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Environmental Energy Technologies Division

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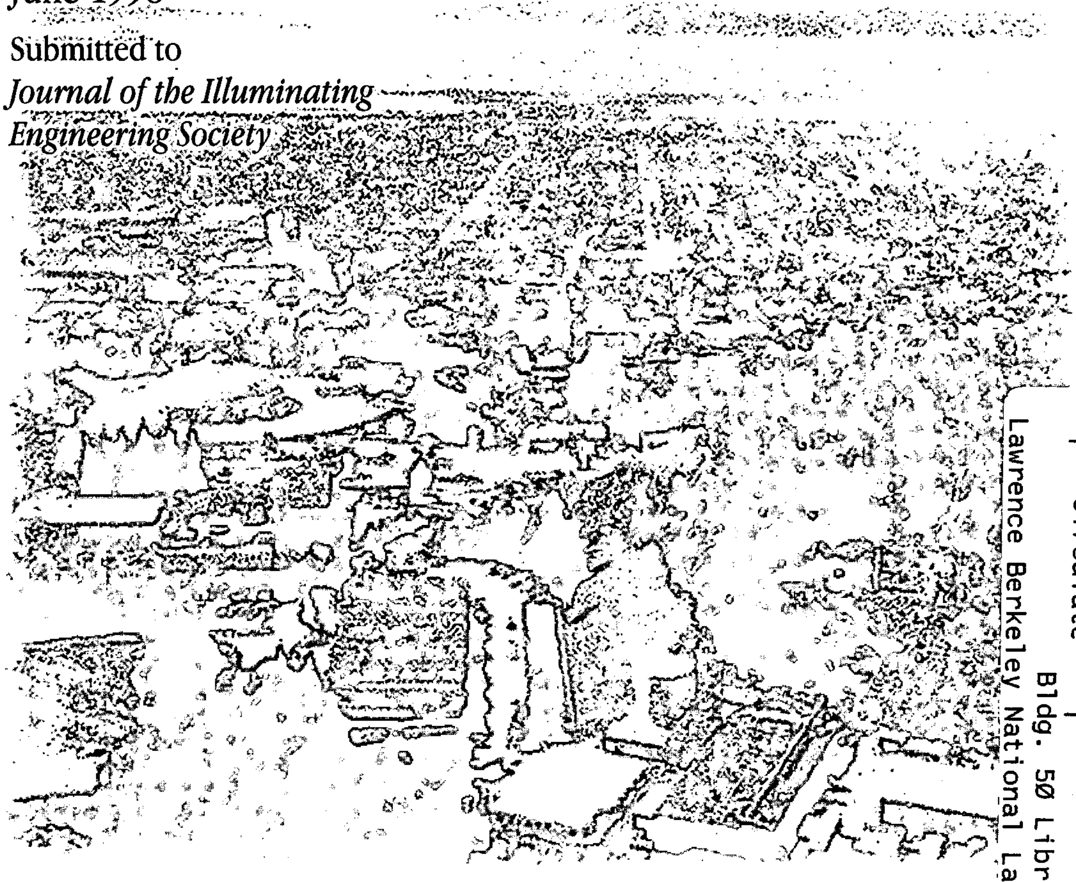

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The Effect of Venetian Blinds on Daylight Photoelectric Control Performance

E.S. Lee, D.L. DiBartolomeo, S.E. Selkowitz

Abstract

We investigate how a venetian blind, a common but optically-complex fenestration system, contributes to the unreliable performance of daylighting control systems. Using a fully instrumented, full-scale testbed facility, we monitored the daylighting performance of a modified closed-loop proportional photoelectric control system in a private office over the course of a year. The ratio of workplane illuminance from daylight to photosensor signal is characterized in terms of solar condition and venetian blind angle. Variations in this ratio causes actual illuminance levels to be periodically insufficient. This type of characterization can be used by the installer to determine whether the initial control adjustments made during commissioning will lead to reliable performance under most daylight conditions. Commissioning guidelines are given with caution, based on our observations from this specific case study.

We quantified the effect of variability in this ratio on control performance. With a middle-of-the-road gain constant, monitored workplane illuminance levels did not fall below 90% of the design setpoint for 91% of the year. When discrepancies occurred, differences between the daylight correlation and measured conditions were the primary cause of insufficient illuminance at the workplane. This performance is not applicable to commercially-available closed-loop proportional systems because 1) typical systems are rarely commissioned properly upon installation, and 2) off-the-shelf systems combine the photosensor's response to daylight and electric light into one gain parameter. Even though the prototype system was subject to the same discrepancies in the daylight correlation fit as commercially-available systems, performance was substantially improved because the prototype was able to separate the electric lighting contribution to workplane illuminance from the daylighting contribution, at no added cost. Commissioning should accommodate the effect of the fenestration system, since variations in luminance distributions produced by the window are the primary cause of unreliable performance.

Introduction

The use of photoelectric or daylighting controls to reduce electric lighting requirements in proportion to available daylight has immense potential to significantly reduce United States building energy consumption and demand. Electric lighting comprises 515,000 GWh or 20% of the nation's electricity consumption. Of this, approximately 10-15% is used to light a building's perimeter zone where daylight is already present. For daytime-occupied commercial buildings, research projections show that total electricity and peak demand savings of 20-40% in lighting and its associated cooling energy can be achieved with the proper use of dimmable daylighting controls throughout the U.S. Even with the availability of more energy-efficient lamps, electronic ballasts, and alternative control systems, the potential for this strategy is substantial.

The concept of daylighting has been promoted over the past few decades but its successful use in buildings has been accomplished in a low percentage of buildings. This may be attributed to a wide array of factors from design through occupancy. At present, designers are unable to devote substantial resources to determine compatibility of various components (i.e., ballast, photosensors, ballast controllers), while component-oriented manufacturers lack the market motivation to make the system design transparent to designers and installers because of lack of volume. Component costs remain artificially high. And like most mechanical systems, the lighting control system is rarely commissioned and checked against a performance standard when installed. At the start-up of the building, the lighting control system may already be inoperative.

A more insidious problem is reliability. Early adoption and subsequent failures in the field gave this energy-efficiency strategy a bad reputation. The source of the problem resides with the simplistic design of the daylighting control system itself. Minimizing the number of sensors reduces equipment cost and simplifies installation. However, inaccurate information on actual interior illuminance levels results in unsatisfactory performance. To track both daylight and electric lighting illuminance levels, conventional daylighting control systems rely on a single source of information: a $10 color-corrected photodiode, which retails for $80-100 with the appropriate housing to mount it on the ceiling or walls. Through this sensor, illuminance at the work surface is indirectly determined and the electric lights are proportionately dimmed. Inherently, the system is inaccurate, so the design illuminance level is often not met and the occupant complains or disables the system.

Research solutions have included determining optimal ceiling or wall positions for the photosensor, determining optimal photosensor shielding configurations from electric lighting and daylighting sources, and devising more sophisticated control algorithms to disaggregate the predictable electric lighting illuminance contribution from the complex daylight illuminance contribution. In the field, installers calibrate the systems conservatively to avoid performance problems, but the energy-efficiency potential is severely undermined.

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In this research, we investigate how a venetian blind, a common but optically-complex fenestration system, affects the performance of daylighting control systems. Using a fully instrumented, full-scale testbed facility, we monitored the daylighting performance of a modified closed-loop proportional photoelectric control system in a private office over the course of a year. The ratio of workplane illuminance from daylight to photosensor signal is characterized in terms of solar condition and venetian blind angle. This type of characterization can be used by the installer to determine whether the initial control adjustments made during commissioning will lead to reliable performance under most daylight conditions. Commissioning guidelines are given with caution based on our observations from this specific case study.

Background

A typical dimmable daylighting control system is designed to dim the electric lighting system at the perimeter zone near windows, skylights or other fenestration apertures in response to available daylight, and by doing so a) meets or exceeds the design task illuminance level and b) reduces the energy requirements of the electric lighting system.

In a sidelit window office, a photosensor is typically mounted on the underside of the ceiling to indirectly determine the illuminance level at the task workplane. The photosensor is often shielded from stray light from the window, electric lights, and ground-reflected light to better track interior illuminance levels. The photosensor signal is processed through a ballast controller or its own built-in electronics, which then sends a dimming control voltage to the electronic ballasts. The ballasts reduce power to the fluorescent lamps and the electric lighting illuminance reduces accordingly.

There are three basic control algorithms that are used to convert the photosensor signal to the required dimming voltage power. These are explained in detail in Rubinstein et al. 1989:

- a) closed-loop integral reset systems adjust the electric light output to keep the photosensor signal at a constant level;
- b) open-loop proportional control systems by definition do not "see" the electric lighting output; the systems simply adjust light output as a linear function of impinging daylight on the photosensor; and
- c) closed-loop proportional control systems adjust the electric light output as a linear function of the difference between the photosensor signal and the maximum electric lighting nighttime photosensor signal.

The closed-loop proportional algorithm (c) offers the most adjustments to the user and accommodates to some degree the different response characteristics of the photosensor to daylight versus electric light. We used a modified version of this algorithm in our tests. Therefore, we focus our study on this algorithm. During the commissioning phase, the electric lighting "offset", or photosensor response to the electric lighting output at full power, is set at night. The "gain", or the slope of the linear function defining photosensor signal to ballast dimming control voltage, is set once during the day with the lights on under typical daylight conditions. The offset is stable over time, subject to degradation due to lumen and dirt depreciation, or to changes within the office (e.g., furniture rearrangement, wall or floor interior finishes). The gain is susceptible to variation with temporal and seasonal changes in daylight conditions within the room and is thus the focus of much research.

Rubinstein et al. (1989) completed a comprehensive analysis of daylight control systems using reduced-scale field tests, where the effects of photosensor configurations, control algorithms, window orientation, and venetian blind angle on illuminance and energy performance were studied. In this work, they noted that the correlation between the photosensor signal and the measured daylight workplane illuminance varied with venetian blind angle.

Mistrick and Thongtipaya (1997) built on this work using the RADIANCE lighting simulation tool to determine photosensor locations that would produce the best correlation to workplane illuminance level. A venetian blind was modeled, but its effects on performance were not directly studied in detail. Other case study building demonstrations have also identified variability of performance associated with the fenestration system, but have not directly studied its effects (Schrum et al. 1996, Benton et al. 1990).

The cause of scatter in the ratio of workplane illuminance to photosensor was attributed to a) the spatial response characteristics of the photocell, b) the location of the photosensor, and c) the differences in luminance distribution within the room produced by varying solar and fenestration conditions. Given practical limits on time and access to data during commissioning, the solutions proposed by Rubinstein and Mistrick were to determine optimum sensor locations and sensor shielding designs that would produce the least data scatter under changing daylight conditions. This reduction in scatter would yield more consistent control performance year round.

We approach the problem from the fenestration perspective. Using monitored data gathered in a full-scale private office, we examine and characterize how the photosensor's response fluctuates under varying solar positions, sky conditions, and venetian blind angles. We also provide examples of control performance and summary statistics on workplane illuminance levels over the course of a year to clarify the consequences of an improperly commissioned daylighting control system. By doing so, we gain an understanding of how and when to commission a system (e.g., sunny or diffuse daylight, horizontal or closed blind) to achieve more reliable and appropriate dimming of the electric lighting system.

