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S.E. Selkowitz

**Environmental Energy
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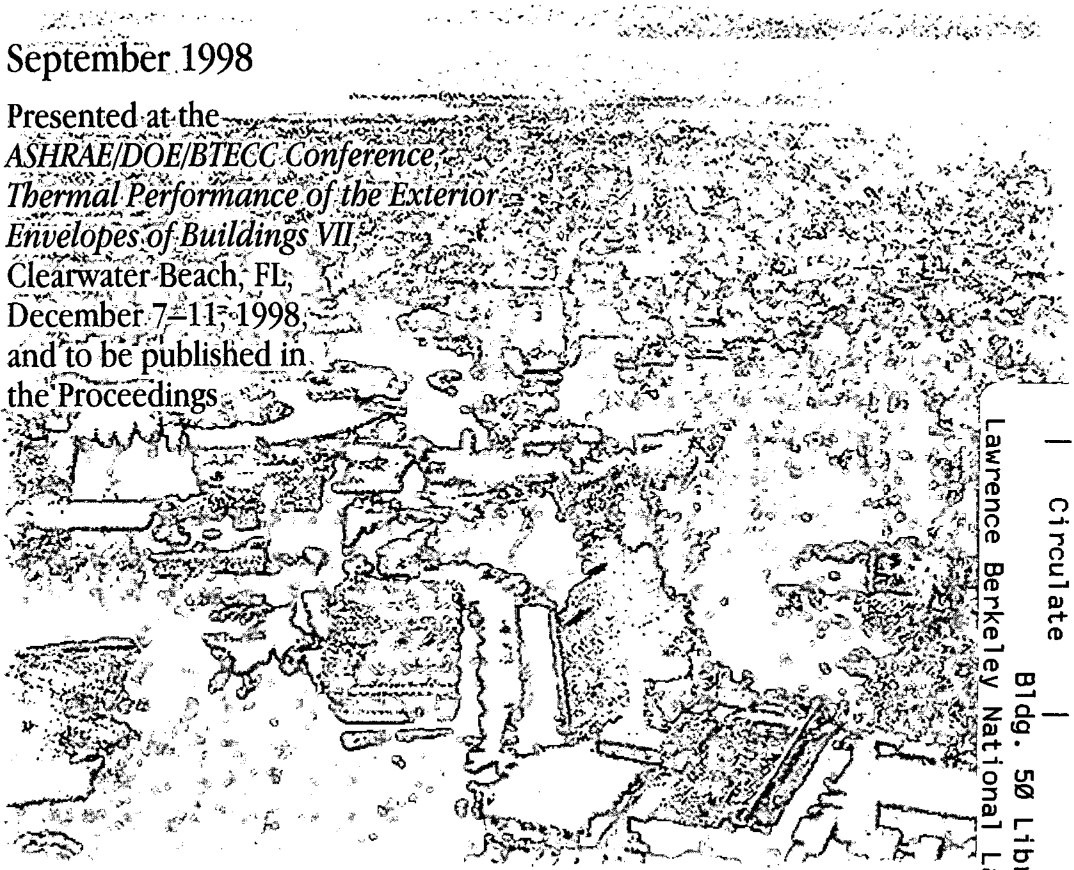

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INTEGRATED PERFORMANCE OF AN AUTOMATED VENETIAN BLIND/ ELECTRIC LIGHTING SYSTEM IN A FULL-SCALE PRIVATE OFFICE

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ABSTRACT

Comprehensive results are presented from a full-scale testbed of a prototype automated venetian blind/lighting system installed in two unoccupied, private offices in Oakland, California. The dynamic system balanced daylight against solar heat gains in real-time, to reduce perimeter zone energy use and to increase comfort. This limited proof-of-concept test was designed to work out practical "bugs" and refine design details to increase cost effectiveness and acceptability of this innovative technology for real-world applications. We present results from 14 months of tuning the system design and monitoring energy performance and control system operations. For this southeast-facing office, we found that 1-22% lighting energy savings, 13-28% cooling load reductions, and 13-28% peak cooling load reductions can be achieved by the dynamic system under clear sky and overcast conditions year round, compared to a static, partly closed blind with the same optimized daylighting control system. These energy savings increase if compared to conventional daylighting controls with manually-operated blinds. Monitored data indicated that the control system met design objectives under all weather conditions to within 10% for at least 90% of the year. A pilot human factors study indicated that some of our default control settings should be adjusted to increase user satisfaction. With these adjustments, energy savings will decrease. The final prototype design yielded a 10-year simple payback for this site. If mechanical system downsizing opportunities and qualitative improvements to worker's comfort are included, this innovative technology could be more cost effective. Marketing information for commercializing this technology is given.

INTRODUCTION

The large variation in daylight availability and solar radiation due to diurnal and seasonal changes in sun position and cloud cover is a major cause of both high energy use and peak demand, and of occupant discomfort. However, an optimum cooling and lighting energy balance exists between the window and lighting system that can be used to advantage to reduce this energy use. Daylight can offset lighting energy use and the heat gains associated with the electric lighting system, but the admission of too much daylight can increase cooling loads associated with solar heat gains. If an

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integrated systems approach is used to combine separate building components, substantial energy savings can be attained with improved occupant comfort compared with conventional design practice. And since lighting and cooling in commercial buildings constitute the largest portion of peak electrical demand, promotion of such integrated systems can become a cost-effective option for building owners and to utilities concerned with containing peak load growth.

For climates with moderate daylight availability and for building types that are cooling-load dominated, dynamic window technologies can be coupled with daylighting controls to actively optimize daylight and its respective solar heat gains at the perimeter zone of commercial buildings. The category of "dynamic" window technologies encompasses numerous conventional components such as motorized louvers, venetian blinds, and shades, as well as more advanced glazing systems such as switchable electrochromics,[1] photochromics, thermochromics, polymer dispersed liquid crystal glazings, and electrically-heated glazings. Substantial research has been devoted to passive heating applications with dynamic window systems working as heat collection systems. Computer simulations, laboratory tests, or reduced-scale field tests document the energy benefits associated with this type of application; e.g., automated between-pane venetian blinds controlled by temperature and solar position (Rheault and Bilgen 1990).

Less research has been devoted to integrated window and lighting systems. Simulation studies have been conducted on electrochromic glazings coupled with daylighting controls (Selkowitz et al. 1994). Other researchers demonstrated external venetian blinds and a dimmable electric lighting system in a test cell and a full-scale occupied building, but results were sparsely documented (Aleo and Sciuto 1993). While there are dynamic shading or dimmable lighting systems commercially available today, there are a lack of comprehensive field-monitored performance data that quantifies the benefits of both systems working interactively.

We have recently completed a multi-phase R&D project that focused on developing and testing viable daylighting solutions for commercial buildings. Three main strategies were followed throughout the duration of the project: (1) develop new prototypes in accordance with practical near-term goals using existing materials and technologies; (2) gather sufficient data and information to document performance to utilities, building owners, or potential industry partners; and (3) develop adequate design tools for the architectural community wishing to incorporate the integration concept into new commercial buildings. An automated venetian blind and dimmable electric lighting system was identified as a practical, near-term technological solution. Prototypes were refined using a series of progressively complex and rigorous evaluation procedures: simulations, reduced-scale lighting and calorimeter field tests, full-scale testbed demonstrations, and human factors studies.

In this study, we present results from a full-scale testbed demonstration that was conducted over the course of 14 months in two side-by-side, fully furnished, unoccupied test rooms located in a federal office building in downtown Oakland, California. These tests completed the development of the prototype design. We refined hardware and control system operational parameters using monitored energy and control system data, and subjective responses from human subjects. The final design solution represents a compromise between energy efficiency, control performance, human factors, and cost. We document the final development of the design solution in five sections:

1. System Design. We explain how hardware and software modifications were made to minimize cost and increase reliability.
2. Control System Performance. The ability of the control system to meet control objectives reliably throughout the year was evaluated using monitored data. We explain how fine-tuning of the hardware and software design minimized discrepancies in performance.

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[1] The electrochromic glazing consists of a thin multi-layer coating on glass that switches from a clear to colored state with no optical distortion (view remains clear), with a small applied voltage.

3. Energy Performance. Energy performance data for the default system and for control parametrics are presented. Detailed results are given in Lee et al. 1998a.
4. Human Factors. A pilot test was conducted to survey user satisfaction with the resultant environment. Data were collected on user-preferred control settings, and these are presented in terms of their impact on system design and energy performance. Detailed results are documented in Vine et al. 1998.
5. Market Transfer. Estimates of the mature market cost and payback are given. We also discuss a market path to commercialization of this technology.

METHOD

The full-scale testbed demonstration facility, located in the Oakland Federal Building, consisted of two 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, furniture, and mechanical systems to imitate a commercial office-like environment (Figure 1). The southeast-facing windows in each room were simultaneously exposed to approximately the same interior and exterior environment so that measurements between the two rooms could be compared.

