Photocontrols and Daylight Savings in Sidelit Spaces – Success Factors in Design and Commissioning

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Synopsis

This paper describes the first large-scale U.S. field study of energy savings from daylight-responsive lighting controls (photocontrols) in commercial buildings that are lit by windows (sidelit spaces). The aim was to determine how much energy is actually being saved, and whether any characteristics of the building, the control system or its commissioning lead to more or less successful outcomes. This information can give designers and commissioning providers the tools to influence design at an earlier stage, and achieve the greatest daylight energy savings and the best-functioning buildings for their clients.

About the Authors

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Lisa Heschong is a principal of the Heschong Mahone Group, Inc. Ms. Heschong led the team that found a correlation between the presence of daylight in classrooms and improved student performance, and has completed three additional studies looking at how daylight and window characteristics influence human performance in offices, schools and retail buildings.

Gregg Ander is the Chief Architect for Southern California Edison. He is the author of over 65 technical and design related articles and was the executive producer of four "Environmental Showcase" television programs for NBC. He was one of the first funders of the U.S. Green Building Council and serves on the Board of the Sustainable Building Industry Council (SBIC), the New Buildings Institute (NBI), the Collaborative for High Performance Schools (CHPS) and the California Commissioning Collaborative (CCC).

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Introduction and Background

This is the first large-scale U.S. field study of the performance of photocontrol systems in sidelit buildings, so we could not use previous research as a starting point. We have therefore collected a very wide range of information about the sample buildings, to find out which factors might be associated with successful photocontrol system performance. The goal was to find out:

- How much energy photocontrols are saving, as installed and operated in real spaces,
- How these savings compare to the expected savings as predicted by simulation models,
- If they are serving to reduce peak electricity usage, and
- If there are any characteristics of the buildings, the control systems or the commissioning of the buildings that are more likely to lead to success or failure in practice.

Magnitude of Potential Energy Savings

Lighting energy consumption in commercial buildings is approximately 33% of all commercial energy end-uses in California[1] Daylighting has the potential to greatly reduce energy use for electric lighting and peak electric demand in commercial buildings. In this field study we found that the top performing quartile of photocontrol systems averaged 51% lighting energy savings (1.1 kWh/sf·yr), and a net peak demand reduction of 0.6 W/sf in daylit areas that they controlled. These values provide a reasonable approximation for the "achievable potential" of sidelit control savings, based on current design, installation, and operating conditions in west coast buildings.

If these savings could be achieved in one quarter of the applicable area in new construction in California, about 9 GWh[2] of new savings would be added *each year*, along with 5 MW of demand reduction. In the Northwest these numbers are about 2 GWh and 1 MW. If the same assumptions are applied to the entire existing national commercial building stock at 58 billion sf, the savings would be 3,190 GWh per year and 1,740 MW, or about the capacity of four medium-sized power plants.

Methodology

In order to gather candidate buildings for this field study, extensive professional networks were tapped to identify over 350 buildings that would potentially fit the study criteria, with daylight provided primarily from the side, and photocontrols installed to reduce electric lighting energy use. A phone survey was conducted with the building managers of 162 of these buildings to verify the status of daylighting, to collect preliminary information and to recruit sites for more detailed on-site surveys. Ultimately, 56 of these buildings were visited, and the monitored performance of 123 spaces in 49 of these buildings was included in the analysis. The breakdown

[1] RLW Analytics, *RNRC Baseline Report,* June 2000

[2] Assumes 157 million sf added per year in California X ¼ with daylighting controls x 20% of area daylit (15' from exterior wall) x 1.1 kWh/yr·sf energy savings (or x 0.6 W/sf demand savings) from top quartile photocontrols. California construction forecast from last four years' construction data from F.W.Dodge database. National forecast from Commercial Buildings Energy Consumption Survey, www.eia.doe.gov/emeu/cbecs/

of spaces by type and location is shown in Figure 1; of the 34 “other” spaces surveyed, 14 were libraries. The onsite surveys were conducted from October 2004 to March 2005.

Figure 1: Number of Surveyed Spaces by Occupancy Type and by Region

Location	Classroom	Office	Other	Totals
Southern California	2	25	13	40
Northern California	28	20	16	64
Northwest	4	10	5	19
Totals	34	55	34	123

On-site Survey Methodology

The onsite survey methodology was based on the study of photocontrols in toplit spaces that HMG carried out for Southern California Edison in 2002[3]. The survey consists of three components:

- A “host interview” with the person who is responsible for the photocontrol system.
- A physical and lighting survey of the space.
- Installation of data loggers that record illuminance and circuit current for two weeks.