Method

The Oakland Federal Building testbed demonstration facility consisted of two full-scale, side-by-side, 3.71 m wide by 4.57 m deep by 2.68 m high (12.17 x 15 x 8.81 ft) rooms that were furnished with nearly identical building materials and

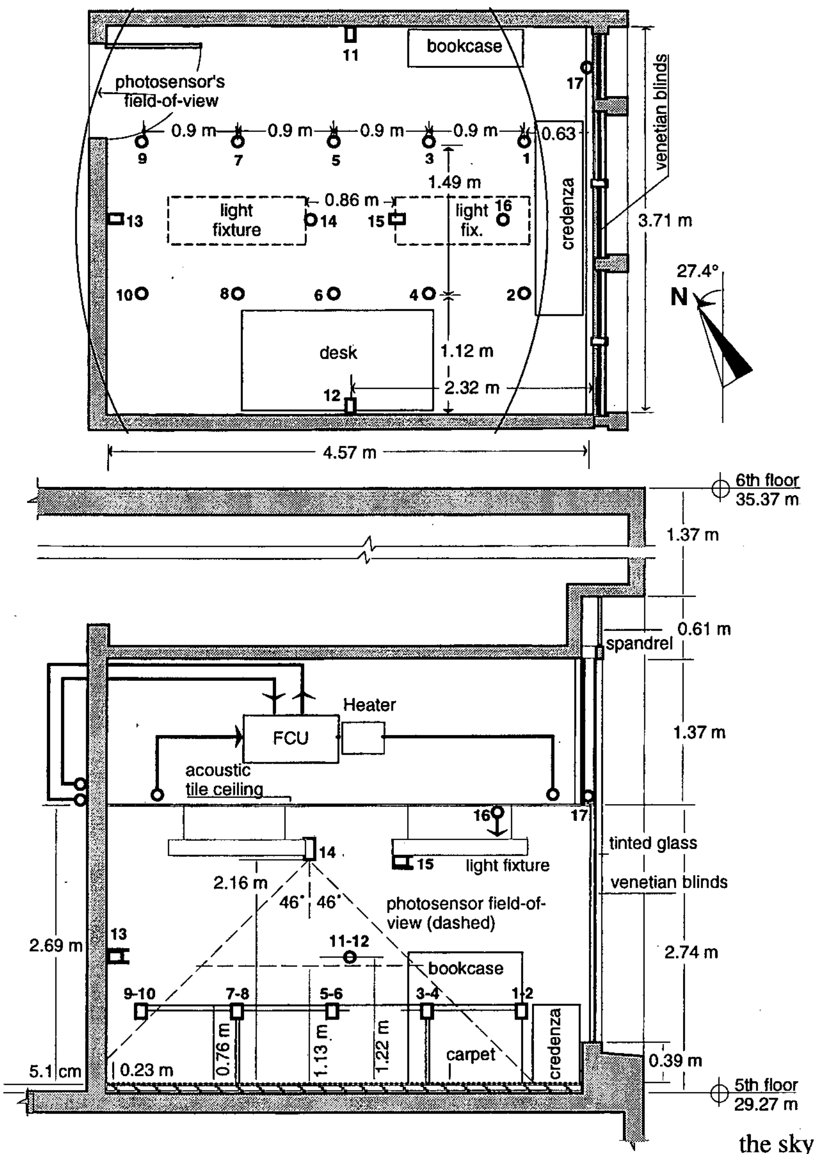

Figure 1—Floor plan and section view of full-scale test room. Photosensor's field-of-view shown on diagram.

Monitored data: 1-10 horizontal illuminance (lx), 11-12 vertical illuminance (lx), 13 shielded window illuminance (lx), 14 photosensor signal (V), 15 shielded window illuminance (lx), 16 ceiling illuminance (lx), 17 photodiode signal (light unobstructed by venetian blind). Average surface reflectances: floor 0.17, walls 0.88, ceiling 0.88, desk 0.05, bookcase 0.06, credenza 0.05, door 0.19, blinds ~0.78.

furniture to imitate a commercial office-like environment (**Figures 1-2**). Both test rooms were built in the southeast corner of a larger unconditioned, unfinished space (213 m^2, 2300 ft^2) on the fifth floor of an 18-story tower. All data reported here are given for the same room, Room A. The building was located at latitude 37°4' N, longitude 122°1' W. The testbed window faced 62.6° east of true south. The window's view was obstructed by five- to eight-story buildings one city block away and by several 24-story buildings three to six city blocks away. These obstructions did not cause direct solar shading of the test room after 7:45 (standard time) from the spring to autumnal equinox.

Window System

The existing window system consisted of 6 mm (0.25 in), single-pane, green-tinted glass (Tv=0.75) with a custom aluminum frame. The overall window opening was 3.71 m (12.17 ft) wide and 2.74 m (9 ft) high, consisting of five divided lights ranging in width from 0.61-0.67 m (2.02-2.19 ft). The transparent glass area was 7.5 m^2 (80.8 ft^2). The window was recessed 0.43 m (1.4 ft) from the face of the building and had 0.13 m (5 in) deep interior and 0.03 m (1 in) deep exterior mullions.

A 0.127 m (0.5 in) wide, curved slat, semi-specular white aluminum venetian blind was fitted in a white painted wood frame and placed in each of the five divided lights, 0.127 m (0.5 in) away from the interior face of the existing glazing system. The blind was tensioned across the full vertical height of the window and was not retractable, only the angle of the slats could be altered. A small, direct-current motor drive at the base of each window blind was used to alter blind angle in synchronization with the lighting controls via National Instruments LabView computer control.

For some tests, blind movement was automated throughout the day to block direct sun, optimize workplane illuminance with daylight, and provide maximum view.[1] The five sets of blinds were synchronized to provide the same angle, where the blind angle was defined by the vertical angle from a horizontal plane. A tilt angle, Σ, of 0° corresponded to horizontal, a tilt angle of 15° corresponded to a downward angle with a view of the ground from the interior, and a tilt angle of -15° corresponded to an upward angle with a view of the sky from the interior. A 60° angle corresponds to the slats just touching, and 68° corresponds to the slats being squeezed to the mechanical limit of the system (daylight still admitted). The accuracy of blind positioning was subject to the relationship of individual slats to the string ladder upon which they rest. On occasion, slats may be caught on the string ladders. However, additional movement of the blind system tended to correct this problem within 1-5 min.

Lighting System

Two pendant indirect-direct (~95%, 5%) fixtures (LiteControl "Classica") with four T8 32W lamps, continuous dimmable ballasts (Motorola Helios M2-RN-T8-10C-277), and a shielded photosensor (Lightolier Photoset) were used in each room. The two fixtures were placed along the centerline of the window with the first fixture spaced 0.61 m (2 ft) from the window wall and the second spaced 0.86 m (2.82 ft) apart.

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[1] This research is part of a larger study to develop a dynamic venetian blind and lighting system (Lee et al. 1998a).

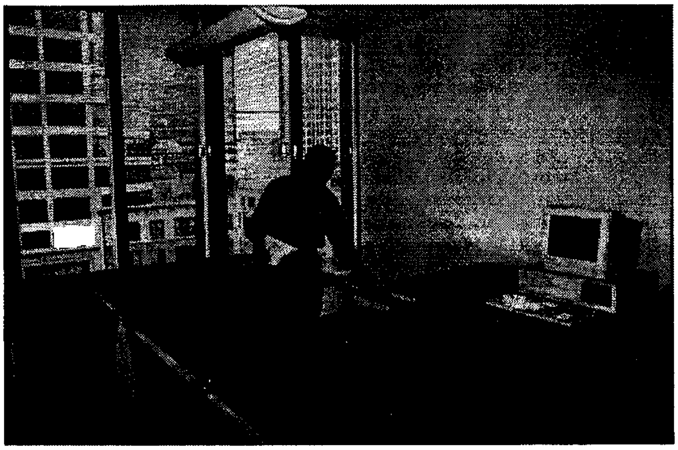

Figure 2—Interior view of testbed

The fixtures were suspended 0.46 m (1.5 ft) from the ceiling at a height of 2.20 m (7.21 ft) above finished floor. The indirect/direct lighting system was selected for its improved lighting quality. The majority of the light (95%) was reflected up by a half-elliptical reflector; the remaining was allowed to filter through a grid of small dot perforations in the reflector. Design calculations using the ControliteTM program estimated 500 lx beneath the fixtures and 350 lx at the farthest corners of the room. Measured workplane illuminance levels at the back area of the room were 540 lx after six months of operation.

The photosensor was centered on the end of the second light fixture and flush with the bottom of the fixture, 2.08 m (6.8 ft) from the window wall, 2.16 m (7.08 ft) above the finished floor. The downward-facing, shielded photosensor sends out a linearly proportional signal in response to the "illuminance" level within its field of view. The response of the sensor is subject to the spatial distributions of light (side versus overhead), temperature, and intermittent obstructions (e.g., person standing directly under it). The photosensor was composed of an irregularly-shaped rectangular, white plastic housing that shielded a color-corrected photodiode placed on a black plastic field. The photodiode's field-of-view (shown in **Figure 1**) had a cutoff angle (100% occluded) of 46° in the direction of the rear wall and window and 56° in the direction of the two side walls. A 0-10 V signal corresponded to ~0-2000 lx under variable daylight conditions. A 0-0.9 V signal corresponded to ~0-500 lx under variable electric lighting conditions.

The ballasts were rated to produce 10% light output for a minimum power input of 33%. Lighting power density was 14.53 W/m^2 (1.35 W/ft^2). The lighting was dimmed as a single-zone system. The lighting system was designed to supplement daylight, if available, and to provide an average design illuminance of 510 lx at the horizontal workplane area towards the rear of the room. The lighting control system was installed and commissioned with a prototype ballast controller so that there was a proportional and instantaneous response to available daylight every 30 sec.

Monitored Data

Illuminance measurements and lighting and envelope status data were sampled and recorded every minute from 7:00-19:00 (standard time) from June 1996 through August 1997 using the National Instruments LabView data acquisition system. Illuminance measurements were taken at a workplane height of 0.76 m (2.5 ft) in a 2 by 5 array of Li-Cor sensors (Figure 1). Li-Cors have an accuracy of 1% of reading for the range of 500-100,000 lx and 3% at ~100 lx. Illuminance measurements were also taken on the side walls at eye level (1.22 m, 4 ft) and on the ceiling near the window, centered above the light fixture. A shielded Li-Cor sensor was placed on the rear wall at eye level to monitor window luminance. Information pertaining to the status of the venetian blind and lighting controls system were also monitored; the photosensor signal to within ±0.0025 V and the venetian blind angle to within ±3°. Because this facility was installed in a commercial office building in a built-up urban area, a limited number of external conditions were measured. A datalogging station located on the roof of a five-story adjacent building wing monitored global and diffuse horizontal exterior illuminance, horizontal global solar radiation, and outdoor dry-bulb temperature (shielded from solar radiation). Exterior illuminance measurements were made with a Li-Cor with a full hemispherical view and a second Li-Cor shielded by a shadowband, which was adjusted as necessary every three to five days. Weather data were sampled and recorded every 1 min by a CR10 datalogger.

Experimental Procedure

The primary objective of the full-scale field test was to further develop a prototype automated venetian blind and lighting system design and to evaluate its performance (Lee et al. 1998a&b). Tests were conducted to a) monitor energy performance, b) verify control system performance, c) assess human factors associated with this system, and d) iteratively refine the control system algorithms and hardware operations according to observations in the field. As such, data to characterize the daylighting control system's behavior relative to the fenestration system are limited. Special tests were conducted periodically throughout the year. Post-processing scripts were also written to pull out applicable data from all data collected.

Analytical Method

Correlations determine how reliably the system meets control objectives. If there is one-to-one correlation between a sensor input signal and the desired variable (e.g., workplane illuminance), then one can achieve perfect control. However, correlations are subject to change with interior and exterior conditions, such as daily and seasonal changes in solar position, or changes in furnishings or paint color. Simple linear correlations are typically used to describe the control system to minimize requirements for instrumentation, time, and installer expertise. When commissioning, the installer allots a brief period to calibrate each lighting zone, but can alter the fenestration system (e.g., blinds open or closed) or set the off-

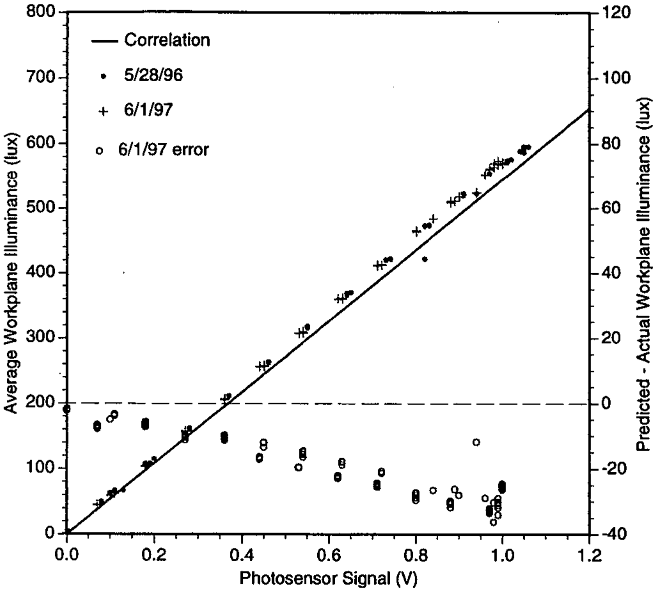

Figure 3—Correlation between photosensor signal and measured workplane illuminance after one year of operation

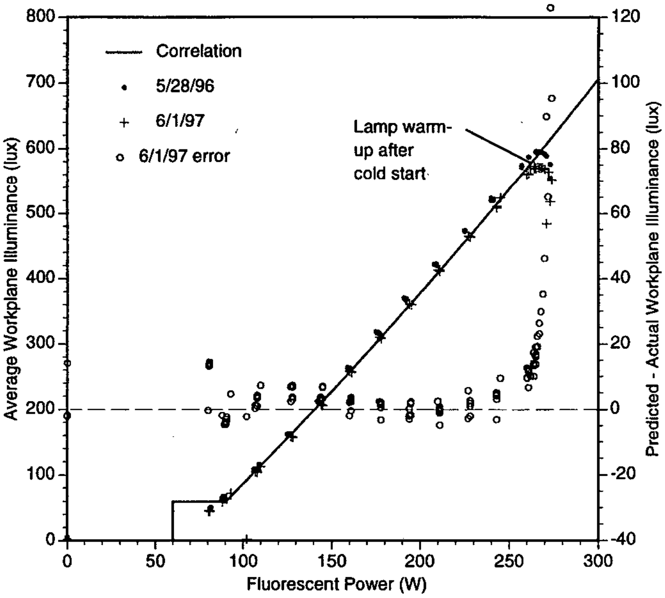

Figure 4—Correlation between electric lighting power consumption and measured workplane illuminance after one year of operation

set and gain more or less conservatively depending on the particular conditions for that hour.

