences to provide highly-efficient lighting that matches the diverse needs of open-office occupants.

Acknowledgements

This work was supported by the US General Services Administration (Region 9), the Assistant Secretary for Energy Efficiency and Renewable Energy's Federal Energy Management Program of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231, and the California Energy Commission's Demand Response Research Center. We would like to thank Pacific Northwest National Laboratory for their help creating the occupant survey.

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