Host Interview

The interview with the host addressed the following issues:

- The size, ownership and age of the building, and whether any assistance had been received from incentive programs during the building’s procurement.
- The history of the photocontrol system: who installed it and when; whether any parts had been replaced, whether any records of installation or commissioning existed
- The host’s judgments about how well the system worked and how much energy it saved.
- Whether anyone had been trained in how to use or adjust the system.
- The responsible party for maintenance and adjustments.
- Whether the control system exhibited any problems

Survey of the Space

Following the interview with the host, the surveyor conducted a physical survey of one or more spaces in the building, gathering data on the daylighting, the electric lighting, and the geometry and reflectances of the space. This data included:

[3] Heschong Mahone Group, *Photocontrol System Field Study*, report submitted to Southern California Edison, 2002

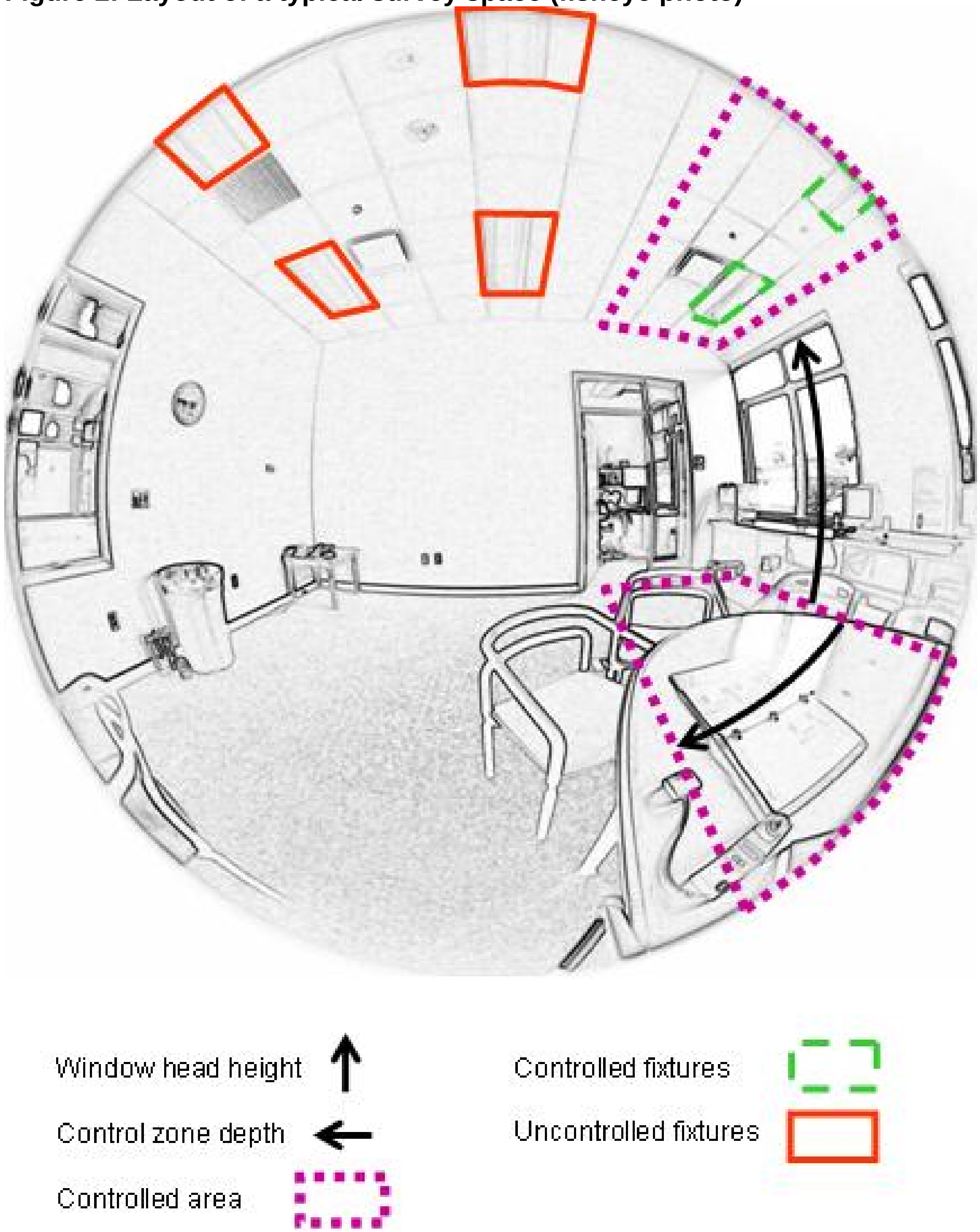
- The physical dimensions and characteristics of the study area, including the position and orientation of windows, any key daylight distribution features, such as light shelves or shading, position and orientation photosensors, location of light switches, and luminaire layout .
- The reflectances of key surfaces - the floor, walls, ceiling and partitions.
- The transmittance of the windows, including the position and net transmittance of any blinds at the time of site survey.
- Illuminance values. This included horizontal at the critical task, horizontal at task level on a 3 x 3 grid across the space; vertical facing four directions in the center of the room four feet above the floor; and at the window.
- A luminance map of the entire space calculated using Photolux® software from 180° fisheye lens photographs taken at a wide range of exposure settings.
- Information about the photosensor, including the make and model, physical condition, and a description of adjustment settings (when they could be discerned).
- Information about the photocontroller (when present). This included the make and model, the type of controller, and what other systems it was connected to.
- Information about the electric lighting system, including the types of light switches provided, whether occupancy sensors were installed, the number, type and wattage and circuiting of lamps, the luminaire light distribution and the luminaire lens or reflector.