In this research, the electronic controls "offset" and "gain" parameters of the closed-loop proportional control systems, described in the Background section above, were reduced to more fundamental correlations to clarify how external factors contribute to variability in the control system's performance. The photosensor response to electric lighting can be described with a linear correlation between the electric lighting workplane illuminance and the photosensor signal, and a quadratic correlation between electric lighting workplane illuminance and the electric lighting power consumption. The photosensor response to daylight can be described with a linear correlation between workplane illuminance from daylight and the photosensor signal.

The electric lighting correlations were made at night at the outset of the experiment then checked quarterly over the course of the 14-month experiment (**Figures 3 and 4**). The average workplane illuminance was measured by four sensors located 2.44 and 3.35 m (8 and 11 ft) from the window wall and ±0.74 m (2.42 ft) from the centerline of the window.[2] Both electric lighting correlations were found to be well characterized (r^2=0.999) and stable over the course of the experiment, subject only to lamp warm-up after a cold start and by dirt and lumen depreciation. The interior surface reflectances were not changed and the fixtures were not cleaned over this time. After 12 months of operation, the first correlation conservatively underestimated the workplane illuminance by -2 to -35 lx over the full photosensor signal range, while the second correlation predicted the workplane illuminance to within -5 to 30 lx over the full fluorescent power range with adequate lamp warm-up. More details are given in the Appendix.

The third linear correlation with daylight was not as well behaved and is the focus of this research. The control system was commissioned at the outset of the experiment over the course of a week, then the correlation coefficient, M_{fit}=197.18 lx/V (r^2=0.982), was set and used for the duration of the tests. **Figure 5** shows this fit, where the blind was set to a fixed angle or was varied over a full day. Note the scatter in the data, producing a difference between the measured and predicted workplane illuminance of up to -121 lx (24%) in the 0-510 lx design workplane illuminance control range.

The three correlations were described with the equations below:

E_{fluor} (lx) = (545 lx/V) * S_{fluor} S=0-10 V (1)
E_{fluor} (lx) = $0.001865*p^2 +$
$2.3536*p - 167.679$ $90<p\leq270$ W (2)
= 59 lx $60<p\leq90$ W
= 0 lx $p\leq60$W
E_{daylt} (lx) = (197.18 lx/V) * S_{daylt} S=0-10 V (3)

where,

E is average workplane illuminance (lx) and S is the photosensor signal (Volts) from either fluorescent lighting or daylight, and p is fluorescent power in Watts.

Monitored M data (the ratio of measured workplane illuminance to photosensor signal for any given instant in time) are compared to this M_{fit} value in the following results. If M is greater than M_{fit}, then the actual workplane illuminance is greater than the predicted workplane illuminance. Lighting levels that are greater than the design workplane illuminance level are tolerated by the occupant unless there is glare or direct sun, in which case the occupant may choose to close the

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[2] The average workplane illuminance within this area will hereafter simply be referred to as the "workplane illuminance."

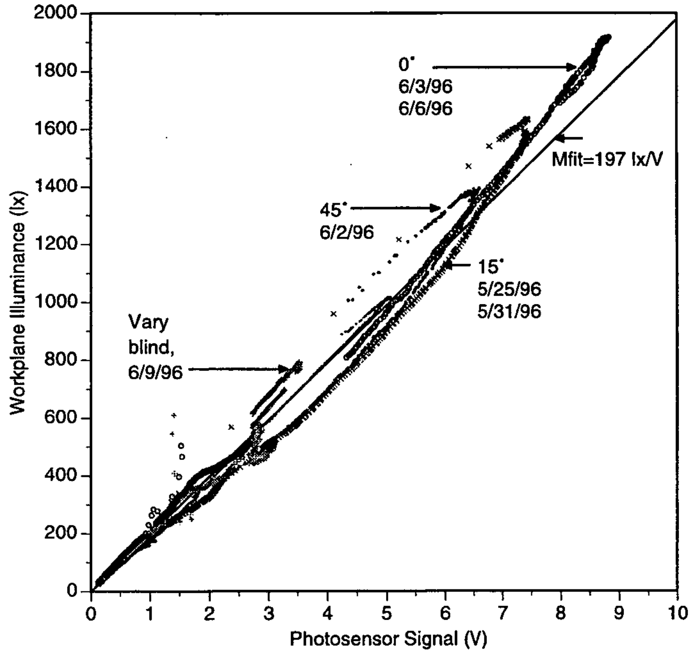

Figure 5—Correlation between photosensor signal and measured daylight workplane illuminance with various blind angles

shading device. If M is less than M_{fit}, then the actual workplane illuminance is less than the predicted workplane illuminance. Here, the daylighting control system is providing insufficient fluorescent lighting, which may not be tolerated by the occupant. The occupant can choose to turn on task lighting or other sources of light if available, or if sufficiently annoyed, disable the daylighting control system by taping over sensors, etc. This source of unreliability has been the historic problem with daylighting controls.

Results

To illustrate the nature of the problem, we show how the monitored slope, M, varies over the course of a clear sunny day with the automated blind (**Figure 6**). With the deviation of M from the fitted slope, M_{fit}=197 lx/V, we see that the measured workplane illuminance from daylight and electric lighting was less than the predicted workplane illuminance[3] from 12:00 to 18:00 with the maximum deviation of 191 lx (M=173 lx/V) or 37% occurring at 14:05. This deviation would probably cause occupants to complain about insufficient illuminance (350-410 lx) or a "gloomy" lighting atmosphere.

M vs. Time of day

For a given fixed blind angle, M varies with solar conditions, time of day, and season (**Figure 7**). We show M as a function of time of day for typical clear summer solstice and autumnal equinox days and for four fixed blind angles (Σ=-15° (autumn only), 0° (summer only), 15°, 45°). The solar azimuth, altitude, and ratio of global horizontal to diffuse horizontal exterior illuminance (E_{glo}/E_{dif}) are given for reference. Data for periods when the photosensor signal exceeded its maximum range of 10 V were excluded. Several observations can be made with these limited data:

1) If direct sun or strong diffuse daylight was present in the space, the sensitivity range of the photosensor was exceeded (>10 V) or M (=450-650 lx/V) was significantly higher than M_{fit}, so that M_{fit} was a poor indicator of the actual workplane illuminance. For example, this is shown in **Figure 7d** from 8:00 to 9:30 and in **Figure 7f** from 8:00 to 11:00.

2) When the sun was in the plane of the window, M decreased from a high to a low value as the sun transitioned to out of the plane of the window. This pattern of variation appeared to be similar between the four blind angles and occurred in both summer and autumn. The partly closed 45° blind produced the least variation in M over the course of the morning period from 7:00 to 12:00 (±2 lx/V summer, ±9 lx/V equinox), the horizontal 0° blind produced moderate variation (±8 lx/V summer), and the 15° and -15° blind produced the greatest variation (±14 lx/V summer and ±56 lx/V equinox for +15° blind; ±41 lx/V equinox for -15° blind).

3) When the sun was out of the plane of the window, the pattern of M variation was less consistent over the course of the afternoon (12:00-18:00) and between blind angles. M exhibited a sharp increase in value as diffuse illuminance levels decreased in the late summer and autumn afternoons (17:00-19:00). Of all four fixed blind angles, the variation of M over the afternoon period was the greatest with the -15° blind (±23 lx/V equinox). All other days and blind angles produced a standard deviation of less than ±17 lx/V.

4) M tended to be lower overall in value in the summer than in the winter for the same hour. With the 45° and 15° blind angles, the shape of the variation over the course of the day was approximately the same in the summer and the fall.

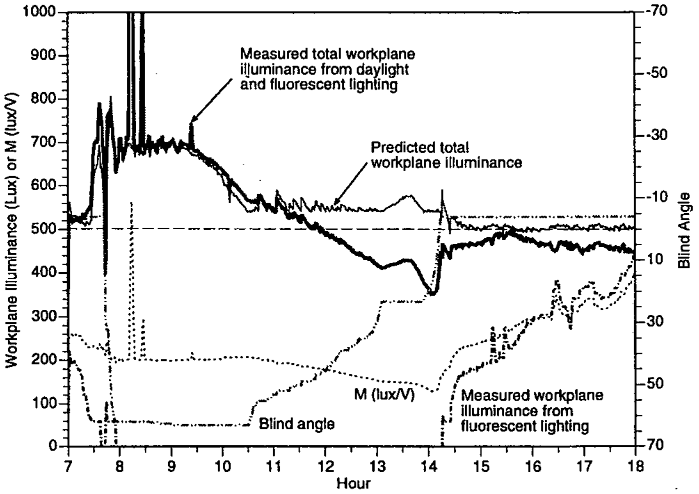

Figure 6—Daylighting control system performance on a clear sunny day, September 10, 1996. Data are shown for a southeast-facing private office in Oakland, California.

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[3] For clarity, Emeasured=M*Sd and Epredicted =Mfit*Sd, where E is the measured or predicted average daylight workplane illuminance at the rear of the test room, M is the actual or filled (predicted) ratio of workplane illuminance to photosensor signal (Volts), and S_d is the photosensor signal from daylight.