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). Interior measurements included horizontal workplane illuminance, vertical illuminance, power consumption of all plug loads and mechanical equipment, cooling load, interior air temperatures, and other information pertaining to the status of the dynamic window and lighting system.

Identical operational dynamic window and lighting systems were installed in each room so that the position of the prototype and base case systems could be interchanged. Both test rooms were located 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. The building was located at latitude 37°4' N, longitude 122°1' W. The testbed windows faced 62.6° east of true south. Both windows' view were 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 rooms after 7:45 from the spring to autumnal equinox.

Window Condition

The existing window system consisted of 6-mm (0.25-in) single-pane, green tinted glass glazing properties: (Tv=0.75, SHGC=0.46, U-Value=6.24 W/m^2-°K (1.1 Btu/h-ft^2-°F)) with a custom aluminum frame. The window opening was 3.71 m (12.17 ft) wide and 2.74 m (9 ft) high with five divided lights ranging in width from 0.61-0.67 m (2.02-2.19 ft). The visible glass area was 7.5 m^2 (80.8 ft^2). The window-to-exterior-wall-area-ratio was 0.65. 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, motorized venetian blind was fitted in a white painted wood frame and placed 0.127 m (0.5 in) away from the interior face of the existing glazing system. A blind was placed in each of the five divided lights. Each venetian blind was tensioned between the head and sill of the window and was not retractable, only the angle of the slats could be altered. Blind angle (Σ) was defined from the horizontal plane, where positive angles allow a ground view from the interior. At 0°, the slats were horizontal, at 60°, the slats were just touching, and at 68°, the slats were squeezed to the mechanical limit of the venetian blind system. Diffuse daylight was still admitted at 68°.

Lighting Condition

Two pendant indirect-direct (~95%, 5%) fixtures with four T8 32W lamps, continuous dimmable electronic ballasts, and a shielded photosensor 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. The photosensor was placed at one end of the second light fixture and flush with the bottom of the fixture, 2.08 m (6.8 ft) from the window wall. The ballasts were rated to produce 10% light output at a minimum power input of 33%. Lighting power density was 14.53 W/m^2 (1.35 W/ft^2).

Experimental Procedure

Data were collected from June 1, 1996 to August 31, 1997. The prototype system was developed iteratively to refine control system algorithms and hardware operations according to observations in the field. Additional system parametrics were performed to address particular issues raised by the human factors study, conducted in July 1996, or to characterize and improve system performance. Although these system parametrics were monitored, the energy-efficiency performance data presented below are given for the same default control system throughout the year, unless otherwise noted.

Data Sampling and Recording

For energy and load monitoring, data were sampled every 6 s then averaged and recorded every 6 min from 6:00-19:00 and every 20 min from 19:00-6:00 (standard time) by Campbell Scientific CR10 dataloggers. For control system monitoring, data were sampled and recorded every 1 min from 7:00-19:00 by the National Instruments LabView data acquisition system. Weather data, collected on a nearby roof, were sampled and recorded every 1 min by a CR10 datalogger.

Electric lighting power consumption was measured in each test room with watt transducers (Ohio Semitronics GW5) that were accurate to 0.2% of reading. Daily lighting energy use was defined as the sum of 6-min data over a 12-h period defined by 6:00-18:00, and between rooms, was found to correlate to within 12±46 Wh (2.6±5.4%, n=25).

Cooling load measurements resulted from a net heat balance on each well-insulated test room where the interior air temperature was maintained at a constant level (±1°C) by an electric resistance heater and a building chilled water liquid-to-air heat exchanger with measured flow rate and inlet and outlet temperatures. Daily cooling load was determined by the sum of 6-min data over a 12-h period defined by 6:00-18:00, while the peak cooling load and hour was defined by the test room with the higher average hourly cooling load over the 12-h period. The daily cooling load of Room A was found to correlate to within 87±507 Wh (0.5±5.0%, n=33) of Room B when the cooling load exceeded 5 kWh. Peak cooling loads (>0) of Room A were found to correlate to within -24±114 W (0.6±6.4%, n=23) of Room B.

SYSTEM DESIGN

While numerous approaches and technologies could have been employed, we selected off-the-shelf and well-utilized, commercially-available technologies to demonstrate the integrated window and lighting concept. All hardware was used as-is or modified slightly to meet the requirements of the control algorithms. All control was derived from acquired sensor data and was designed to not rely on date, time, or site-specific information, since such reliance would increase the complexity of the commissioning process. The automated venetian blind/lighting system was checked and adjusted, if necessary every 30 s to meet the following control objectives:

- Control interior illuminance. Provide a workplane illuminance design level of 540-700 lux with daylight. If there is insufficient daylight, supplement daylight with fluorescent lighting to a design level of 510 lux. This range was designed to offset electric lighting use while minimizing unnecessary solar heat gain loads on the cooling system.

- Block direct sun at all times. Direct sun may create visual discomfort and glare, and may cause thermal discomfort during the cooling season.
- Turn lights off. For greater energy-efficiency, the electric lights were turned off if there was sufficient and stable daylight[2] after a 10-min time delay. The delay reduces potentially annoying on/off cycling of the lights (from 10% light output to 0%) during partly cloudy conditions.
- Permit view. During overcast conditions, early morning and late afternoon hours, or when there was no direct sun in the plane of the window, the slat angle was set to horizontal to permit a view if the maximum lighting level of 700 lux was not exceeded.
- Control glare. The range of motion for the blind was restricted to positive, downward tilting angles to limit sky-view glare; i.e., Σ=0-68°. Negative, upward blind angles permit a view of the sky and were therefore not allowed in the default system. Parametrically, we tested a wider range of blind angles to see if this would increase lighting energy savings.
- Restrict blind movement. A very responsive window system may meet all control objectives adequately, especially under transient conditions (partly cloudy skies), but large angle and/or frequent blind movement may cause distraction. Our default setting was activation every 30 s with unlimited blind movement. We parametrically tested a number of algorithms that changed 1) the interval of activation and 2) the amount of change in blind angle within an interval of activation. We also tested "smarter" algorithms that incorporated time delays before a blind could reverse the direction of movement to avoid hunting and oscillations that can occur during partly cloudy conditions.

Any automatic system, if it is to meet with user approval, must allow for adjustment of some of its parameters. These adjustments must be easy to use and few enough to not add unduly to the system's expense. The amount of control given to users, and the energy-efficiency consequences of doing so, is the subject of on-going discussion and debate. We designed an interface to enable occupants to fine-tune the system's operation with the following options:

- Illuminance level. A slider switch allows the user to adjust the design workplane illuminance setpoint between 240-1650 lux. The system will meet the setpoint with available daylight or electric light, but will not allow direct sun admission.
- Time delay for lights off. The time delay before the fluorescent lights are shut off can be set by the user to 5, 10, or 20 min.
- View blind position. Instead of the default horizontal blind angle, the user can customize the view blind angle using a slider switch (up to Σ=0±35°) to control view or glare, if present.
- Blind adjustment interval. The user can set how often (1-10 min) the blinds are activated.
- Magnitude of blind motion. The user has the option of restricting the amount of blind movement per interval of activation by setting a toggle switch from "unlimited" to "limited." If unlimited, the blinds will move as much as is necessary within an activation period to meet control objectives. If limited, the blinds will adjust a small amount each activation interval (~10°), if necessary, until the control system is satisfied. Note, under stable daylight conditions, the blinds may not move for four to five hours.

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[2] This is a typical condition for buildings with a high daylighting effective aperture (high glazing area and/or glazing transmission), or for buildings located in areas with high daylight availability (low-rise areas, sunny climates).

To implement the above control algorithms, hardware requirements included 1) interior[3] venetian blinds with a modified DC motor and necessary power requirements, 2) fluorescent lighting with dimmable electronic ballasts, 3) a shielded photosensor typical of daylighting applications, 4) a prototype sun sensor[4] situated in the plane of the window, and 5) a microprocessor with appropriate electronics and low-voltage wiring to interface with window and lighting hardware (Figure 2). We explain the design modifications made to off-the-shelf, commercially-available hardware components below.

Motor

A small DC motor with step-down gearing and output shaft position sensing was designed by the venetian blind manufacturer to fit in the lower right-hand corner of the blind. We connected the power and blind position signal from each motor to a power-control-signal multiplexing box which was operated by the main control system. We also correlated blind angle to the venetian blind shaft position sensor and incorporated these data into the control software. To move the blind to the correct angle, the DC motor was powered a maximum of 10 pulses per system control cycle. Pulse duration was 20-50 ms. The motor required 12 V at 150 mA. Additional electronics used to synchronize movement required 4-5 W (per room) for the "on" state, but this could be minimized with larger scale multiplexing.