Data Logging

Data loggers were installed by the surveyor and gathered data for two weeks before being removed and mailed to HMG for downloading and processing. The number of loggers installed in each space varied from three to eight, depending on the complexity of the space. The locations in which loggers were installed are as follows:

- The photocontrolled circuit(s). Sufficient loggers were installed to monitor the electrical current (or light output) of every photocontrolled circuit.
- One or more non-controlled circuits. Where the space had luminaires that were *not* controlled by the photocontrol system, we monitored these additional circuits as a proxy for the occupancy of the space, to work out energy savings during occupied periods. Note that we did *not* install logging occupancy sensors due to time and budget constraints.
- The window. This logger recorded the amount of daylight entering the space (vertical illuminance inside the window pane).
- The photosensor. If sufficient loggers were available, the surveyor placed a logger next to the photosensor (i.e., on the ceiling) to record the amount of light reaching it. This logger provided more accurate information about how the photocontrol system responded to light, and gave an insight into the functioning of the photocontrol systems, but it was not essential for our analysis.

Figure 2: Layout of a typical survey space (fisheye photo)



Results

Characteristics of Surveyed Spaces

The sample of spaces had the following characteristics:

- 45% were offices, 28% classrooms and 28% other types of spaces
- 15% were in OR or WA, 33% in Southern CA and 52% in Northern CA
- 45% of the spaces had windows facing only north and/or south
- The average view-window head height was nine feet
- 65% of the control systems were dimming and 35% switching
- The installed lighting power density for the surveyed spaces averaged 1.2 W/sf

Energy and Demand Savings

On average, the photocontrol systems were saving only one-quarter as much energy as they would if working in an ideal way. However, excluding the non-functioning systems, those systems that *were* working were achieving slightly more than half of their predicted energy savings. The top quartile of systems achieved on average over 80% of their predicted savings. This demonstrates that significant savings *can* be achieved in many spaces.

In Figure 3, energy savings are quoted using two different units – annual kWh/sf *of controlled area*, and “daily full load hours” (FLH). This quantifies how many hours of lighting energy the photocontrol system saved per day, e.g., a ballast dimmed to 50% power for four hours would save two FLH per day. Peak demand savings are quoted in kW/sf *of photocontrolled area*.

For this project we defined an additional outcome variable, the “realized savings ratio” (RSR, which measures the monitored performance of the photocontrol system relative to a DOE-2 prediction of theoretical ideal savings for the same time period. RSR is affected by how well DOE-2 models the real space. RSR is a dimensionless quantity and has no unit of measurement.

For comparison, Figure 3 also shows the savings achieved by photocontrols in toplit spaces, studied in a previous field survey by HMG. The toplit spaces achieved higher average savings than the sidelit spaces mainly because almost all of them were functional. Also, when toplit systems were overridden by occupants, they switched the lamps *off* whereas in sidelit spaces they switched the lamps *on*.