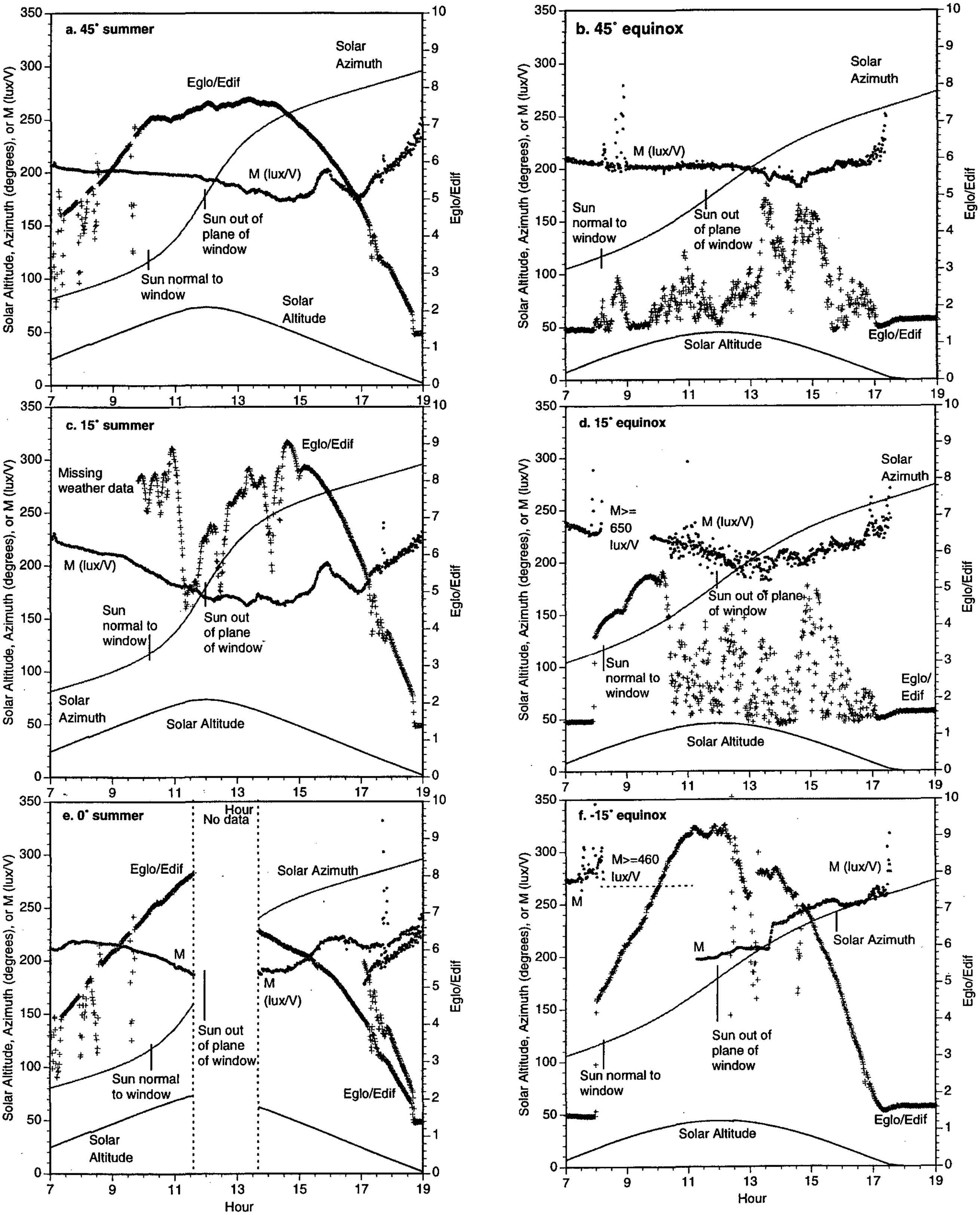

Figure 7—Variation in the daylight correlation coefficient, M (lx/V), over the course of day for a) blind angle fixed at 45° on clear day, June 2, 1996, b) 45° on partly cloudy day, October 13, 1996, c) 15° on partly cloudy day, June 1, 1996, d) 15° on partly cloudy day, October 9, 1996, e) 0° on clear days, June 3 and 6, 1996, f) -15° on sunny day, October 12, 1996. The ratio of global to diffuse horizontal exterior illuminance, Eglo/Edif, and the solar altitude and azimuth angles are also given.

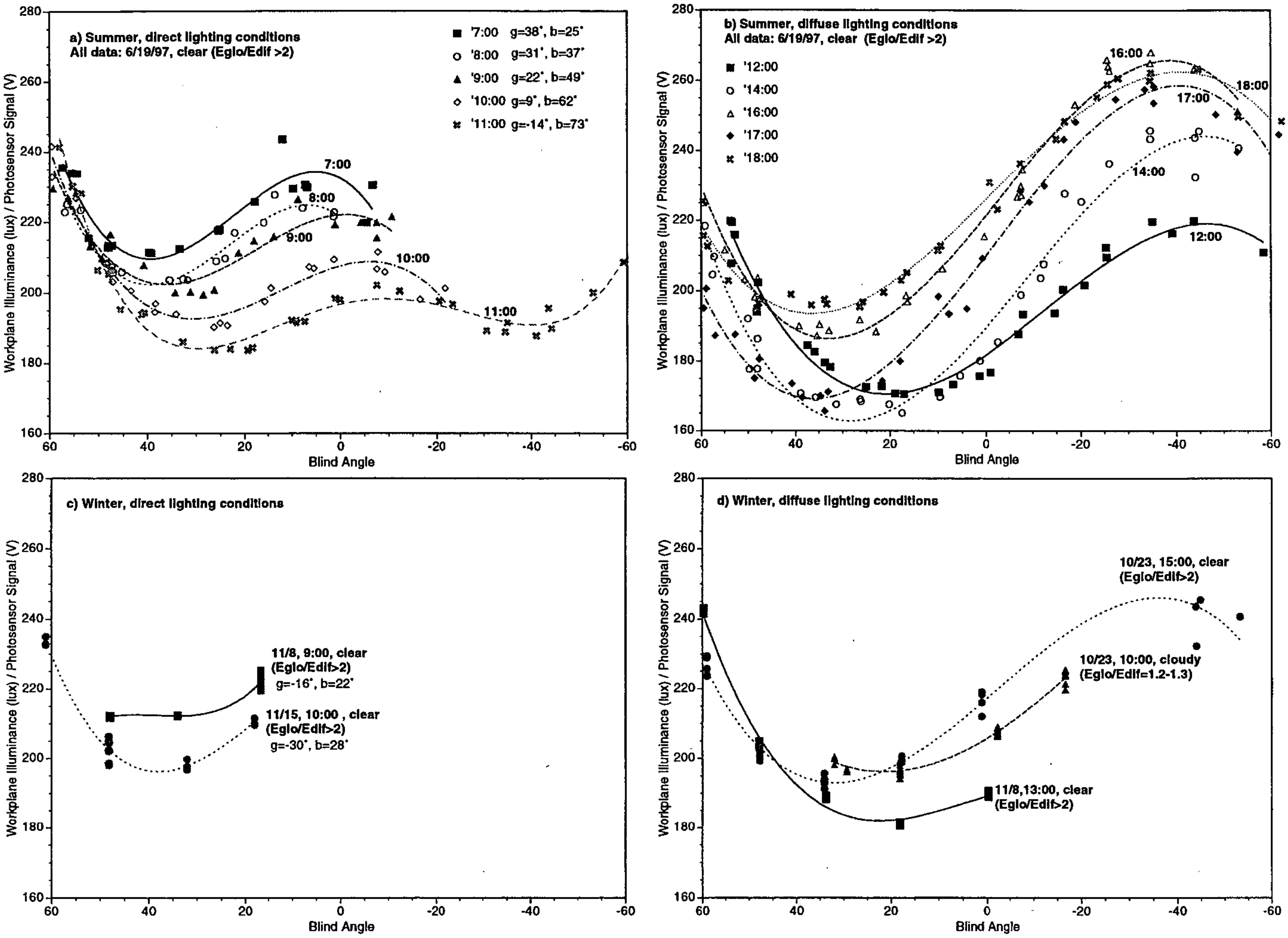

Figure 8—Variation in daylight correlation coefficient, M (lx/V), as blind angle is varied for a) summer direct lighting conditions, b) summer diffuse lighting conditions, c) winter direct lighting conditions, d) winter diffuse lighting conditions. Note: g is the solar surface azimuth angle and b is the solar altitude angle.

Seasonal data was not available for 0° and -15° blind angles.

5) Partly cloudy conditions as indicated by variations in E_{glo}/E_{dif} did not necessarily cause minute-to-minute variability in M. As reference, when E_{glo}/E_{dif} is greater than 1.5-2.0, direct sun is strong enough to cause distinct-edged shadows.

M vs. Blind angle

We show how the blind angle affects M for fixed solar positions in **Figure 8**. The "fixed" solar position was defined over a 30 min period. Data for periods when the photosensor signal exceeded its maximum range of 10 V were excluded. With these data, we note that M varies with blind tilt angle in a fairly consistent pattern, whether the sun is in or out of the plane of the window or under sunny or cloudy conditions. M decreases from a high value at Σ=60° to its lowest value at Σ=20-45°, then increases to a high value again. The blind angle range corresponding to this second high value depends on whether the lighting condition is direct or diffuse. A direct lighting condition occurs when it is a clear sunny day and the sun is in the plane of the window. A diffuse lighting condition occurs when the sun is out of the plane of the window or when the sky condition is cloudy. For direct light, the second high value occurs within Σ=+10° to -10°. For diffuse light, the second high value occurs between Σ=-30° to -50°. The average difference between the maximum and minimum value of M over the range of blind angles was 70 lx/V with diffuse sun summer conditions while a smaller difference of 40 lx/V occurs when the sun is in the plane of the window. In the winter, the average difference is 40-60 lx/V, given these limited data.

Annual Data

To substantiate the above observations made from single-day datasets, we analyzed all data collected over the year for periods when the fluorescent lights were off. These data were binned by blind angle, sunny or cloudy conditions (E_{glo}/E_{dif}>2 is sunny), season (defined by the solstice or equinox ±1.5 months), and whether the sun was in or out of the plane of this southeast-facing window. Summary statistics are given in **Table 1**. The data reflect test conditions when the photosensor signal was within 0.05-10.0 V and when solar data were available.

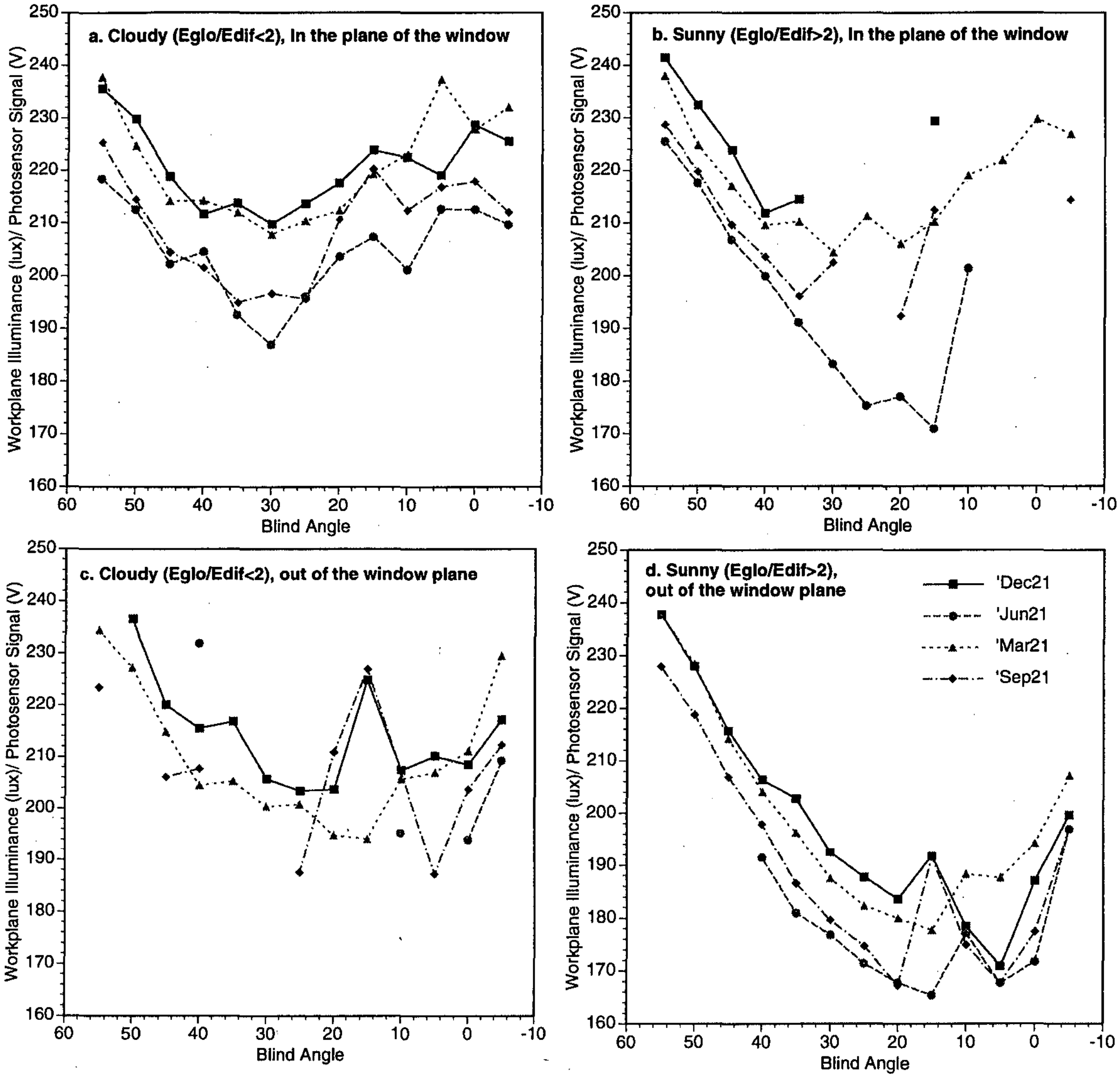

Figure 9—Variation in the average daylight correlation coefficient, M (lx/V), as blind angle is varied for a) cloudy conditions when the sun is in the plane of the window, b) sunny conditions, sun in the window plane, c), cloudy, sun out of window plane, and d) sunny conditions, sun out of window plane. Average represents data collected for each season (solstice or equinox ± 1.5 months).

These more comprehensive data support the observations made above. With one exception, the M averaged data for summer were less than winter values for all binned conditions. With five exceptions (out of 52 conditions), average M data for the March 21 season were greater than September 21 season data. Exceedingly low M values (M=2.6-8.2 lx/V) occurred at sunrise or sunset when the photosensor signal and illuminance levels were low. Consistently low M minimum values (130-165 lx/V) occurred throughout the year during sunny conditions, when the sun was out of the window plane, and the blind was positioned between 5-35°. The previous trends of M variation with blind angle from high to low to high again were generally supported with the M average data for both cloudy and sunny conditions, as shown in **Figure 9**.