Because the motor with gear train produced a small, high-pitched sound, modifications were made to reduce both the sound level and the frequency and speed of blind movement. As designed, the miniature high-speed, low-cost DC blind motor was geared down to deliver sufficient torque to operate the blind apparatus. A change in blind angle of about 5° required a DC pulse of approximately 50 ms, which resulted in a quick twist of the blinds which was visually distracting. The motor speed could be reduced by decreasing the supply voltage, and therefore torque, but this would cause the blind to stall under high load conditions (e.g., when closed). Instead, we modulated the duty cycle[5] of the applied DC power to deliver more power when needed to maintain blind movement. A pulsed DC power source at a frequency of ~100 Hz with a variable duty cycle was used to power the motor for a fixed-pulse duration. The rate of blind angle change was reduced by a factor of four while not causing a stall in movement at high loads. In addition, the motor noise was reduced to a soft ticking similar to that of a small clock. Additional noise control can be achieved by placing the motor in a sound-dampening housing. Interference by furniture or by other extraneous events will not be automatically detected.

Photosensor

The shielded photoelectric sensor performed the same function as in conventional daylighting control applications. We made no unique hardware modifications to this sensor. We simply amplified its microamp output signal to produce a linear signal (0-10 V), in response to the luminance level within its field of view, corresponding to an illuminance range of 0-2000 lux. All built-in electronics that modify the output signal were overridden by our control system. The downward-facing, shielded sensor was mounted so that its view was not skewed by direct light from the fluorescent lamps or the window, but its response could still be subject to various spatial distributions of light (side versus overhead), temperature fluctuations, and intermittent obstructions (e.g., person standing directly under it).

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[3] Thermally, between-pane venetian blind systems would be more energy-efficient; however, these systems were not tested here.

[4] The number of sensors was minimized to reduce equipment cost and simplify installation but still maintain satisfactory performance. Four input signals were required, three of which were gathered from existing daylighting controls hardware, the other of which required this new physical sensor.

[5] The duty cycle is the percentage of time that a signal is on (for the remainder of each cycle, it is off). A 100 Hz signal has a 10 ms period. If the duty cycle is 10%, the power was applied to the motor for 1 ms out of every 10 ms.

Sun Sensor

To determine the position of the sun and if direct sun was present relative to the window, a sun position sensor was developed and tested in previous work (DiBartolomeo et al. 1997). In the full-scale testbed facility, a physical electrical connection from the testbed interior to the exterior sensor was not possible, so this prototype sensor could not be used. Instead, we installed a simple photometric photodiode at the window to detect when direct sun was present and in the plane of the window. A real-time clock and geographic location (longitude and latitude) was used separately to calculate the sun's position.

The photodiode estimated exterior illuminance at the window. If the sensor's signal was above a certain level, direct sun (strong shadows) was observed to be present and within the window plane. This sensor will be subject to shading by exterior surroundings (e.g., muntins, overhangs, or fins). If used, care must be taken to ensure that its placement reflects incident daylighting conditions for the majority of the window surface area.

Solar position relative to the window plane is difficult to determine with simple cheap hardware. The temporary design solution using the real-time clock requires special information to commission, so it can not be used for practical applications. Exploratory research was done to come up with an economical design solution that would circumvent the use of the real-time clock and avoid potential commissioning errors and cost. Monitored solar data from the rooftop weather station and from within the test room were used to independently validate the accuracy of this approach. Results from both databases were similar; it took an average of 12 days of operation to determine latitude within a 5° error. This decreased to less than 3° after 30 days of observation. For direct sun control using venetian blinds, a 5° error in latitude is acceptable. A 12-day delay in optimal operation is also acceptable, since control systems are typically installed well before occupants move in. During this initial period, the control system can still prevent admission of direct sun using a conservative value of latitude. Given these results, this design solution was considered to be a viable solution and its use introduced no added cost to the prototype design.

Fluorescent Power

A watt transducer, used in earlier reduced-scale work to determine fluorescent lighting power for control, was replaced by an internally-generated control signal. This signal's correspondence to fluorescent power was determined to be stable and accurate over time. A watt transducer is an expensive sensor and its removal significantly reduces the system's complexity and expense.

Microprocessor

The control system was linked by low-voltage wiring to a desktop computer located outside the two test rooms. The "smarts" of the system reside in a LabView controller program and was adjusted using toggles and switches on a virtual instrument panel. This design facilitates debugging and testing of the system. The final control algorithm can be coded onto a microprocessor. Since we operate the control loop at a fixed repetition rate, duration of environmental parameters (such as exterior light levels) can be monitored by internal loop counters without requiring a real-time clock.

CONTROL SYSTEM PERFORMANCE

We show an example of how the dynamic system performs compared to a static system in Figure 3 for August 15, 1996. The dynamic system achieved substantial reductions in cooling load (21%), peak cooling load (13%), and lighting energy use (21%) compared to a static horizontal blind with the same daylighting control system. Cooling load reductions were the result of the automated blind's control over solar heat gains. Lighting energy reductions were due to the active control of daylight illuminance. Note how the dynamic blind closed at 7:00 then started to open at 11:00 to maintain a constant daylight illuminance at the workplane as daylight availability changed. After

14:30, the dynamic blind moved to a horizontal position to maximize view and daylight admission. Average illuminance levels at the back of the room were well controlled in the morning hours to within 500 to 1000 lux (the blinds were closed to the mechanical limit when illuminance exceeded the 700 lux design level), while the static system resulted in illuminance levels of 1000-2500 lux. Visual and thermal comfort may be compromised with the static system.

We evaluated the control performance of the dynamic system over a solar year defined by June 1996 to June 1997 from 7:00-19:00 (720 min). The performance was represented by 147 non-contiguous days of dynamic system operation in either of the two test rooms. These results are presented below.

Direct Sun

Direct sun was blocked fairly consistently throughout the day and when admitted, tended to be corrected within a one- to five-minute period. We were unable to determine if this control objective was met throughout the entire year using independent monitored data. Instead, a time-lapse video was made for a week in July 1996 under partly cloudy to sunny conditions. The office interior was recorded at ten images per minute.

We observed direct sun in the space when: (1) the interior sun sensor was shadowed by exterior local obstructions while portions of the window were not; (2) when the rate of change in daylight conditions exceeded the 30-s control activation rate and/or the rate of blind angle control; (3) when the tension on the blind was insufficient to provide the same angle at the top and bottom of the window; and (4) when individual blind slats were stuck on the string ladders.

The sun sensor was used to determine when the sun was in the plane of the window and if direct sun was present. Since the sensor was placed at the interior face of the window above the blind header, it was shadowed by window mullions or building projections when the sun was very oblique to the window plane. For example, in the early morning, a small triangle of sun was incident on the upper portion of the sidewall 0-1.5 m from the window for 6 min before the blinds were closed.

Under rapidly changing, partly cloudy conditions, direct sun was admitted occasionally when the blinds were either not moving fast or frequently enough. In these cases, larger areas of direct sun were observed on the floor and sidewalls. This problem was corrected within 1-5 min. We designed and tested smarter blind control algorithms to maximize control performance and minimize occupant distraction. These refinements are discussed below.

When individual slats were stuck on the string ladder, direct sun was observed on the floor and sidewalls for 1-5 min. The modulated blind motor design, implemented later, accommodated differences in tension and load as the blind opened or closed. This improved positioning accuracy of blind angle across the entire height of the window.

Because of the inherent venetian blind design, direct sun was admitted through the sides of the blind system (at vertical muntins) and through the holes for the string ladder upon which individual slats rest. This was not a significant problem since the sun patches were very small (<0.25 ft^2).

Workplane Illuminance

The illuminance control objective was met satisfactorily throughout the year to within -10% and +25% of the design illuminance range of 510-700 lux. Less tolerance was given for insufficient illuminance than for excessive illuminance. To determine how well the dynamic system performed, we binned monitored workplane illuminance data[6] collected throughout the year. For the subset of data when the monitored illuminance was not within the design illuminance range, we also computed the average illuminance for each day.

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[6] 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.

We show the distribution of all monitored illuminance data collected throughout the year in Figure 4. For 70% of the year, the monitored illuminance was within the design illuminance range. For 15% of the year, the monitored illuminance was less than 510 lux. For 15% of the year, the monitored illuminance was greater than 700 lux.

When the monitored illuminance was less than 510 lux (ranging from 0-60% of a 12-h day), the monitored illuminance was within 10% of the setpoint for 91% of the year. The number of times when the monitored illuminance was less than the 10% limit or 459 lux was infrequent, on average 13 min/day, with a maximum of 139 min/day occurring on a partly cloudy day (Figure 5).

When the monitored illuminance was greater than 700 lux (ranging from 0-30% of the 12-h day), the monitored illuminance was within 25% of the setpoint for 76% of the year. The number of times when the monitored illuminance was greater than the 25% limit or 875 lux was also infrequent, on average 26 min/day, with a maximum of 112 min/day occurring on a clear sunny February day.

If the blinds were completely closed and the design setpoint was exceeded, we did not consider this to be a control discrepancy. Daylight could not be controlled below 700 lux on sunny days even with the blinds completely closed because of the high transmission glass and large window area. This occurred on clear sunny days from 7:00-9:30 in June and from 8:00-10:30 in October. Of the times when the design setpoint was exceeded, 19% occurred when the blinds were not completely closed (Figure 6).