Toplit spaces are generally more straightforward to control because they have fewer occupants to please, because skylights cause less discomfort glare than windows, and because skylights cannot usually be covered by blinds. Also, because the floor area is usually larger in toplit spaces, the maintenance staff has a higher incentive to keep the photocontrols working.

There was a great deal of variety in the achieved savings between different spaces. 64 spaces had non-functional controls and achieved no savings at all; and there were 59 functioning spaces. We classified 28 of the functional spaces as “high functioning” (RSR>0.5) as shown in Figure 3.

Figure 3: Energy and Demand Savings; for all spaces, functioning spaces, high function spaces and comparisons

	All spaces	Functioning (RSR>0)	High functioning (RSR>0.5)	Comparison: toplit spaces
Number of spaces	123	59	28	33
Average RSR	0.25	0.53	0.82	0.98
Energy savings per photocontrolled sf (kWh/sf•year)	0.4	0.7	1.1	1.2
Energy savings in daily full load hours (FLH)	1.0	2.2	3.4	Not available
Peak demand savings per photocontrolled sf (W/sf)	0.2	0.4	0.6	Not available

Failure Modes of Photocontrol Systems

Occupant complaints seemed to be the most common reason for disabling a system, while incomplete or improper installation and commissioning was the second most common cause a system was not working.

We did not find any evidence that any photosensors or photocontrols had failed on their own after they had been observed to be working. Indeed, the older systems we studied were saving *more* energy than younger systems. Although this result is probably due to a sampling bias, it at least suggests that there is good persistence in savings once a functional system is established. For those systems where we could diagnose a specific failure mechanism, the majority (35/50) had been intentionally disabled: by setting the sensor setpoint too high (17), taping over the sensor (7), disconnecting the wire to the sensor (4), or inactivating the whole system (7).

Other reasons why systems did not function included the system had never worked (5), the system had never been initiated (4), not enough daylight for various reasons (4), incompatibility with the overall building energy management system (1). For 14 systems we could not diagnose a failure mechanism.

Characteristics Associated with Success or Failure

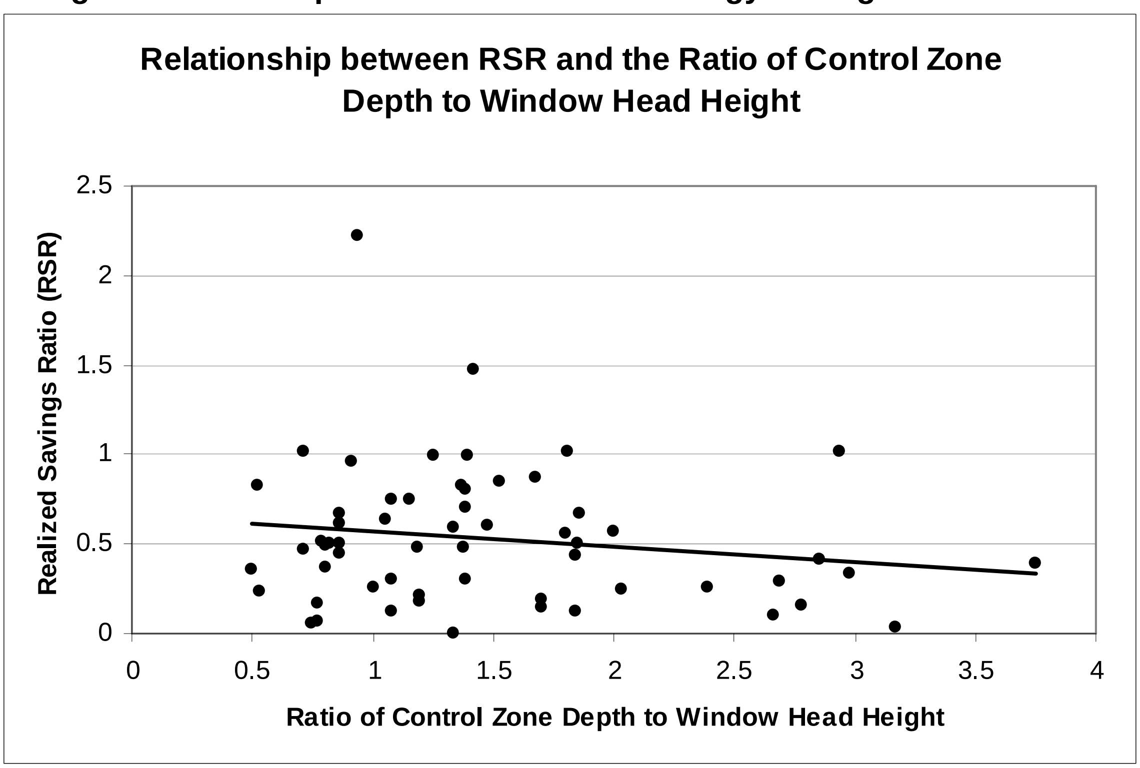
We searched for statistical links between *characteristics* (i.e., features of the space, the controls or the occupants) and the outcomes in terms of functionality and energy savings. These links are summarized in Figure 5 and Figure 6, in which "+" means that the characteristic increased the outcome and "–" means that the characteristic decreased the outcome. Only the statistically significant relationships are shown. We used three types of statistical test: the chi-squared test when both variables were discrete, the student's t-test when one variable was continuous, and linear regression when both were continuous.