Cause of M Variation

Insufficient data were collected to determine definitively the underlying cause of variations in M. At best, we could establish only weak links between the room's luminance pattern, indicated by 12 discrete illuminance measurements, and the photosensor signal. Solar position, sky conditions, exterior surroundings (obstructing buildings, ground conditions, etc.), window geometry, blind angle, and the interior characteristics and geometry of the room affect the spatial distribution of daylight within the room interior. The luminance pattern seen within the photosensor's field of view produces an aggregate voltage reading that is proportional to the photosensor's bi-directional response characteristics.[4] This single aggregate reading obscures the complexity of the daylit environment. We present the following generalizations, therefore, with caution:

Table 1—Ratio of workplane illuminance to photosensor signal, M (lx/V), for all data collected over the year

			-------- Eglo/Edif≤2 (cloudy or overcast)----					----------------Eglo/Edif>2 (sunny)-----------				
blind angle	season	sun @window	n	M average	M std.dev	M min	M max	n	M average	M std.dev	M min	M max
-5 to 0°	Dec21	in	76	225.5	9.0	212.4	272.6					
	Mar21	in	294	232.0	16.3	209.7	288.2	44	226.9	33.2	203.4	366.6
	Jun21	in	38	209.7	2.6	202.5	212.9					
	Sep21	in	132	212.1	4.4	203.5	231.2	261	214.4	7.0	189.3	225.4
	Dec21	out	69	217.1	30.5	*2.6	252.8	56	199.6	11.0	174.5	223.5
	Mar21	out	471	229.5	17.6	197.1	366.2	712	207.1	11.6	179.1	255.2
	Jun21	out	92	209.2	3.5	198.0	216.0	326	196.9	22.9	147.1	435.5
	Sep21	out	322	212.3	9.3	189.6	280.5	764	196.9	18.5	161.0	333.1
0-5°	Dec21	in	61	228.6	14.7	208.5	285.9					
	Mar21	in	53	227.8	17.3	210.8	274.2	8	229.7	17.5	208.2	251.0
	Jun21	in	10	212.6	1.8	209.3	214.6					
	Sep21	in	61	217.9	8.3	204.5	239.0					
	Dec21	out	60	208.5	11.2	187.7	252.6	17	187.0	14.2	170.7	217.2
	Mar21	out	87	211.1	6.5	200.0	226.6	54	194.2	10.7	170.8	219.0
	Jun21	out	10	193.9	1.7	192.3	198.5	50	171.7	4.0	165.7	194.0
	Sep21	out	2	203.7	12.9	194.6	212.8	65	177.4	16.7	145.2	238.9
5-10°	Dec21	in	35	219.1	12.1	202.0	266.7					
	Mar21	in	38	237.3	44.6	206.9	408.8	2	221.9	8.2	216.1	227.7
	Jun21	in	65	212.7	6.6	206.7	229.8					
	Sep21	in	38	216.9	9.9	204.7	232.7					
	Dec21	out	46	210.1	7.8	197.3	249.8	17	170.9	46.4	*8.2	215.8
	Mar21	out	55	206.9	12.8	168.3	265.5	76	187.6	11.8	167.4	222.1
	Jun21	out						35	167.7	5.3	163.3	187.5
	Sep21	out	2	187.2	35.3	162.2	212.1	92	167.7	9.8	133.4	209.7
10-15°	Dec21	in	63	222.5	11.6	207.1	265.2					
	Mar21	in	148	223.1	9.6	194.3	257.3	491	219.0	12.0	194.6	292.4
	Jun21	in	146	201.2	8.1	188.4	225.0	752	201.4	11.8	174.8	225.0
	Sep21	in	27	212.5	12.0	199.5	239.2					
	Dec21	out	60	207.4	9.4	192.2	251.8	58	178.4	12.5	158.8	216.4
	Mar21	out	141	205.7	12.4	184.1	300.6	761	188.3	14.2	160.5	245.4
	Jun21	out	365	195.3	7.0	180.0	231.7	1263	177.1	15.0	156.0	250.8
	Sep21	out	32	207.1	2.5	200.1	210.9	107	174.9	37.7	130.4	378.4
15-20°	Dec21	in	434	223.8	4.4	208.5	236.5	167	229.3	5.1	215.9	250.8
	Mar21	in	35	219.3	20.8	200.6	328.5	3	210.2	8.8	200.0	215.6
	Jun21	in	10	207.4	2.4	204.5	211.2	3	170.9	0.6	170.3	171.5
	Sep21	in	90	220.3	18.1	194.3	279.9	696	212.5	14.2	195.0	329.9
	Dec21	out	1757	224.8	12.7	195.4	287.9	251	191.8	16.1	159.5	223.4
	Mar21	out	28	194.1	7.7	182.2	211.2	171	177.7	9.6	160.1	212.9
	Jun21	out						411	165.4	5.3	155.3	183.4
	Sep21	out	469	226.9	20.2	171.9	348.4	1580	190.5	23.5	128.5	385.4
20-25°	Dec21	in	18	217.6	6.6	206.0	224.9					
	Mar21	in	36	212.4	10.1	191.5	235.3	7	206.0	9.0	194.2	219.4
	Jun21	in	25	203.7	3.4	197.9	210.0	7	177.0	11.3	172.0	202.6
	Sep21	in	24	210.7	3.0	202.8	214.7	2	192.4	7.1	187.4	197.4
	Dec21	out	22	203.7	5.6	184.5	210.2	195	183.6	7.3	163.1	206.9
	Mar21	out	46	194.8	9.9	167.8	221.2	452	180.0	6.7	158.5	207.5
	Jun21	out						165	167.8	3.2	160.6	180.6
	Sep21	out	3	210.9	1.6	209.3	212.4	1243	167.2	7.2	133.4	226.3
25-30°	Dec21	in	14	213.7	5.2	207.2	228.3					
	Mar21	in	35	210.4	9.1	194.1	239.1	11	211.3	26.5	184.3	267.6
	Jun21	in	6	196.1	0.8	194.6	196.7	10	175.2	1.2	172.8	177.1
	Sep21	in	13	195.6	4.2	191.6	208.2					
	Dec21	out	40	203.4	7.8	164.3	213.6	166	187.7	7.6	173.9	211.1
	Mar21	out	39	200.8	15.2	183.6	257.5	308	182.3	6.9	164.3	219.4
	Jun21	out						104	171.4	3.5	165.8	180.6
	Sep21	out	5	187.5	17.7	166.2	209.6	473	174.7	6.2	151.4	207.0

Table 1—Ratio of workplane illuminance to photosensor signal, M (lx/V), for all data collected over the year (continued)

			-------- Eglò/Edif≤2 (cloudy or overcast)----					----------------Eglo/Edif>2 (sunny)-----------				
blind angle	season	sun @window	n	M average	M std.dev	M min	M max	n	M average	M std.dev	M min	M max
30-35°	Dec21	in	31	209.8	4.6	203.0	222.1					
	Mar21	in	35	207.9	5.8	196.9	227.8	11	204.4	6.0	195.8	213.6
	Jun21	in	19	187.0	7.0	172.9	203.7	36	183.2	12.8	176.7	251.8
	Sep21	in	53	196.7	5.6	176.2	207.0	11	202.5	19.1	190.7	255.9
	Dec21	out	31	205.7	3.2	195.2	210.8	324	192.5	5.5	179.6	211.1
	Mar21	out	34	200.4	6.0	189.9	208.1	389	187.5	5.2	172.3	220.3
	Jun21	out						263	176.8	3.8	161.3	190.1
	Sep21	out						487	179.6	5.2	153.4	195.7
35-40°	Dec21	in	119	213.8	4.9	197.4	231.8	139	214.5	2.2	198.8	217.7
	Mar21	in	53	212.0	5.7	199.5	229.7	142	210.2	7.6	194.4	271.2
	Jun21	in	18	192.6	2.6	186.1	195.4	60	191.1	8.3	181.9	207.5
	Sep21	in	30	195.1	2.1	190.5	201.9	9	196.1	3.5	190.1	201.5
	Dec21	out	436	216.8	12.2	188.4	290.8	858	202.8	9.0	181.9	226.9
	Mar21	out	23	205.3	8.0	187.9	224.1	713	196.3	5.9	180.1	221.3
	Jun21	out						161	181.0	3.3	170.6	188.3
	Sep21	out						831	186.6	6.0	158.6	212.1
40-45°	Dec21	in	443	211.7	4.2	170.9	228.6	429	211.9	3.9	190.1	221.0
	Mar21	in	58	214.3	15.7	188.8	272.0	349	209.6	17.0	188.5	350.1
	Jun21	in	315	204.6	5.5	153.8	219.7	821	199.9	4.2	175.1	223.1
	Sep21	in	163	201.6	9.8	181.0	306.2	751	203.6	10.8	182.6	312.5
	Dec21	out	1763	215.5	10.3	179.8	283.1	950	206.4	8.2	187.9	236.1
	Mar21	out	22	204.5	10.2	167.3	213.7	806	204.1	5.1	179.2	219.2
	Jun21	out	48	231.9	16.5	188.2	273.3	1345	191.5	10.9	171.8	233.5
	Sep21	out	312	207.7	9.1	196.8	255.3	1541	197.9	7.8	170.6	264.1
45-50°	Dec21	in	43	218.8	7.2	187.9	234.1	19	223.8	6.9	215.3	238.9
	Mar21	in	57	214.2	11.4	196.1	280.2	64	217.1	24.2	198.6	365.2
	Jun21	in	4	202.3	3.6	197.8	206.6	914	206.8	4.3	190.1	257.8
	Sep21	in	33	204.5	7.9	183.6	215.3	575	209.6	4.8	192.4	221.6
	Dec21	out	14	220.0	8.5	205.6	233.0	258	215.7	7.3	201.5	232.9
	Mar21	out	18	214.8	7.0	204.0	226.9	798	214.2	6.2	198.2	226.9
	Jun21	out										
	Sep21	out	5	206.1	1.5	204.4	207.7	1049	206.9	5.8	177.7	225.4
50-55°	Dec21	in	18	229.8	4.6	223.2	241.7	69	232.4	7.5	207.3	266.1
	Mar21	in	67	224.7	5.5	209.0	241.7	230	224.8	6.5	176.9	253.0
	Jun21	in	10	212.6	6.0	198.9	218.4	1329	217.6	6.6	151.1	264.2
	Sep21	in	27	214.5	9.6	203.7	256.7	1062	219.8	7.3	187.1	233.2
	Dec21	out	3	236.6	2.6	233.7	238.5	356	227.9	6.8	212.7	245.5
	Mar21	out	24	227.2	10.6	202.6	255.5	509	228.4	6.5	152.5	245.6
	Jun21	out										
	Sep21	out						161	218.8	7.0	187.5	251.4
55-60°	Dec21	in	30	235.6	4.8	224.7	245.9	161	241.4	5.4	225.6	260.4
	Mar21	in	44	237.8	10.5	217.8	278.6	367	238.0	10.3	215.4	338.8
	Jun21	in	4	218.4	43.8	157.6	262.2	2056	225.5	2.6	204.4	262.0
	Sep21	in	31	225.3	9.4	210.7	241.0	1505	228.7	5.9	179.5	245.6
	Dec21	out						170	237.7	6.9	226.3	249.6
	Mar21	out	11	234.4	12.0	207.7	252.6	155	237.7	4.9	220.8	247.5
	Jun21	out										
	Sep21	out	5	223.4	3.3	218.5	227.5	359	227.9	5.6	214.2	280.0

Data for photosensor signal between 0.05-10.0 V, when sun data exists, and when electric lights are off.
n=number of 1-minute sampled datapoints; M is the ratio of average workplane illuminance to photosensor signal (lx/V); Eglo/Edif is the ratio of horizontal global to diffuse exterior illuminance; season is defined by equinox or solstice data ± 1.5 months; sun@window is whether the sun is in or out to the plane of this southeast-facing window

* Photosensor signal and illuminance levels were very low (e.g., 0.26-0.86 V).

1) Although the photosensor signal curve has roughly the same shape as the average workplane illuminance curve as blind angle is varied, differences in M appeared to be caused by shifts in the photosensor's response to different daylight patterns (**Figure 10**).[5] For example at 15:00, the blind angle of 34° and -53° produced the same photosensor signal of ~1.1 V but the measured workplane illuminance was 181 and 260 lx respectively, resulting in M values of 160 and 244 lx/V—a difference of 20% from M_{fit}=197.