The illuminance control objectives were not met when 1) when the rate of change in daylight conditions exceeded the 30-s control activation rate and/or the rate of blind angle control and 2) the control system's predicted illuminance level differed from the actual monitored illuminance.

On occasion, the daylight conditions changed faster than the blinds could be opened or closed. For example, on a clear day when the sun was just coming into the plane of the window, the blinds were horizontal. Because the conditions were rapidly changing, it took 6 min for the blinds to completely close, during which the monitored illuminance dropped from 1600 lux to 900 lux. On another day, partly cloudy conditions changed more rapidly than the blind could move causing the monitored illuminance to exceed 700 lux for 50% of the time between hours 8:00-11:00 (Figure 7).

Inaccuracies in predicted illuminance levels caused additional control discrepancies. To implement illuminance control, we used the photosensor signal to predict both the electric lighting and daylighting contributions to the workplane. Linear correlations between the photosensor and measured workplane illuminance were made at the beginning of the 14-month test period, then programmed into the control system. The blind and electric lighting systems were adjusted according to these predicted values. Inaccuracies in the correlations were the primary cause of differences between the monitored and predicted illuminance levels. The electric lighting correlations introduced minimal error—at the most 5.5±7 lux—due to the stability of this system. The daylighting correlation produced larger errors because the photosensor's response varied with the complex spatial distribution of daylight, up to -121 lux (24%) in the 0-510 lux range. We show a worst case example in Figure 8 where the monitored illuminance is less than the predicted illuminance from 11:15-18:00. Selecting a more conservative daylighting correlation coefficient would decrease the number of times when illuminance levels fall below the design setpoint, but this would also increase energy consumption and the level of light provided. Excessive illuminance could also cause visual discomfort for some tasks (i.e., computer work).

View

Maximum view, defined by blind angles within +2° to -35° of horizontal, was possible on average for 56% of the day throughout the year. Clear sky, sunny conditions define the lower y-axis boundary of data points in Figure 9, while partly cloudy and overcast conditions define the scatter of data above this lower limit. In general, view was possible when the sun was out of the plane of the window and/or when there was insufficient daylight to meet the design illuminance level (i.e., overcast conditions or in the late afternoon). See Figure 8 for an example of how the blind was activated on a clear fall day. On this day, view was possible from 15:15 to sunset. We defined the blind angles for "sufficient" view by personal observations of the window with a horizontal line of sight when seated 2.5 m (8.2 ft) from the window wall.

There was no appreciable diminishment of view (< 2%) when the frequency of blind activation was slowed from 30 s to 15 min. If the design illuminance setpoint was increased, view was possible for a larger percentage of the day because the blinds were positioned to a more open angle to increase daylight availability. For example, if the illuminance setpoint was increased from 540-700 lux to 740-900 lux, view availability increased from 46% to 60% on a clear sunny summer day.

The presumption of the control algorithm is that more view is desirable as long as direct sun is blocked. Our direct observations of the space revealed that glare was an important factor to consider, since in the afternoon hours, when the sun was not in the plane of the window and the blinds were horizontal, the opposite buildings reflected a substantial amount of daylight. Calculations made of the window luminance and various glare indices revealed that for the week of July 1996 under sunny conditions, glare indices were within "just acceptable" levels. Still, glare may cause the occupant to set the view blind angle to a more closed position.

Electric Light Cycling

The fluorescent lights were designed to turn off if the lights were on at a minimum output for the past 10 min and there was sufficient daylight during that period to turn the lights off and meet the design setpoint. There was no time delay for turning the lights back on, since we believe that occupants would want light immediately if there was a noticeable dip in daylight levels. Despite this, we tallied the number of times lights were turned from off to on within 5 min, since off-to-on cycling of lights within a relatively short period may be noticed; i.e. by the difference in illuminance levels when the lights cycle between 10% minimum output (60 lux) and off, or by the very slight clicking noise when turned on or off (as with occupant sensors).

The electric lights were turned on within 5 min of having been turned off a maximum of 8 times in a 12-h day over the year. The cause of this behavior was due to partly cloudy conditions, with the control system on the threshold of just meeting the design illuminance setpoint with daylight (e.g., Figure 10). During stable clear sky conditions, this behavior was non-existent.

Blind Movement

On occasion, the blind reversed direction or moved significantly within a short period of time in a manner that may be perceived as distracting. With 30-s blind activation, the blind was moved more than 10° total in any direction within 5 min on average 53 times per day (7% of a 12-h day) throughout the year, with a maximum of 234 times occurring on a partly cloudy summer day. The blind reversed direction at least twice within a 2-min period an average of 12 times per day (1.6% of a 12-h day) throughout the year, with a maximum of 70 times occurring also on a partly cloudy day. The tally may be lower than actual because the blind was activated every 30 s while data was recorded every 60 s. Contiguous movement for more than 10 min will result in a higher tally than if non-contiguous.

There were three causes for this behavior: (1) large, temporary changes in the photosensor signal caused the blind to move significantly to meet daylight optimization or view control objectives; (2) large, temporary changes in the sun sensor signal caused the blind to move significantly to meet the direct sun control objective; and (3) blind hysteresis. Temporary changes in sensor signals were caused by partly cloudy conditions or when the sun transitioned out of or into the plane of the window.[7] The blind would be moved only if the sensor signal and blind angle were within control range. For example, if the photosensor signal indicated that the 700 lux illuminance setpoint was

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[7] In the an occupied room, these changes could also be caused by occupants' actions (e.g., standing under the sensor).

well exceeded, temporary increases to the sensor signal would not cause blind movement if the blinds were already closed. Blind hysteresis, or small oscillations in movement, was caused by the motor as it tried to achieve a particular angle with a non-linear tensioned blind. This was eliminated in September 1996 with adjustments to the position signal calibrations and by modulated power.

Unnecessary movement can be reduced with smarter control algorithms that accommodate temporary environmental changes. We designed and tested a number of blind algorithms that lengthened the activation cycle, restricted angular movement per activation cycle, and/or delayed angular movement in the opposite direction. In Figure 11, we compare blind operation on a partly cloudy day if blind movement is not permitted within 15 min of the last time it was moved. In Figure 12, we compare blind operation if blind movement in the opposite direction is not permitted within 15 min of the last time it was moved. In each case, control objectives were not met as consistently, fluorescent lighting use increased, but movement was reduced which may lessen potential occupant distraction. System longevity may also be increased. Drawbacks include less stability in interior illuminance levels and periodic direct sun. Lighting and cooling energy reductions may also be affected (see energy section below). Design improvements to the blind's motor system over the year resulted in very quiet and smooth motion, which may lessen the importance of these control refinements. User adjustment of blind activation settings may also increase occupant satisfaction.

ENERGY PERFORMANCE

We used energy simulations and reduced-scale field tests initially to determine the energy-savings potential of the dynamic system, then we segued into full-scale tests to monitor performance using real envelope and lighting equipment. DOE-2 building energy simulations were used to model automated venetian blinds with daylighting controls, manually-operated shading systems (activated every hour when glare or direct sun was detected), and advanced electrochromic glazings (Lee and Selkowitz 1995). Total annual energy savings of 16-26% were attained with the automated blind compared to an unshaded low-E spectrally-selective window system with the same daylighting controls in Los Angeles, California. Separately, accurate heat flow measurements were made using the dual-chamber calorimeter Mobile Window Thermal Test (MoWiTT) facility in Reno, California (Lee et al. 1994). Field data indicated that an automated interior blind with spectrally-selective glazing and a less than optimal control algorithm was more than twice as effective at reducing peak solar gains under clear sky conditions as a static unshaded bronze glazing with the same daylighting control system, while providing the same level of useful daylight. A year-long field test was also conducted in a 1:3 reduced-scale test cell to measure lighting energy use of the automated venetian blind/lighting system under real sun and sky conditions and to further develop the control algorithm and hardware solution (DiBartolomeo et al. 1997). Lighting energy savings of 34% (winter) and 42-52% (summer) were achieved on clear sunny days compared to a fixed, partly closed blind ($\Sigma \approx 50^\circ$) with the same daylighting control system for south to southwest-facing windows in Berkeley, California.

Testbed Results

With the full-scale testbed facility in Oakland (described in the Methods section), we compared the energy performance of the dynamic system to a static venetian blind with or without the same prototype daylighting control system. Daily energy use was defined from 6:00-18:00.

Compared to a static blind (set at any tilt angle) with *no* daylighting controls, daily lighting energy savings of 22-86% were obtained with the dynamic system, where the degree of savings was proportional to daylight availability. On clear sunny days, daylight displaced lighting energy use completely for approximately 50% of the daylight hours. On overcast days, electric lighting was required to supplement daylight for a much larger percentage of the day. Peak lighting demand savings were largest during peak cooling periods—for periods of high daylight availability and peak cooling, the dynamic system shut the lights off, realizing a savings of 100% compared to the non-daylit static blind. Cooling load data were not collected for this non-daylit basecase on a routine basis. However, measurements made on three clear days in late July show that daily cooling load reductions of 28% were obtained by the dynamic system compared to the static horizontal blind. Peak cooling load reductions of 28% were attained for these same conditions.