Figure 5 shows many of the characteristics that can be influenced by commissioning providers as part of the building design team. For instance, **dimming controls** were more likely to be functioning than switching controls, but did not save significantly more energy (they saved slightly more energy per linear foot of façade, and slightly less in terms of RSR). This finding that dimming controls do not save more energy is unexpected and may be because switching controls tend to be used in spaces with no permanent occupants and so can be set to save energy more aggressively because occupant complaints are unlikely. An additional explanation is that because malfunctioning switching systems are annoying, occupants "fix it or break it", so that the few switching systems that a*re* functioning are saving comparatively more energy.

There are several simple design choices that can improve the success of photocontrols; for instance: using multiple **separately-controlled circuits parallel to the window** rather than a single controlled circuit for the entire space; positioning the **photosensor close to the window**, and designing **shallow control zones** relative to the window height.

The result concerning shallow control zones requires some interpretation, because this result does not achieve statistical significance when measured against any of the outcome variables. However, it comes close to significance against two of the outcome variables, and as can be seen in Figure 4 high savings (RSR>0.5) are almost impossible to achieve in deep spaces where the control zone depth is more than twice the window head height. Thus, although the overall trendline is only slightly downward, the ratio appears to limit the achievable savings.

Figure 4: Too-Deep Control Zones Limit Energy Savings



Spaces in which occupants were trained how to use photocontrol system were more likely to have functioning systems. This training was carried out by different parties but was usually done either by the photocontrols manufacturer or a commissioning provider. Surprisingly, buildings in which the operator kept a record of the photocontrol settings had *lower* energy savings; however, this finding is uncertain because none of the building operators were actually able to find records of the settings, and most did not distinguish between records of installation and records of system settings (i.e., commissioning).

Figure 5: Summary of the statistical effect of characteristics of the controls, occupants and building operator

Explanatory Variables	Functional vs. non-functional	Performance (RSR)	Energy savings (FLH)	Energy savings (kWh/sf•yr)	Demand savings (W/sf)
Lighting controls					
If dimming vs. switching	⇧	⇩			⇩
If photosensor is looking down	⇧	⇩	⇩		
If single daylight circuit vs. multiple	⇩	⇩			
Number of years of photocontrol operation			⇧	⇧	⇧
Control Zone					
Ratio of window head height to ctrl zone depth					
Distance of photosensor from window (ft)		⇩	⇩	⇩	⇩
Depth of control zone (ft)					
Size of controlled load (Watts)					
Area of daylit control zone (sf)					
Window controls					
If windows have blinds			⇩	⇩	
Occupants and Operator					
If site host has records of PC settings			⇩	⇩	
If building has off-site management					⇧
If occupants were trained about system	⇧				
If operator believes system is working (1-7)	⇧				
If operator is satisfied w system (1-7)	⇧				

Spaces with off-site management, i.e. where the building operator would call someone in to repair or adjust the photocontrol system, had higher energy savings; in most cases the person called in would be an electrical contractor, in other cases an architect or commissioning provider.

Surprisingly, older photocontrol systems had higher energy savings and demand savings than newer systems. We believe there may be a selection bias, in that we were more likely to be told about the more successful older systems, whereas poorly functioning or failed systems may be more likely to be forgotten over time. However, system age did not predict greater rates of failure or success, as one would expect if we were never told about failed older systems. This finding remains unexplained.

We did not find that the manufacturer of a photocontrol system could be used to predict failure or better performance. While two manufacturers dominated our survey, both were equally represented among poorly and well performing systems.