2) If the photosensor's field of view is influenced by asymmetric front-to-back or side-to-side luminance patterns, then the *average* workplane illuminance, used to determine M, would be a poor indicator of actual illuminance levels. For example, M would be less for asymmetric versus uniform daylight luminance patterns, if the photosensor response is greater with an asymmetric distribution. For a 3:1 illuminance distribution from the front to the back of the room, we found that M values were in fact less than that for uniform illuminance distributions. When the sun was normal to the plane of the window at 11:00 on a clear sunny day (June 19) and there was a 3:1 illuminance ratio (Σ= -20 to -60°), M ranged from 188 to 209 lx/V, whereas for more uniform diffuse lighting conditions at 15:00 and the same Σ, M ranged from 243 to 258 lx/V (~65 lx/V greater range).

For side-to-side luminance distributions, one would again expect M values to be less for strong side-to-side luminance patterns compared to uniform patterns. When the sun was in the plane of the window and at a oblique angle at 9:00 and the west sidewall illuminance was greater or equal to the average workplane illuminance (Σ= 35° to -10°), M ranged from 210 to 240 lx/V, whereas for diffuse lighting conditions at 15:00 and the same Σ, M ranged from 160 to 230 lx/V (overlapping

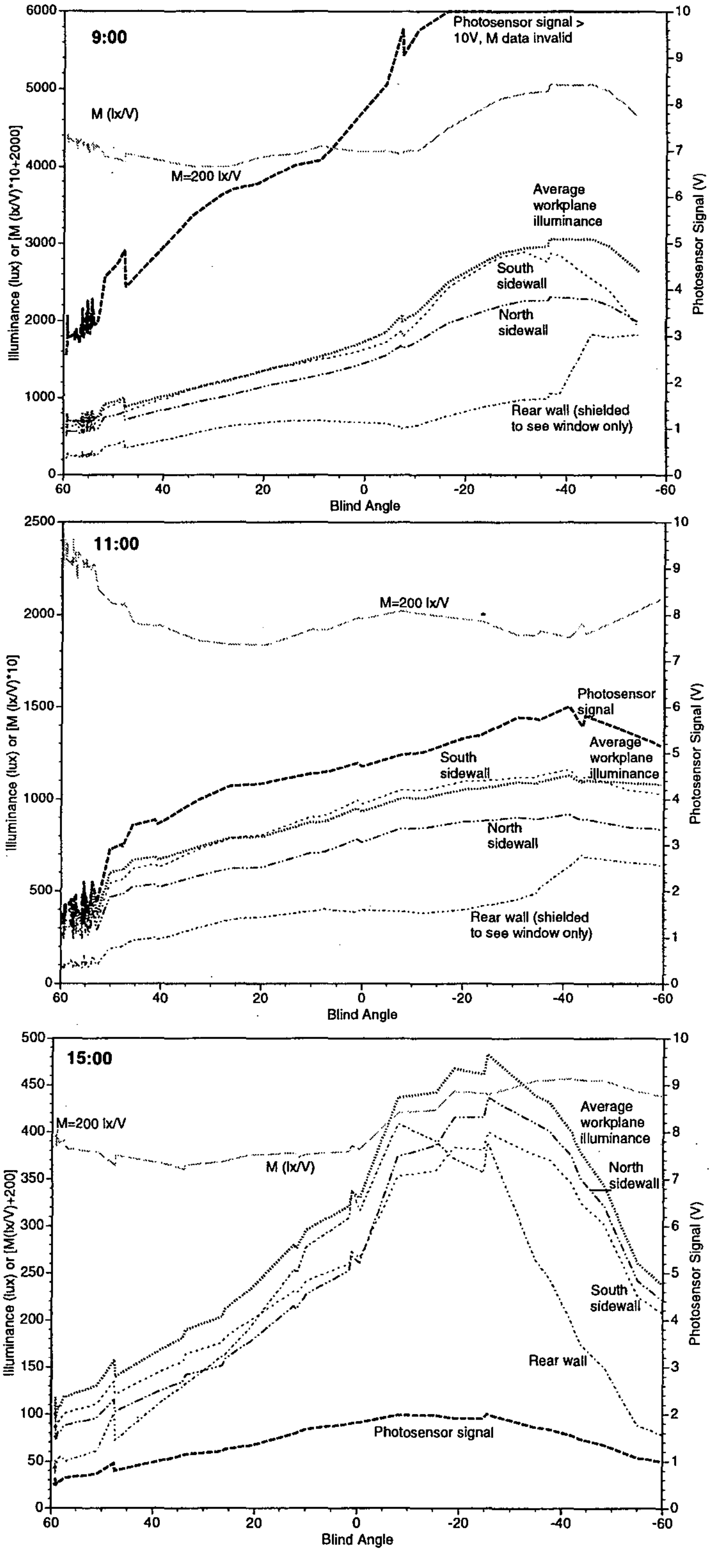

Figure 10—Variation in daylight correlation coefficient, M (lx/V), as blind angle is varied for a) 9:00 direct sun oblique angle to window, b) 11:00 direct sun normal to window, c) 15:00 diffuse lighting conditions for June 19, 1997. Sidewall vertical illuminance, rear wall shielded (window) illuminance, average workplane illuminance, and photosensor signal are also shown.

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[4] We would expect the photodiode to respond proportionately to impinging visible daylight assuming proper filtering to correct its response photometrically. For this photosensor design, we estimate a 10-20% error from ideal photometrically-corrected instruments (e.g., the carefully-calibrated Li-Cor sensors, used to measure the average workplane illuminance, are significantly more accurate than this photodiode). We would also expect the proportional response to be linear across its full operational range. The photosensors' photodiode response is very linear over the 0-10 V range (we installed an amplifier to convert the microamp signal to 0-10V). The data collection system may introduce small errors at very low signal levels (±0.0025 V); e.g., 10% if the signal is 0.025 V. With the multi-tasking WINDOWS NT environment, the photosensor signal and the workplane illuminance data may be recorded within 5 sec of each other at worst case. This may introduce error under quickly changing sky conditions.

[5] The floor, which predominates the photosensor's field of view, has an average surface reflectance of 0.17. The side and rear walls have an average surface reflectance of 0.88. The side wall illuminance sensors were 0.09 m (3.6 in) above the photosensor's field of view. Photosensor signal error may be introduced by the sensor's shield. While the photodiode itself is placed on a black field, the surrounding plastic shield is white (with the photodiode recessed ~1.27 cm (0.5 in) from the bottom edge of the shield), which increases the photosensor's actual field-of-view. The photosensor's field of view is described in the Method section and is diagrammed in Figure 1.

but lower range).

3) Nearly closed, downward blind angles (Σ=60-50°) diffused ground-reflected daylight to the ceiling and diminished the strong asymmetric distribution of daylight from the front to rear areas of the office. The greater M values for this range of blind angles may correspond to the more uniform balance in luminance levels across all surfaces seen by the photosensor.

4) Partly open blind angles (Σ=20-40°) reflect daylight from direct sun upwards or horizontally toward the back wall and ceiling, creating stronger luminance levels on the wall surfaces versus the floor. The lower M values for this range of blind angles may correspond to the higher proportion of luminance coming from side and back wall surfaces.

5) Upward tilted blind angles illuminates the floor plane with daylight from the direct view of the sky (Σ=10° to -10°) or from diffused direct sunlight (Σ=-20° to -60°). The greater M values again correspond to the proportional luminance from the floor plane.

M vs. Control system performance

Using data gathered from June 1996 through August 1997 with automated blind operation, we determined the consequences of this variation in M on the daylighting control system performance. The monitored data reflects the combined performance of the prototype electric and daylighting control system. Three correlations (described by equations 1-3) contributed to error in meeting the design workplane illuminance. The two lighting correlations, described in the section "Analytical Method," introduced minimal error over the course of a year's operation: on average -17.6±10.2 lx for equation (1) and 5.5±7.0 lx for equation (2). Lamp warm-up contributed to a maximum error of -10 lx, if the power was switched from 0% to 30% with cold lamps and was monitored within 5 min of start-up. This did occur throughout the day, since the control system shut lights off after a 10-min delay if sufficient daylight was available. For each day, a tally was made of the number of minutes between the period of 7:00-19:00 (12 hr) when the measured workplane illuminance was lower than the design lluminance setpoint with electric lights and daylight. For this subset of data, we also computed the average workplane illuminance[6] from daylight and fluorescent lighting.

When E_{design} (=510 lx) was not met, the average workplane illuminance was within 10% of E_{design} (459-510 lx) for 91% of the year represented by 147 monitored days (**Figure 11**). The average workplane illuminance was less than 459 lx, an average of 13 min per day, with a maximum of 139 min occurring on a partly cloudy day. For most cases, the daylight correlation ($M<M_{fit}$) was the primary cause of insufficient illuminance at the workplane. This was illustrated in the worst case example above (see **Figure 6**) when E_{design} was not met for 60% of the day, and measured total workplane illuminance levels fell to as low as 350-410 lx from 13:45-14:15 when Σ=0-22°. Lamp warm-up did not contribute substantially to insufficient illuminance (<10 lx) when the electric lights were switched on at 14:15 after being turned off since 8:00. Decreasing M_{fit} to a more conservative value would improve the control performance but would also increase energy consumption.

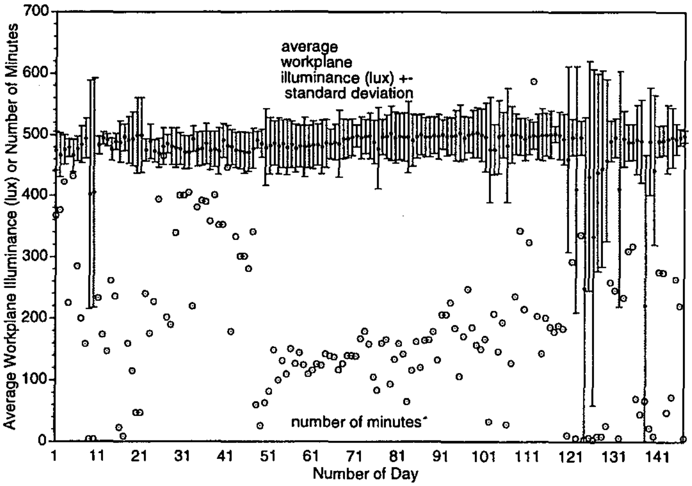

Figure 11—Average workplane illuminance when measured workplane illuminance was less than 510 lx target and number of minutes in a 720-min day when this occurred. Non-contiguous data collected over a year.

This generally "good" control performance is unfortunately not applicable to commercially-available daylighting control systems. This prototype system is substantially better because the system was properly commissioned and because commercially-available closed-loop proportional control systems *combine* the slopes from the electric lighting and daylighting correlations into a single "gain" parameter, forcing interdependency between two distinctly different relationships. Because the slope from daylight (M_{fit}=197 lx/V) is substantially lower than the slope from fluorescent lighting (M_{fluor}=545 lx/V from equation 1), the commercially-available control system must have reduced sensitivity to compensate for these gain differences. The more the sensitivity is decreased to obtain good daylighting performance, the less accurate the control will be for electric lighting changes.

As suggested in Rubinstein et al. 1989, commercially-available photoelectric control systems can be designed to "know the difference" between electric light and daylight by using separate photocells to determine the instantaneous electric light output and by using a sensor that detects input power to the electric lighting system. The prototype system we have designed in this research achieves this disaggregation between the daylight and electric lighting contributions to the workplane illuminance without added cost to conventional commercially-available systems and without added sensors. We intend to approach lighting control manufacturers to determine their level of interest in our design. If implemented, reliability in conventional daylighting control systems could be increased substantially.

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[6] Note this is the average of the subset of workplane illuminance data when the design workplane illuminance was not met. The workplane illuminance data are the average workplane illuminance measured by four illuminance sensors.

Commissioning Guidelines

For real-world applications, the person commissioning a closed-loop proportional system typically has one opportunity over a short period (10-30 min) to commission the daylighting control system during the day (night commissioning of the electric lighting system is also required). Commissioning is conducted after the lighting control system has been installed and should be done after furnishings are in place. It is assumed that before commissioning, the designer has selected a photoelectric sensor that has been designed properly by the manufacturer to produce a proportional response to illuminance changes at the workplane, that the correct sensitivity range has been specified for a particular application (i.e., the range of the photosensor response corresponds to the illuminance range within the lighting zone), that the installer has placed the sensor above an area that is representative of most task locations (e.g., two-thirds towards the back of the room) and that the sensor's field of view has been restricted from direct light from the window, electric lights, and ground-reflected light. These assumptions are non-trivial and have been addressed in other research (e.g., Mistrick and Thongtipaya 1997, Benton et al. 1990, Floyd and Parker 1995).