If both the dynamic and static blinds have the *same* daylighting control system, then daily lighting energy savings and cooling load reductions resulting from the dynamic blind were roughly proportional to the openness of the static blind's angle and its relation to solar position (Table 1 and Figure 3 from 8/15/96 above). Lighting energy savings were achieved through the optimal response of the dynamic blind to changing exterior daylight levels, primarily in the mid-afternoon when the sun was out of the plane of the window and when exterior daylight illuminance levels were diminishing. The dynamic blind was able to maintain a greater level of illuminance for a longer period than a partly closed static blind. Compared to a horizontal blind, the dynamic system's lighting performance was nearly the same. Cooling load reductions were achieved principally by the control of direct transmitted solar heat gains and to a lesser degree, by reduced heat gains from the electric lights. The more closed the angle of the static blind, the lesser the savings achieved by the dynamic system. On clear sunny days, peak lighting demand was the same in both cases since the design illuminance setpoint was exceeded during the peak period, causing the lights to shut off. Peak cooling loads occurred in the early to mid-morning hours when the sun was in the plane of the window and again reflects largely the difference in direct transmitted solar heat gains resulting from the average hourly blind position.

Control Parametrics

Increasing the daylight illuminance setpoint significantly reduced lighting energy savings since more daylight and/or electric lighting was needed to meet the higher illuminance level throughout the year. If the blind's illuminance setpoint range was increased from 540-700 lux to 740-900 lux or 940-1100 lux, daily lighting energy savings decreased from 81% to 65% and 54%, respectively, compared to the non-daylit base case on clear sunny summer days. Note, the illuminance setpoint was not met for 1 h and 2:15 hr, respectively, in the late afternoon even with the electric lights on at full output (~540 lux design). Cooling load savings were not measured.

If the frequency of blind activation was reduced to 5-min or 15-min with limited angular movement per cycle, daily lighting energy use was increased by 31-43% or 72-86%, respectively, compared to the default 30-s blind activation rate with unlimited movement on clear sunny summer days. Daily cooling load and peak cooling loads remained unchanged (to within 1%) in both cases. The slower-activated blind limited daylight and caused the electric lights to make up the deficient illumination requirement. On a partly cloudy summer day, daily lighting energy use was increased by 24%, while the cooling peak increased 11% with the 15-min restricted blind compared to the 30-s unlimited blind (Table 2).

Several "smarter" short-term delays were also tested to decrease blind movement. With a 10-min delay on either reversal of blind direction (to prevent oscillations), any movement, or movement to a horizontal view angle, daily lighting energy use was decreased by an average of 2-6% (n=15) compared to the default 30-s unrestricted blind on sunny and partly cloudy spring days. With a 15-min delay, daily lighting energy use increased by an average of 9% (n=19) compared to the default system. Increases in daily cooling load (>5 kWh) and peak cooling loads averaged 5% and 1% with 10- or 15-min delays, respectively.

To control glare, the default blind angle range was restricted to a horizon to ground view (0-68°). If the blind was allowed to move between -35° (sky view) to 68°, daily lighting energy use was decreased by an average of 34% compared to the default operational range on partly cloudy to overcast spring days. Daily cooling loads (>5 kWh) and peak cooling loads decreased by an average of 5% and 0%, respectively. The blind tended to operate within the 0° to -35° range when daylight levels were decreasing in the afternoon.

If the fluorescent lights were dimmed to 10% output and never turned off, daily lighting energy savings were reduced substantially while cooling load reductions were moderately affected, compared to the default lights-off operation. Compared to a 15° static blind with the same daylighting system (no shut-off as well), the dynamic system reduced daily lighting energy use by 7-8%, daily cooling load by 9%, and cooling peak by 8% on clear summer days. Compare these data to average summer reductions in daily lighting use of 22±17%, daily cooling load of 13±5%, and cooling peak by 13±10% *with* the fluorescent lighting on/off option from Table 1.

Mitigating Factors

All energy performance data were given for a window with high transmission glazing and large area. For windows with lower transmission glazing or smaller area, one could expect the default dynamic system's savings to decrease. With manual operation of retractable blinds, lighting energy savings would be decreased, but cooling loads may increase compared to the dynamic unretractable blind. If the window is shaded by deep exterior overhangs, fins, or exterior obstructions closer than a city-street-width away, lighting and cooling energy savings could be reduced, especially for orientations that are subject to direct sun (i.e., south, east, west). This southeast-facing window had a city view with moderate sky obstructions. If an advanced glazing is used (e.g., spectrally selective dual-pane glazing) instead of the tinted monolithic glass used in these tests, cooling load reductions would decrease. Greater reductions in cooling load would be obtained for south- and west-facing exposures. Substantial reductions in cooling load with approximately the same lighting energy savings would be obtained for between-pane or external dynamic venetian blind systems.

Energy savings were achieved with (1) the use of a properly-commissioned prototype lighting control system with a proportional response to available light; (2) the optimal operation of the automated blind to provide sufficient daylight when available; and (3) the lights being turned off after a 10-min delay if there was sufficient daylight to meet the design illuminance setpoint. Commercially-available dimmable daylighting systems installed in offices today cannot achieve the lighting energy savings obtained by this prototype lighting system due to design and commissioning problems, and because they typically have no daylight shut-off option.

Daylighting control systems are notoriously unreliable because they dim the fluorescent lighting improperly. Commercially-available systems combine the photosensor's response to electric light and daylight into a single "gain" parameter, forcing interdependency between two distinctly different relationships and building in error (and unreliability) to the basic design (Lee et al. 1998b). To compensate for insufficient light and to reduce occupant complaints, building managers will often set the gain (if permitted by the manufacturer) to a very conservative setting—to a point where the lights are almost never dimmed. This prototype's performance will be substantially better because the system was properly commissioned and because it was designed to "know the difference" between electric light and daylight contributions to the workplane. Our design refinement can be incorporated into existing commercial designs without added cost or sensors. Reliability was increased. Workplane illuminance was maintained to within 10% of the design setpoint for 98% of the year.

While the energy savings overall are substantial, one could argue that if occupant behavior was more energy-conscious, the benefits of the dynamic system could be incurred without the added cost. The following arguments are offered to place occupant behavior and standard building practice into the context of what is realistically "achievable" today.

First, standard commercial office lighting practice does not include dimming photosensor controls. Dual-level switching is the minimum switch requirement specified by the California Title-24 code and ASHRAE Standard 90.1, which allows the occupant to manually turn on and off individual lamps (e.g., 100%, 50%, 0% light output) using a wall-mounted switch. This least expensive switching strategy requires that the occupant be willing to switch the lights off when there is sufficient daylight—which is known to be atypical behavior. Lighting energy savings will be degraded if the occupant consciously decides to exercise the options for dual-switching or if other automatic lighting control strategies are being used effectively in this space (i.e., occupancy sensor, etc.).

Second, manually-operated systems rarely achieve the consistent energy-savings potential of dynamic systems. A survey of occupants in several high-rise buildings in Tokyo (Inoue et al. 1988) indicated that if the occupant operates the venetian blind (60% were never used during the day), then its activation was most frequently motivated by extremely uncomfortable conditions; e.g. direct sun incident on the occupant or task or by glare. Often the occupant is not present in the workspace for a significant percentage of the day. If activated, the blind will not be actively tuned by the occupant to optimize daylight and solar heat gain admission. We made an informal photographic record of each facade of the Oakland Federal Building every 20 min throughout a hot sunny summer day. We found that 85% of the perforated vertical blinds remained in the same position throughout the day, with 55% and 35% of the south and west facades' blinds, respectively, remaining completely retracted. When the blinds were moved (16% were moved during some part of the day), the movement did not correlate well with direct sun. The building managers register numerous complaints related to thermal and visual discomfort every summer.

HUMAN FACTORS

A pilot study was designed to learn how people would respond to the dynamic prototype and whether the resultant interior environment would be satisfactory. We were specifically interested in how the subjects' level of satisfaction was related to the operation of the dynamic system and what control settings subjects preferred. Fourteen volunteer federal office workers were tested for three hours in the morning or the afternoon in July 1996. For each subject, the blind/ lighting system was activated for an hour to operate (in random order) with either: (1) manual operation of lighting (on or off) and blinds (tilt angle), as in typical offices; (2) automatic operation of the dynamic system; or (3) semi-automatic operation with user-preference settings input via a remote control device. About 75% of the subjects performed their own reading or writing tasks facing the desk and southwest sidewall, while computer work was done by the other 25%. Over half were between 40-49 years old. At the end of each hour, subjects filled out a questionnaire. Window/lighting control parameters and remote control settings were recorded. Weather varied from partly cloudy to clear sunny conditions. Detailed results are given in Vine et al. 1998.