Figure 6 shows the effect of design variables that are typically under the control of the architect or end-user, or which are just inherent properties of the building. The most evident finding is that *uniform daylighting* and *high levels of daylight* are both strongly linked with functionality and with higher energy savings. Both these ends can be achieved by having windows on more than one side of the space, by having higher view windows and clerestories, by *not* using tinted windows, and by providing high-reflectance finishes on the floor and walls. Uniformity is strongly reduced by the presence of partitions in office spaces.

Figure 6: Summary of the statistical effect of characteristics of the building

Explanatory Variables	**Functional vs. non-functional**	**Performance (RSR)**	**Energy savings (FLH)**	**Energy savings kWh/sf•yr**	**Demand savings**
Building Characteristics					
Small bldg (<15,000 sf) v all others		⇧			
K–12 school building	⇧		⇩		
Large bldg (>50,000 sf) v all others	⇩				
Office bldg	⇩				
Owner-occupied building	⇧				
Office bldg or K-12 school					
Number of years building has been occupied					
Space Type					
Library space v all others	⇩		⇧	⇧	⇧

Classroom space	⇧	⇩		
“Other" type space		⇧		
Office space	⇩			
Open office vs. all others	⇩			
Private office space v all others				
Fenestration Design				
Ratio of (netT_{vis}*window area) to control area		⇧	⇧	⇧
Ratio of window area to control area		⇧	⇧	⇧
Net T_{vis} of windows w blinds	⇧			
Window head height (ft)	⇧			
If space has high windows (>8') v low only	⇧			
T_{vis} of glass	⇧			
Luminaires/illuminance				
Illuminance ratio, horizontal min to max	⇩			⇧
Luminaires use direct light distribution	⇩			
Illuminance ratio, from front to back of room	⇩			
Illuminance ratio, horiz. std. dev./average	⇩			
Illuminance ratio, vertical min to max				
Space Design				
Space has partitions	⇩			
Weighted reflectance of surfaces	⇩			
Ceiling height in room	⇧			
Room size (sf)				
Window Type				
Space has clerestory vs. no clerestory		⇩	⇩	
Daylight comes from only one direction	⇩			
Space has only north facing windows	⇧			

Summary of Findings Relevant to Commissioning Providers

The results show that well-designed and well-commissioned systems can continue to function and accrue savings for many years. Photocontrol systems therefore present a major opportunity for commissioning providers to achieve significant and persistent energy savings in commercial buildings, and to provide a unique professional service. Although many of the results provide insight into how and why photocontrols work, there are a few results that are immediately useful to commissioning providers.

- Better energy performance seems to be most attributable to appropriate application and design of the daylighting system *as a whole*. Therefore, helping the design team to understand the success factors of photocontrols early in the design process, and integrate these into the design of the building and the space, is critical.
- Spaces that have *more daylight illumination* and *more uniform daylighting* (from clerestories or from windows on more than one side of the space) perform best. Furnishings that absorb daylight and make it non-uniform (such as office partitions, low-reflectance walls and floors, or dark-colored window blinds) reduce savings.
- Training the occupants and the building operator how to use and maintain the photocontrol system means the system is more likely remain functional.
- Owner-occupied buildings are better candidates for photocontrols than rented buildings.
- Many systems fail simply because nobody "follows up" to ensure that the system was installed and commissioned.
- Control systems that don't overestimate the depth of the "daylit zone" perform better
- Circuiting the lights parallel to isolux contours of daylight penetration is recommended.

Our best estimate is that, as of December 2004, there were 200-500 *sidelit* buildings with installed photocontrols on the west coast. This number is growing rapidly, with most of those buildings less than three years old.

We found that only half of the installed systems are currently saving any energy. This is certainly an opportunity for retrocommissioning. Systems seem to be mostly disabled due to occupant complaints, and secondarily due to frustration with the complexity of the system. Solutions for correcting these non-functioning systems may involve changes to the control system or interior furnishings, as well as simple adjustments to control settings.

It is important to note that the systems that are working well are saving significant amounts of energy, and reducing peak electric demand impacts on their buildings. These savings impacts are on a par with those possible with toplighting (skylighting) per square foot of controlled area. These savings appear to persist over time. Therefore, working photocontrol systems in sidelit spaces offer an important opportunity for energy and demand savings, especially once higher success rates are achieved.

Demystifying the design, installation and commissioning of daylighting controls is the next logical step in improving the performance of photocontrol systems in real buildings.