The goal of commissioning is to find a middle-of-the-road *gain* adjustment that achieves dimming of the electric lighting system while minimizing control system errors. The offset, corresponding to the electric lighting output at full power, is set at night and requires no estimation under unstable conditions. Tolerance for failure to meet illuminance targets is dependent on the nature of occupant's visual tasks, on whether the occupant can resort to other options (e.g., task lighting defeats energy-efficiency objectives but satisfies occupant requirements), on how frequently a deficiency occurs (e.g., is the 2% deficiency rate obtained by the prototype system acceptable?), and on how severe the deficiency is (e.g. is 10% below E_{design} acceptable?). In addition, other confounding factors can contribute to the occupant's acceptance of the control technology (Boyce 1984). For example, the spatial distribution of daylight within the room cavity influences the occupant's perception of illuminance at the workplane. We have found that even with the provision of adequate daylight at the workplane (electric lights off), occupants desired more light—on the order of 800-1400 lx—perhaps to compensate for the darker surface luminance levels in the back of the room produced by sidelighting (Vine et al. 1998). Other studies have shown that occupants with a relatively glare-free lighting environment are satisfied with lower workplane illuminance levels than E_{design} (Hunt 1980). An occupant's sense of autonomy and control over their environment is also a factor in their level of satisfaction with the lighting environment—provision of a means to adjust the controls can sometimes placate occupants. An assessment of tolerance must be made by the lighting system designer and conveyed to the installer. Building managers should plan to make future adjustments in order to tailor the system to individual preferences.

In closed-loop proportional systems, the gain is usually set with the person standing on a ladder adjusting a very small potentiometer in the sensor housing, so that the total illuminance, measured by a sensor(s) placed on the task worksurface, meets the proper design level. Prior guidelines advise that this adjustment be performed under "typical" daylight conditions, when the daylight level is less than the design illuminance level, when the fluorescent lighting is moderately dimmed (not at minimum power), and when the daylight workplane illuminance is not unusually high relative to the photosensor signal. We have assumed that there are no "hidden" algorithms embedded in the photosensor or ballast controller by the manufacturer, such as a delayed response or an asymmetrical response to impinging light (fast increase, slow decrease in dimming). One may be able to ascertain whether such an algorithm exists by observing the response time of fluorescent dimming to changes in light (using a flashlight on the photosensor), or by asking the manufacturer for more detailed specifications.

Given our observations of M for this private office located in a built-up metropolitan area, we would advise that a closed-loop proportional daylighting control system with an adjustment option for gain be commissioned with the additional guidelines given below. These guidelines are given for a shielded photosensor with an exposed photodiode (i.e., no white diffuser covered the photosensor)—photosensors of alternate design would have its own unique sensitivity and response characteristics. These guidelines are also given for windows with venetian blinds in a fully extended position, but they may be applicable to other shading systems as well. We present the following guidelines with *caution* since they are based on a single, albeit extensive, case study:

- Commission the system during the day when there is no direct sun in the room and when workplane illuminance levels are at least 100 lx. Eliminate any high-reflectance surfaces within the photosensor's field of view that are temporary; the photosensor's field of view should see a typical interior environment.
- Commission the system during stable daylighting conditions (clear sunny days or overcast days). Partly cloudy conditions produce significant variations in daylight on a minute-to-minute basis, making it difficult to assess performance.
- Determine if the sensitivity range of the photosensor is exceeded. Check manufacturer's specifications or measure interior illuminance levels to determine if light levels are within the photosensor's sensitivity range or E_{design}. If so, reduce daylight levels (by adjusting the blinds) and check to see if there is any response from the fluorescent lighting. If none, the photosensor's range may be exceeded. If windows are large and/or have high transmission glazing, the blinds can be completely shut against direct sun while the photosensor range may still be exceeded. Return and commission the system under less bright conditions.

- Determine the range in the gain for a given time of day by adjusting the venetian blind over its full range of tilt angles and noting the range of potentiometer adjustments.[7] The blind should be extended to cover the full height of the window. Position the blind angle at 15° increments to capture the full range of variation; two or three angles may not capture the full range. Avoid blind angles that admit direct sun. If more than one blind, position all blinds to the same angle. This task may be very difficult to accomplish if the gain adjustment on the photosensor is difficult to reach or to determine relative position. If this is too time-consuming, position the blind to a 20-45° tilt angle (view of the ground from the interior) and note the gain position. Assume that this will yield the lower sensitivity limit for the gain.
- If commissioning will be performed once, use the following guidelines to determine if the gain or gain range is high (sensitive) or low (insensitive) relative to the particular solar conditions and time of year when the commissioning is being performed. Though improbable, if settings will be checked later, note the range, then return and recheck the range under different daylighting conditions to determine if the gain setting is adequately conservative.
- Determine whether this range is low or high relative to variable solar conditions. Under clear sunny weather, a) if the sun is normal to the plane of the window and the lighting distribution from the front to the back of the lighting zone is more than 3:1, assume that the gain or gain range is low, b) if the sun is normal to the plane of the window and the lighting distribution from the front to the back of the room is less than 3:1, assume that the gain or gain range is moderate, and c) if the sun is at a very oblique angle and in the plane of the window, assume that the gain or gain range is low. If the sun is out of the plane of the window or conditions are overcast, assume that the gain or gain range may be low (—diffuse interior lighting conditions contributed to more variation in the gain, so here it is difficult to generalize).
- Determine whether this range is low or high relative to the time of year. If the system is commissioned during the summer, the gain may be low (conservative); if winter, the gain may be moderate to high.
- Make the final adjustment to the gain according to the expected level of tolerance. A low setting will reduce occupant complaints but reduce potential energy savings. A moderate setting may result in some complaints from the occupants. Avoid high settings.

Conclusions

Reliable daylighting control system performance relies on key correlations between the daylighting system hardware and the interior illuminated environment. Significant deviations of actual data from the fitted correlation between the photosensor signal and daylight illuminance were identified as a major cause of control failure to provide sufficient illumination at the workplane.

Observations of the relationship between photosensor signal and daylight workplane illuminance were made for a specific case study. For a given solar position, the pattern of variation in the daylight correlation coefficient as the blind tilt angle was varied was found to be consistent under both direct and diffuse lighting conditions. Other patterns of variation with time of day or under diffuse or direct sun conditions given a constant blind angle were not consistent and were difficult to generalize upon given the limited data. The *cause* for the variation was attributed to the spatial distribution of daylight within the room interior. However, we were unable to definitively link the degree of deviation from the fitted correlation coefficient to specific asymmetric or uniform illuminance distributions, given only 12 discrete illuminance datapoints.

An evaluation of the prototype daylighting control system's ability to meet performance objectives over the course of year was made using middle-of-the-road correlation coefficients and a prototype daylighting control system design. This performance was very good. Monitored workplane illuminance levels did not fall below 90% of the design level for 98% of the year, and if it did, discrepancies occurred an average of only 13 min per day within a 12-hr day. This performance is unfortunately not typical of daylighting control systems available today because most applications are not properly commissioned and commercially-available closed-loop proportional control systems *combine* the slopes from the electric lighting and daylighting correlations into a single "gain" parameter, forcing interdependency between two distinctly different relationships.

The installer typically does not have the time or access to the data that were gathered in this year-long study. Yet, the installer is expected to set the gain to an "average" slope within a short period to achieve minimum occupant dissatisfaction and maximum lighting energy savings throughout the year. We used our detailed observations of the gain's variation patterns to produce practical commissioning guidelines. These general guidelines may enable the installer to better estimate the yearly average slope, but are presented with caution, given that this is a specific case study. Varying the venetian blind angle to assess the range of the gain variation during commissioning would enable installers to reduce the potential guesswork in determining a conservative but energy-efficient setting. Clearly, when commissioning a daylighting control system, we should not discount the impact of the fenestration system on control performance, since variations in the spatial distribution of daylight produced by the window is the primary cause of unreli-

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[7] In Rubinstein et al. 1997, the authors noted that precise adjustment of the potentiometer may be difficult if not impossible, since the potentiometer may be overly sensitive in the range of interest. Sensors should include both a coarse and fine adjustment to allow efficient calibration regardless of light level.

able control performance. Additional field or simulation work will be required to determine if the trends noted here can be generalized or applied to different room shapes, open plan offices, window types, and lighting controls. Ultimately, we expect to provide a simulation tool that will allow a designer or manufacturer to explore these photocell control effects in a virtual space, then provide a reliable cost-effective solution.

We believe that the prototype daylighting control system that we designed and tested in this study significantly improved upon conventional daylighting control system performance, even though it too was subject to the same deviations from the fitted daylight-to-photosensor correlation. This modified closed-loop proportional control system, unlike commercially-available systems, separated the electric lighting contribution to workplane illuminance from the daylighting contribution at no added cost. A system that meets design illuminance requirements for 91% of the year—with realized lighting energy savings—may increase acceptability and cost-effectiveness of daylighting controls.

Acknowledgments

We are indebted to our LBNL colleagues, Francis Rubinstein and Robert Clear. Thanks are also in order to Philippe Duchesne and Arnaud Voog, visiting students from L'École Nationale des Travaux Publics de L'État, France. This research was funded by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Additional support was provided by the Pacific Gas and Electric Company and the U.S. General Services Administration. In-kind support was provided by Pella Corporation, LiteControl and Lightolier. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor. Additional related support was provided by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Discussion

The authors have provided an important extension to the general understanding of photoelectric controls in daylighted spaces with valuable information related to the performance of these systems in spaces with venetian blinds. This information is vital to manufacturers, designers, and end-users of this equipment because daylight is often controlled in this manner. To provide further clarification and understanding to this work, I have the following comments and questions for the authors.

1. The authors description of photocell performance and output signal was based on illuminance readings of 0 to 2000 lx for daylight and 0 to 500 lx for daylight. Were these readings taken at the plane of the photocell (and if so, what were the directional characteristics of the incident light), or were they taken at the workplane in the test room?

2. Based on the research conducted by Mistrick & Thongtipaya, a photocell controlling an indirect lighting system appeared to be the most difficult to properly coordinate to

maintain a target illuminance level. Based on information provided in this paper, this could be due to the fact that the value of M for electric light deviates more from the value of M for daylight for indirect lighting than for direct lighting systems. If true, the new control approach proposed by the authors (of separating out the daylight signal) would be more beneficial in a space with indirect lighting, but should have no negative impact on system performance when used with a direct lighting system. It would be interesting to determine what level of benefit is provided for direct lighting systems.

3. The general agreement between the rear wall photosensor and the average workplane illuminance (for blind angles in the range of -20° to 60°) confirms previous work indicating that a rear wall position is viable for locating a photosensor. Also, the manufacturer of the photosensor used in this study recommends directing the sensor toward the rear wall of the room. This approach may also be a reasonable approach, but was apparently not tested in this study. The values of M provided for electric lighting and for daylight for these locations would also be of interest.

4. The findings that M is low in the summer and high in the winter agree with results obtained through computer analysis for clear window conditions (Choi and Mistrick, 1998). Lee et al. have extended this to blind conditions and solar elevation azimuth angle (azimuth angle of the sun from the window normal), which is a valuable contribution.

5. The authors' general guidelines for commissioning a daylighting control system appear to be quite reasonable. Do the authors see any advantage in marking the minimum and maximum gain setting on a photosensor control during commissioning for possible future reference and fine tuning/adjustment? This would provide a record of conditions studied at the time of commissioning and may provide a suggested range for future adjustments.

6. This paper addresses the importance of control algorithms, sensing ranges, adjustment limitations, etc. of photoelectric control products. At present, much of this information is not part of the manufacturer's literature. Do the authors agree that a standardized product performance report is needed to better evaluate and compare these products?

Richard Mistrick
Pennsylvania State University

I commend the authors for delving into the complexities of the relationship between photcell performance and fenestration. The paucity of information on this relationship has certainly contributed to the variable performance and lack of realized savings for photocell controls and retarded the infiltration of this technology into standard practice.