In general, most of the subjects felt the overall lighting[8] in the room to be comfortable—not too bright, no deep shadows, not affected by reflections, and not bothered by glare from ceiling lights. Although the general levels of satisfaction and dissatisfaction were similar among the three different modes of operation, there were a few differences:[9] (1) in the automatic mode, almost 75% of the sample preferred more daylight; (2) in the semi-automatic mode, more people were comfortable with the lighting and experienced less discomfort with dimness and lighting distribution; and (3) in the manual mode, the highest percentage of people (85%) felt the lighting to be comfortable and experienced very few complaints related to brightness, dimness, shadows or lighting distribution. However, relatively more people in the manual mode were dissatisfied with specific sources of brightness and glare: lighting fixtures too bright (14%), glare from ceiling lights (7%), and glare from windows (15%).

Monitored workplane illuminance data showed that the levels were 18% higher in the semi-automatic mode, and 110% higher in the manual mode, compared to the automated mode (Table 3). Horizontal workplane illuminance data does not adequately describe the visual environment. And satisfaction with the interior lighting environment is tied to a variety of factors including the nature of the task, the perceived brightness of the work task and surfaces surrounding the task, sources of glare, outdoor daylight conditions, and the direction, distribution, and source of light.

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[8] "Lighting" includes both daylighting and electric lighting.

[9] Tests of significance were not presented due to the small sample size (n=14). The findings are illustrative.

For some subjects, the desire for more light did not necessarily mean that more light was required for performing tasks. In one case, the subject wanted to remain alert. In another case, the subject may not have understood how to properly operate the remote controller. An existing office condition can also have an effect on preferred illuminance levels. One subject said he lived in a "cave environment" with dark walls, small windows, and direct light fixtures, finding the test room cheerful and bright.

With the partly cloudy and clear sunny weather that occurred during the tests, users set the electric lights-off time delay to 6-8 min compared to the 10-min automatic mode setting. With the manual mode, three out of the 14 people (21%) opted to get up and turn off the electric light switch at some point during their 1-h session. In the automated mode, the dimming of lights was bothersome for 21% of the subjects, while 21% thought the lights being turned on and off was bothersome.

Subjects set the view angle on average to 3° to -11° on overcast mornings or in the afternoon (when direct sun was not present) for the semi-automatic mode. On clear sunny afternoons, when glare might be experienced from the bright opposing buildings, two subjects set the view to an upwards sky view (-14° and -45°) while the remaining five set the angle nearly horizontal (3° to -7°). With manual control, the blind was set to 15±32° and 3±34° (for view, illuminance, or whatever reason) during morning and afternoon hours, respectively. A few people (14%) were dissatisfied with the window view in the automated mode. One subject reported that of all factors possible (e.g., chair, carpet, etc.), the view of artificial sights rather than natural ones was found to be the one factor they liked least about the room.

Subjects set the blind adjustment interval to an average of 3 min with almost unlimited movement per cycle in the semi-automatic mode. The preferred settings for blind activation and limited motion was difficult to compare since instant feedback was not provided to subjects. For example, under stable conditions, the blind would move occasionally if at all to meet control criteria. Only a few people were bothered by the operation of the blind in the automated mode (30 s unlimited movement): 14% thought the sound from the blinds was bothersome, while 7% found the intermittent opening/closing of the blinds bothersome. Most subjects (86%) found the level of noise to be satisfactory (before improvements were made to the blind motor). Satisfaction increased with the semi-automatic mode.

If we were to consider the preferences of this sample (n=14) representative of typical office workers, some default control settings should be modified: (1) daylight illuminance setpoint increased from 540-700 lux to 740-900 lux during periods when cooling load control is not critical; (2) blind activation frequency increased from 30 s to 5 min; (3) 10-min "smart" delays to decrease blind movement under partly cloudy conditions; (4) lights off according to occupancy; and (5) user override with the remote controller at any time, but return to default settings when occupant is absent or after 30 min. These modifications would decrease energy-savings but could increase user satisfaction over a larger population.

The remote control design will require further refinements and testing. With our short 5-min explanation of the questionnaire and use of the controller, we observed that many of the subjects did not understand at least some of the five control options offered. Some of the confusion resulted in the lack of instant feedback. An indicator light could be added to assure users that the device is working. We found that users were confused by the blind activation cycle option and movement per cycle option. Bundling these two features would simplify the controller and probably still satisfy most users.

Overall, many workers had very positive responses to the system: "I noticed there was good lighting during all three scenarios," "The system works very well and definitely has potential," and "How often can this be done and how soon?" And almost 60% of the workers indicated that they would recommend the system be used in their building (30% were not sure).

MARKET TRANSFER

We estimate the mature market incremental cost of the automated venetian blind/ lighting system to be approximately \$7-8/ft^2-glass or \$3-4/ft^2-floor for the motor, drive electronics and hardware, microprocessor and software, power supply, sun sensor and photosensor, dimmable ballasts, remote controller, wiring, installation, commissioning, and maintenance compared to the cost of a static venetian blind with no daylighting controls. No glazing upgrade costs were included and no credits for potentially smaller HVAC systems is assumed. Commissioning costs were approximately the same as with conventional daylighting controls. We designed automated nighttime and daytime calibration routines to simplify commissioning and insure proper control. Maintenance will be required periodically to clean sensors, change out motors, and adjust the system as space conditions change (no maintenance was required during our 14-month test). Few problems are expected with normal operation, given the reliability demonstrated by the control performance data above. Interference with the blind or lighting system (e.g., obstruction with furniture, wind, etc.) will reduce reliability.

If we consider lighting and cooling energy savings alone, we estimate that the dynamic system has a simple payback of about 10 years for the Oakland testbed site, assuming a flat \$0.09/kWh rate, a COP of 3.5, and a 12-h operating schedule compared to the 15° partly-closed static blind with no daylighting controls. In regions where utilities have tiered or time-or-use rate structures, the payback will be shorter with the peak load reductions. First cost can also be reduced. Normally, the mechanical engineer must assume worst case conditions when sizing the mechanical system, and will oversize the system capacity. The peak reductions will not only reduce expensive demand operating charges, but may also enable the owner to capture first-time cost reductions by downsizing the mechanical system capacity in new construction. In a broader view, the collective reduction in peak load may defer the future growth of utility generation facilities.

An assigned value for qualitative benefits would make this system even more economical. Few technologies have such an immediate impact on the quality of the inhabited environment and the comfort of its occupants. Aside from energy-efficient qualities, window and lighting technologies can change the mood of the interior, the comfort of occupants sitting beside it, and the character of the building. Demonstrating value for the amenity these systems deliver could increase market viability. As an example, the market growth popularity of low-E window glazing may have been partly due to its improvement in thermal comfort, not simply to its increased energy-efficiency. Correlating increases in worker satisfaction and productivity would build an even stronger economic argument but will require a significant R&D investment.

The system can be tailored for a variety of commercial applications. Other blind or lighting products can be used with the basic control system interchangeably with few modifications. The light fixture type is interchangeable. Recessed direct fixtures would have no effect on the control system design or on reliability. Similarly, the electronic dimmable ballasts could be interchanged with other similar products. Vertical blinds would require testing to determine the robustness and accuracy of the relationship of slat angle to position signal. The bottom edge of the slats is typically gravity hung, so any perturbation of the slats would require time to dampen out. More complex information on solar position may also be required to determine blocking angles for direct sun. Highly-reflective blinds (e.g., metallized low-E surface) would require some investigation into its effect (if any) on the shielded photosensor. Perforated slat systems would reduce the range of transmission control (for glare and direct sun control), but with small area and/or low transmission windows, this may be a minor issue. Between-pane venetian blind systems or exterior blind systems would have no impact on control system design; to their benefit, cooling loads would be significantly reduced. More difficult would be the incorporation of retractability, primarily due to the cost of the motor.[10] Other window system types would require further development of the control algorithm. A pull-down shade, for example, would have an entirely different set of control criteria. Variable-transmission glazings such as electrochromics would require less modifications.

Because the system crosses traditional component boundaries, marketing and commercializing this integrated product poses unique challenges; i.e., should it be sold by a window or lighting manufacturer or a control systems supplier? Since few manufacturers sell both lighting and windows, a good solution may be to market an independent controller package that would allow various window and lighting components to be interchanged in a plug-and-play fashion. If packaged with each component, the only overlapping hardware is the ceiling-mounted photodiode—and this sensor is conventionally packaged with the lighting system.

CONCLUSIONS

An automated venetian blind was operated in synchronization with dimmable fluorescent lighting to optimize workplane illuminance, block direct sun, and permit view in response to changing solar conditions and occupant-set preferences. Practical hardware and control software design issues were solved to minimize installation, commissioning, and maintenance costs, yet insure reliability and occupant acceptance of the system. We used increasingly detailed tests to iteratively refine the system and presented our detailed findings for the final full-scale test in this paper.