As is characteristic for LBNL, the wealth of data reported is substantial, thorough, and rich with future research ideas. The graphs of M versus blind angle are especially intriguing. Overall, the analysis of the data is careful and thoughtful. However it does not seem to take into consideration the potential difference in spectral response between the Li-Cor sensors at the workplane and the photodiode ceiling sensor. Li-Cor sensors have a spectral response curve that is very closely correlated with the CIE photopic response curve; but photodiodes used for electric lighting control are usually less well correlated. They may peak at the same frequency, but have a response function that is much broader than the CIE curve. Thus, they may respond differently to light sources that have similar spectral characteristics (for example, electric versus daylight or sunlight versus sky light). If the Li-Cor sensors and the photodiode do indeed have different sensitivities across the visible spectrum, this could contribute to variations in M as the mix of light sources varies. The authors have not addressed this in the paper and have attributed the variations in M primarily to differences in luminance distribution within the room.

Finally, I applaud the authors for concluding the paper with recommended commissioning guidelines. This endeavor of directly applying research results toward commercial field installations increases the speed of technology transfer of valuable research information. However, I have concerns that the level of complexity in the calibration procedure being recommended by this paper would further burden the measure cost effectiveness. I would like to see improvements to current commercial products that would allow for the increased complexity while minimizing the commissioning expense. For example, the recommendations for testing calibration at a variety of angles strongly indicates the need for dip switches or marks on the gain setting to allow the commissioning agent to return to a previous setting (already available on a few commercial products). And further, as the commissioning complexity expands it suggests the need for product with a self learning commissioning mode similar to occupancy sensors currently on the market. This photocell learning mode might be set up for a period of time (the duration of the commissioning procedure or potentially a whole work week) to take input from a desk mounted photocell and "learn" how to maintain the target illumination level over a variety of conditions.

Barbara Erwine
Lighting Design Lab

The authors have studied the very common application of Venetian blinds and their effect on our ability to sense daylight in an office environment. This is a very difficult task, and the authors need to be complimented on a job well done and well presented. I have the following questions:

Figures 3 and 5 show the relationship between the photosensor signal and workplane illuminance for fluorescent lighting and daylight, respectively. The correlation coefficients, M, are shown for each case, with values of 545 lx/V and 197 lx/V, respectively. What is the reason for the large difference in these correlation coefficients between different light sources?

Several of the figures, collectively numbered Figure 7, show the variation in M, the ratio of workplace illuminance to photosensor signal, as a function of time and weather. Also shown is a measure of the character of the daylight, E_{glo}/E_{dif}. It is also stated in the text that M grows much larger than the 197 lx/V, given as the correlation coefficient, when daylight is strongly diffuse. This does not seem to be supported by the values of E_{glo}/E_{dif} shown in the Figures, if I understand them correctly. Could the authors comments please.

Figures 8-10 indicate that workplane illuminance varies greatly with changing blind angle. Do the authors have a feeling for how much of this variation is a result of the particular photosensor that was used, and how much is inherent to Venetian blinds? Why is the 15° blind angle worse that either 0° or 45° with regard to variation in M? Do the authors recommend the use of Venetian blinds with daylight control systems, or would some other types of blinds be more suitable?

Finally, could the authors explain what they mean by "closed loop proportional" feedback, and why they think such systems are not available. I am confused because I have always thought that the Lutron Electronics system (*viz.* microWATT) fits the description for a closed loop proportional system as defined by Rubinstein *et al.* in the cited 1989 publication.

Pekka Hakkarainen
Lutron Electronics Co., Inc.

I represented EPRI on the review board for this project on numerous occasions, so this research is not new to me. It is tempting to say "Nice Job" and leave it at that, but I think that a few more comments could be useful.

I feel that this research shows a careful analysis of complex data, that is rather site specific. The paper correctly points out that few (if any) non-research installations could come close to the detailed control and analysis necessary to achieve similar results. The commissioning instructions are a welcome result of this research, but they are too complicated to be useful except to other researchers or perhaps to manufacturers trying to commercialize a system design. Do you anticipate that your research will lead to simplified, practical methods to automate a venetian blind system?

Would you recommend this type of venetian blind control for any other users? Do you know if GSA, one of the research sponsors, plans to use automated blind systems in their buildings?

Larry Ayers, L.C.
Lighting Specialist
EPRI Lighting Information Office

I would like to thank the authors for conducting a study that has direct impacts on daylighting applications in real buildings. The authors should be commended for setting up a very comprehensive methodology to investigate the impact of venetian blind angle on the performance of a closed-loop daylight-linked lighting control system. I have the following comments and questions:

A lighting control system should be commissioned based on it's control algorithms. The authors should specify that the suggested commissioning guidelines apply to closed-loop systems only. Commissioning procedures for open-loop systems are very different.

The photosensor "responds" to the illuminance distribution in the zone it controls rather than to a test-point illuminance. What distribution would we expect for M ratio for different test points of the office? In other words, what would the results be if the average workplane illuminance was not selected as a performance indicator?

Some details need to be provided related to the automation of the blind movement. For example, how long was the duration of the test where different blind tilt angles were investigated for "fixed" sun angles?

Once the commissioning is completed to optimize a system combined with blind control, does that mean that the system is also optimized when all blinds are "retracted" to the top of the window?

Finally, the authors had to deal with a problem with many variables such as tilt angle, sun position, sensor response, commissioning procedures, illuminance. The writing of the article should be organized and improved by clearly stating the objectives of the article, and summarizing results in the conclusion. The conclusion in the article did not specify the impact of the blinds on the daylight photoelectric control performance. It is also difficult to provide commissioning guidelines based on a small office case study. When given, they should be in a sequential process.

Morad R. Atif
National Research Council Canada

Author's Response

To R.G. Mistrick

The output signal of the photosensor was related to the average workplane illuminance measured by four sensors at workplane height. The bidirectional response characteristics of the photosensors were not measured. Results from Rubinstein et al. 1989 show the same significant difference in slope between the photosensor's response to electric light versus daylight with recessed lighting fixtures. In addition, we would expect the same level of benefit for direct or indirect lighting systems since the fitted slope and r^2 values for the south-facing window with horizontal blinds, given in Mistrick and Thongtipaya 1996, were nearly the same between the fixture types for the photosensor located at the lower plane of the light fixture towards the rear of the room.

While Dr. Mistrick and others did show good correlation to rear-wall photosensors, we did not show data directly relating the workplane illuminance to the photosensor signal mounted on the rear wall. Window luminance data were collected with a shielded Li-Cor sensor mounted at the rear (see Figure 10), but correlation to these data would not be useful for typical daylighting applications.

Dr. Mistrick has quite correctly pointed out our omission in referencing previous work. We have now included Choi and Mistrick 1997 in our references. With this body of research, we hope that manufacturers will continue to develop their hardware, software, and supporting documentation to increase daylighting controls, usability and reliability.

To B. Erwine

B. Erwine raises two very relevant issues. With respect to the spectral response differences between the Li-Cor and photodiode, the parameter M was characterized for daylight only, so no error was introduced with the mixing of the two spectrally-dissimilar light sources. The significant variations in M are thus attributed to variations in the room's luminance distribution. And for our prototype control system, we separate the fluorescent and daylighting illuminance contributions to within ±15 lx, using data collected independently from the photodiode. With commercial systems, the mix of sources may indeed contribute to error in performance.

In retrospect, the additional commissioning guidelines do appear to be complex and time-consuming. In our tests, we developed self-calibrating algorithms to automatically check our correlations on a monthly basis. These can be embedded in existing commercial systems to reduce costs associated with tuning the system.

To P. Hakkarainen

The large difference in the correlation coefficients for daylight and electric light can be attributed primarily to the photosensor's response to the spatial distribution of window sidelighting versus electric toplighting, and secondarily to the spectral characteristics of the two light sources. In Rubinstein et al. 1989 (Table 6-1), these same large differences are noted for a variety of photosensor, window, and room configurations.

In Figure 7d from 8:00 to 9:30 and Figure 7f from 8:00 to 11:00, the ratio of E_{glo}/E_{dif} is greater than 4, indicating bright sunny outdoor conditions. The interior daylight conditions, as modified by the venetian blind, were either strongly diffuse or had direct sun, causing the photosensor signal to exceed 10 V. This was clarified in the text.

The venetian blind, or any other commercially-available operable shading device, will modify the spatial distribution of daylight within a space. For a specific solar condition, the amount of variation in this distribution will depend on the optical properties of the shading device (i.e. how does it transmit, reflect, and scatter incident light?) and its operational degrees of freedom. For example, a simple pull-down shade made out of a light-diffusing fabric and deployed only in the full-extended position will produce no variation in M as a function of a specific solar condition. Variation in M as a function of time of day and season would also probably be less, particularly for north-facing windows. The design of this exposed-photodiode sensor may contribute to greater variability than the Lutron microPS, which employs an unshielded hemispherical diffuser, if positioned towards the rear of the room. If the unshielded sensor is influenced by stray light from the window, variability may be comparable between the two sensor designs. The Lutron sensor can be called a closed-loop proportional system, depending on it's use. It would be worthwhile to investigate these parameters further.

To L. Ayers

L. Ayers has long been a thoughtful and valuable contributor to this multi-year research project; we have been lucky to have his continued participation. The broader goal of our research has been to develop advanced integrated technological solutions using common, commercially-available envelope and lighting components to achieve greater energy-efficiency and improved comfort in commercial buildings. This research has resulted in a well-tested, proven automated venetian blind/lighting system that is market ready (Lee et al. 1998a). We have had on-going discussions with the U.S. General Services Administration to conduct a long-term evaluation of this system in a limited number of offices. However, GSA is not planning to use this system at present in their building.

To M. Atif

We characterized the variation in M for the rear area of a single-zone private office, a typical and recommended photosensor location. F. Rubinstein (1989) measured the distribution in M given a variety of parameters, including a semi-infinite room, and fully-retracted venetian blind with an outdoor reduced-scale model. Mistrick and Thongtipaya (1997) and Choi and Mistrick (1997) showed the distribution in the gain for various parameters as well, including photosensor location, using the Radiance simulation program. Using these other sources, we can broaden the characterization of M to other envelope and lighting configurations. As M. Atif notes, this research clearly raises more questions than it fully answers. We believe that fundamental improvements to the reliable performance of daylighting control systems will require basic hardware and algorithmic changes (e.g., change from PID to adaptive fuzzy logic?) to compensate for the numerous and confounding factors found in typical building applications.

Appendix

Lighting Power Correlation

The relationship between input power to the ballasts and the average workplane illuminance (electric lighting only) over the full electric lighting dimming range was determined after operating the newly installed lamps for 100 hr 1) during daylight hours, by measuring the workplane illuminance with daylight only, then measuring electric and daylight workplane illuminance during stable daylight periods, and 2) during night hours by turning on the lights from off to full power for 30 min to allow for lamp temperature stability, then reducing power by 10% at 10 min intervals.

The correlation was performed in February 1996. The quadratic fit (r^2=0.999), defined by equation (2) above, estimated the measured workplane illuminance to within -6 to +7 lx over the full power range. In typical practice, daylighting control systems are rarely commissioned again within a year or more, so this initial correlation was used throughout the test period without further modification.

The correlation was checked periodically using the nighttime calibration method to determine stability over time. Lumen depreciation, dirt, and equipment drift can contribute to degradation of the initial correlation's accuracy. Over the course of three months of daytime operation with on/off switching from 0% to 30% power and with continuous dimming, the initial correlation fit estimated the measured workplane illuminance appreciably well in both rooms: to within +3 to -51 lx over the full power range. After twelve months, lumen depreciation caused the initial fit to estimate the measured workplane illuminance to within -5 to 30 lx in the 90-270 W range, and 0 to 15 lx in the 0-90 W range, on average 5.5±7 lx.

If the fluorescent tubes are turned off and allowed to cool down, significant reduction of light output occurs as expected upon restarting the lamps: light output within the first 2 min is 75-84% of full light output, and reaches 95% within 4-5 min. At 10-12 min, the lamps reach 99-100% of full light output. These transitory effects were not included in the above estimates of error (if included, the fit overestimated the illuminance by 30-123 lx after 12 months of operation, if the lamps were turned on to 100% power from a cooled down state, which never occurred with this control system). The on/off option of the control algorithm cycled the fluorescent lights between 0% and 30% power (50-60 lx). The degradation in light output at this end of the power range was 10 lx. This behavior can contribute in part to the deficit in the measured workplane illuminance.

Electric Lighting Illuminance Correlation

A linear correlation between the ceiling-mounted photosensor signal and the average electric lighting workplane illuminance over the entire electric lighting dimming range was also determined (equation 1 above). The same daytime and nighttime procedures were used. Data indicate a stable relationship over a year's operation: the initial fit estimated the measured workplane illuminance to within -1 to -36 lx, on average -17.6±10.2 lx. The photosensor is fairly robust, so no drift is expected over time. The sensor is temperature dependent, but space conditions were kept within a fairly tight range of ±1 °C by the monitored mechanical system.

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