With the dynamic system operating as designed, monitored energy savings and peak load reductions were substantial. Compared to a partly closed 15° blind with the same prototype daylighting control system, the dynamic system reduced daily lighting energy use by 1-22%, daily cooling loads by 13-28%, and peak cooling loads by 13-28% for clear sky and overcast conditions over the course of a year for this southeast-facing private office in Oakland, California. Without daylighting controls, daily lighting energy savings of 22-86% were obtained for overcast and clear sky conditions throughout the year, while daily and peak cooling load reductions of 28% compared to a static horizontal blind were obtained on clear days in July. These savings are more indicative of the technology's potential since daylighting controls are used in a very small percentage of U.S. commercial buildings (and if used, the systems are rarely working at their full potential). Experience has also shown that manually-controlled shading devices are not effectively used. A pilot study of human factors indicated that satisfaction increased if users could alter control settings via a remote-control device. If we modify the default settings to those preferred by the users, energy-efficiency would decrease, but satisfaction may increase over a wider population.

With the default design, the control system met all design criteria satisfactorily throughout the year under variable weather conditions. Minor control glitches were either corrected shortly (< 5 min) or were within 10% of design setpoints for at least 90% of the year. Smarter control algorithms were tested to decrease blind motion, particularly during unstable partly cloudy conditions, and were found to improve performance without significant degradation in energy-efficiency.

The technical design required few modifications to commercially-available components. The key "component" was the control system that properly integrated the operation of conventional hardware. In our prototype solution, we developed a refinement (that could be used independently from the dynamic system) to increase the reliability of conventional daylighting control systems at no added cost. We intend to approach lighting manufacturers to implement this refinement. Sensors were developed and were found to provide sufficiently accurate information at a low cost. The off-the-shelf blind motor was modulated to produce a very quiet ticking noise and to smooth angular movement. These hardware modifications and the remote controller may increase user

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[10] Our blind system will work properly if retracted. However, much of the energy savings will be subject to the occupant keeping the blinds down since direct solar gains represent a significant portion of the day's window heat gains.

acceptance of this new technology. For global, building-wide control, this control system could also be linked to the residing energy management control system to implement load-shedding and demand-limiting control.

The dynamic system increased visual and thermal comfort. Arguably, we were able to prove an increase in visual comfort using subjective surveys. While satisfaction increased with manual control, more subjects (7-15%) were dissatisfied with particular sources of glare and brightness from the windows or light fixtures. These pilot test results (n=14) are possibly indicative of general trends. Testing over a broader number of subjects and for a longer period would be more conclusive. We used monitored data to calculate the glare index for subjects facing the sidewall and the indices fell within "just acceptable" levels throughout clear sunny days in July. Direct sun was controlled throughout the day, and if errors occurred, they were corrected within 5 min. The variation in interior illuminance levels was reduced compared to static systems. This too, may increase visual comfort over the long term, particularly for computer-based tasks. Thermal comfort may be increased simply because direct sun and thermal loads were well controlled.

We estimate a 10-year simple payback (with a fixed utility rate) if this system is used instead of a conventional static blind with no daylighting controls on the east, south, and west facades of a typical commercial office building in Los Angeles. The economics of the dynamic system is improved if one takes advantage of the peak load reductions to "rightsize" the mechanical system. Mechanical engineers typically overdesign the mechanical system to accommodate peak loads. Material and installation costs of the dynamic system could be partially offset by the first-cost reductions in HVAC capacity, resulting in even shorter paybacks if occupant comfort benefits could be quantified, the resultant "economics" would be even more favorable.

Industry adoption of this technology has proved to be difficult because the technology spans multiple separate and distinct industries: envelope systems, electric lighting systems and control systems. Manufacturers were interested in the concept, some of which had investigated similar products internally, but most had little basis to evaluate the other portions of the integrated technology for which they had little expertise. We proposed an interoperable control solution that was separate from either industry, but was able to integrate any manufacture's window blind or lighting system for commercial building applications.

Given the results of this research, we believe that this prototype design is ready to be transferred to the marketplace and commercialized. Additional research can be conducted to further develop control algorithms to meet occupants comfort criteria, but the authors believe that these refinements can be incorporated into later products. Extending this local control solution to a building-wide global solution is also a refinement that can be incorporated later, but this option would eventually yield powerful load-shedding capabilities. We view the motorized system as the primary market barrier to widespread adoption in U.S. commercial buildings (motorized exterior blind systems are more commonly used in Europe). The solid-state electrochromic window may ultimately be a more elegant dynamic glazing alternative to the venetian blind.

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TABLE 1. Monitored Daily Lighting Electricity, Cooling Load, and Peak Cooling Load Reductions with a Dynamic Venetian Blind and Lighting System compared to a Basecase Static Venetian Blind System with the Same Daylighting Control System

Basecase Static Angle	Season	No. of Days	Lighting Electricity	No. of Days	Cooling Load	No. of Days	Peak Cooling Load
45°	Spring	9	27 ± 5%	4	15 ± 7%	8	11 ± 6%
	Summer	8	52 ± 9%	8	6 ± 6%	8	6 ± 8%
	Autumn	18	37 ± 12%	13	7 ± 3%	16	8 ± 5%
	Winter	4	19 ± 4%	0	— —	4	15 ± 11%
15°	Spring	12	14 ± 8%	7	28 ± 16%	11	22 ± 6%
	Summer	14	22 ± 17%	12	13 ± 5%	13	13 ± 10%
	Autumn	3	7 ± 2%	3	22 ± 11%	3	21 ± 6%
	Winter	4	1 ± 1%	0	— —	1	28 ± 0%
0°	Spring	13	-1 ± 4%	10	32 ± 16%	11	25 ± 8%
	Summer	11	-14 ± 19%	11	17 ± 6%	11	24 ± 7%
	Autumn	6	11 ± 10%	5	17 ± 10%	6	18 ± 11%
	Winter	5	-1 ± 3%	0	— —	3	32 ± 3%

Monitored in a full-scale private office with a southeast-facing window in Oakland, California. Basecase static blind angle defined as downward angle from horizontal, occupant view of ground. Static settings (0° and 15°) may allow direct sunlight to penetrate the room. See: Lee, DiBartolomeo, & Selkowitz 1998a.

TABLE 2. Percentage Increase (+) in Monitored Daily Lighting Electricity, Cooling Load and Peak Cooling Load Compared to the Default Dynamic Venetian Blind and Lighting System

Date	Control	Lighting Electricity			Cooling Load				Peak Cool	
	Parametric	Δ (Wh)	Δ%	E_{vgh} (klux)	Δ (Wh)	Δ%	E_{egh} (W/m^2)	T_{dbt} (°C)	Δ (W)	Δ%
Activation Cycle: 30 s, unlimited movement, default										
7/6/96	5 min, limited	131	31%	76	-149	-1%	7,361	12.0	-28	-1%
7/7/96	5 min, limited	177	43%	76	188	2%	7,272	12.0	17	1%
7/8/96	5 min, limited	278	38%	63	—	—	6,048	12.0	39	4%
8/12/96	10 min, ~limited	276	51%	67	-950	-8%	6,373	29.1	-93	-4%
8/13/96	10 min, ~limited	169	35%	67	-136	-1%	6,354	27.7	-24	-1%
8/14/96	10 min, ~limited	216	44%	69	-121	-1%	6,644	24.5	-51	-3%
6/4/96	10 min, limited	217	55%	n/a	-45	-0%	n/a	17.4	1	0%
6/18/96	10 min, limited	168	34%	n/a	-254	-2%	n/a	28.0	52	3%
7/4/96	10 min, limited	230	31%	67	—	—	6,539	21.4	77	7%
7/30/96	10 min, limited	311	70%	73	129	1%	6,965	26.9	-33	-2%
7/31/96	10 min, limited	267	57%	73	118	1%	7,117	28.7	-16	-1%
8/5/96	15 min, unlimited	81	7%	42	—	—	3,905	17.5	70	9%
8/6/96	15 min, unlimited	284	43%	67	-159	-2%	6,523	22.8	-246	-14%
8/7/96	15 min, unlimited	244	27%	60	—	—	5,842	21.8	-132	-12%
8/4/96	15 min, ~limited	322	70%	72	-914	-8%	6,981	27.4	-387	-19%
8/10/96	15 min, ~limited	261	55%	69	96	1%	6,567	27.1	-83	-4%
8/11/96	15 min, ~limited	405	70%	66	1,931	17%	6,286	28.6	67	4%
6/5/96	15 min, limited	357	86%	n/a	194	1%	n/a	16.7	37	2%
8/1/96	15 min, limited	234	24%	39	—	—	4,741	18.5	53	11%
8/2/96	15 min, limited	335	72%	73	-286	-3%	7,181	27.7	-101	-5%
Blind movement: no delay before reverse direction of movement										
5/10/97	10 min delay	92	9%	40	—	—	4,768	20.9	43	10%
5/11/97	10 min delay	85	10%	51	—	—	6,186	21.5	1	0%
5/12/97	10 min delay	99	14%	52	—	—	6,361	18.9	-49	-4%
5/13/97	10 min delay	-54	-11%	55	553	6%	6,554	16.7	44	3%
5/14/97	10 min delay	-38	-6%	56	425	5%	6,560	25.1	46	3%
5/15/97	10 min delay	-106	-23%	59	655	5%	6,969	27.7	93	5%
5/16/97	10 min delay	-82	-17%	57	593	4%	6,811	22.5	85	4%
4/8/97	15 min delay	53	8%	52	-376	-5%	6,312	19.3	-230	-12%
5/2/97	15 min delay	295	64%	47	-74	-1%	5,683	21.8	23	2%
5/3/97	15 min delay	217	35%	53	211	3%	6,280	26.9	64	5%
5/4/97	15 min delay	69	14%	58	-610	-6%	7,055	21.4	-142	-7%
5/5/97	15 min delay	109	21%	56	-579	-6%	6,833	20.1	-209	-12%
5/6/97	15 min delay	-29	-6%	58	651	7%	6,858	15.7	-25	-1%
5/7/97	15 min delay	-74	-16%	57	541	6%	7,073	19.3	183	10%
5/8/97	15 min delay	-27	-3%	51	—	—	6,225	19.3	-50	-4%
5/9/97	15 min delay	-74	-16%	58	936	11%	7,065	19.3	172	11%
5/22/97	15 min delay	37	6%	51	-67	-1%	6,020	21.5	33	3%
5/23/97	15 min delay	93	6%	37	—	—	4,379	20.9	26	4%
4/1/97	20 min delay	3	0%	51	—	—	6,341	20.6	-202	-12%

(continued on next page)

TABLE 2. Percentage Increase (+) in Monitored Daily Lighting Electricity, Cooling Load and Peak Cooling Load Compared to the Default Dynamic Venetian Blind and Lighting System

Date	Control	Lighting Electricity			Cooling Load				Peak Cool	
	Parametric	Δ (Wh)	Δ%	E_{vgh} (klux)	Δ (Wh)	Δ%	E_{egh} (W/m^2)	T_{dbt} (˚C)	Δ (W)	Δ%
Blind movement: no delay before next blind move, default										
4/17/97	10 min delay	-123	-19%	52	503	6%	6,081	24.0	157	10%
4/18/97	10 min delay	-137	-11%	28	—	—	3,193	19.3	-53	-5%
4/19/97	10 min delay	-193	-24%	31	—	—	3,437	21.4	3	0%
4/20/97	10 min delay	-125	-12%	31	—	—	3,481	21.3	57	6%
4/22/97	10 min delay	92	8%	28	—	—	3,092	19.5	68	12%
4/23/97	10 min delay	12	2%	57	108	1%	6,968	20.4	22	1%
4/24/97	10 min delay	15	3%	57	581	7%	6,963	22.4	125	8%
4/25/97	10 min delay	45	7%	56	593	5%	6,739	28.0	-182	-10%
4/26/97	15 min delay	164	24%	55	414	4%	6,547	25.4	112	6%
4/27/97	15 min delay	199	27%	48	622	6%	5,845	22.1	173	10%
4/28/97	15 min delay	-310	-46%	38	—	—	4,414	19.0	97	10%
4/29/97	15 min delay	-346	-65%	47	-237	-3%	5,556	20.0	-59	-5%
4/30/97	15 min delay	129	19%	54	862	10%	6,452	22.2	126	8%
5/1/97	15 min delay	178	37%	55	-116	-1%	6,843	20.6	-118	-7%
6/4/97	15 min delay	203	41%	62	132	1%	7,590	24.2	131	7%
6/5/97	15 min delay	122	27%	62	-183	-2%	7,492	26.1	-59	-3%
View: no delay if view possible, default										
9/22/96	5 min delay	-23	-3%	56	-37	-0%	5,312	24.9	150	8%
9/24/96	5 min delay	-52	-5%	49	—	—	4,775	21.3	-67	-4%
9/25/96	5 min delay	-30	-3%	45	—	—	4,377	20.7	-60	-4%
9/26/96	5 min delay	-24	-2%	45	—	—	4,286	20.2	-70	-8%
9/27/96	5 min delay	-59	-6%	48	—	—	4,609	21.7	-143	-9%
9/28/96	5 min delay	-11	-1%	48	—	—	4,572	22.6	-8	-1%
9/29/96	5 min delay	-65	-5%	39	—	—	3,694	20.5	-23	-2%
10/3/96	10 min delay	-12	-1%	47	-320	-5%	4,431	23.7	-29	-2%
10/4/96	10 min delay	-35	-4%	47	-883	-10%	4,430	26.3	153	8%
10/5/96	10 min delay	-3	-0%	49	-1,018	-9%	4,625	28.6	71	3%
10/6/96	10 min delay	-18	-2%	49	97	1%	4,632	29.7	213	10%
Range of tilt angle: 0-68˚ default										
3/15/97	tilt: -35° to 68˚	-314	-35%	33	—	—	3,808	17.1	48	5%
3/16/97	tilt: -35° to 68˚	-455	-23%	12	—	—	1,245	13.4	0	0%
3/17/97	tilt: -35° to 68˚	-300	-39%	42	-781	-10%	4,878	20.8	-75	-4%
3/18/97	tilt: -35° to 68˚	-187	-19%	40	-308	-6%	4,667	22.2	21	2%
3/19/97	tilt: -35° to 68˚	-406	-46%	37	-533	-8%	4,310	23.5	17	2%
3/21/97	tilt: -35° to 68˚	-368	-47%	34	-17	-0%	3,839	25.2	-4	-0%
3/22/97	tilt: -35° to 68˚	-269	-37%	40	-486	-9%	4,579	20.1	-37	-3%
3/23/97	tilt: -35° to 68˚	-220	-30%	46	-278	-4%	5,358	21.3	2	0%
3/24/97	tilt: -35° to 68˚	-235	-30%	49	-47	-1%	5,319	26.2	19	1%

Average error of measured daily lighting energy use was 12±46 Wh (2.5±5.4%), n=25.

Average error of measured daily cooling load between test rooms was 87±507 Wh (0.5±5%), n=33. Days where daily cooling loads were less than 5 kWh were discarded.

Average error of measured peak cooling load between test rooms was 24±114 W (0.6±6.4%), n=23.

E_{vgh}: Average daily horizontal global illuminance (klux).

E_{egh}: Total daily global horizontal irradiance (W/m^2).

T_{dbt}: Average daily exterior dry-bulb temperature (˚C).

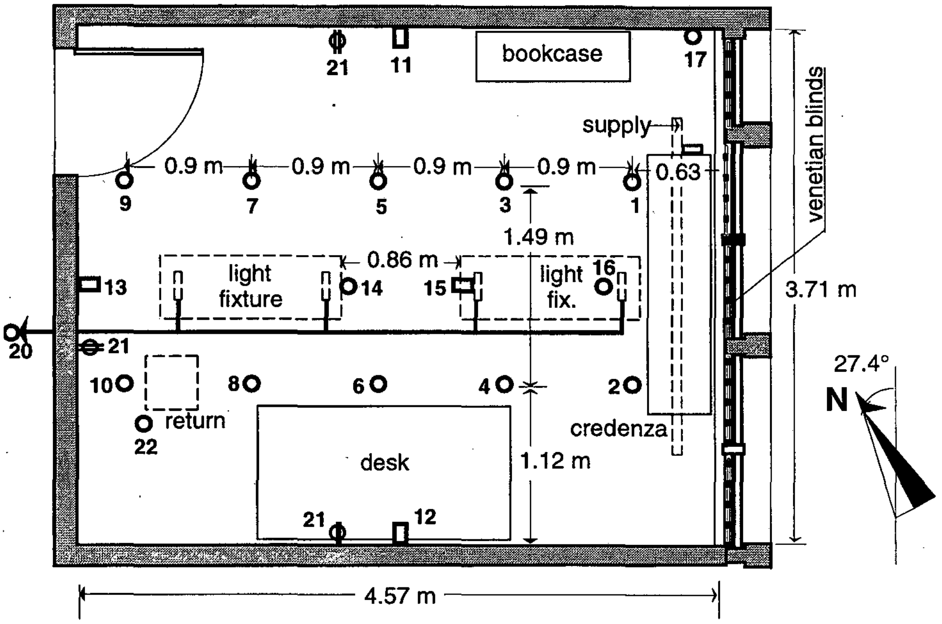
TABLE 3. Pilot Human Factors Test Control Settings

		Automatic	Semi-Auto	Manual
Workplane illuminance (lux)	Morning	598±60	735±162	1493±658
	Afternoon	588±36	700±74	1030±248
Time delay before lights off (min)	Morning	10 min	6±2 min	2 turned off
	Afternoon	10 min	8±5 min	1 turned off
View angle	Morning	0°	9±16°	17±34°
	Afternoon	0°	-11±16°	5±34°
Frequency of blind adjustment	Morning	30 s	3±2 min	—
	Afternoon	30 s	4±4 min	—
Allowable movement per control cycle (1=limited, 10=unlimited)	Morning	10	9±2	—
	Afternoon	10	8±3	—

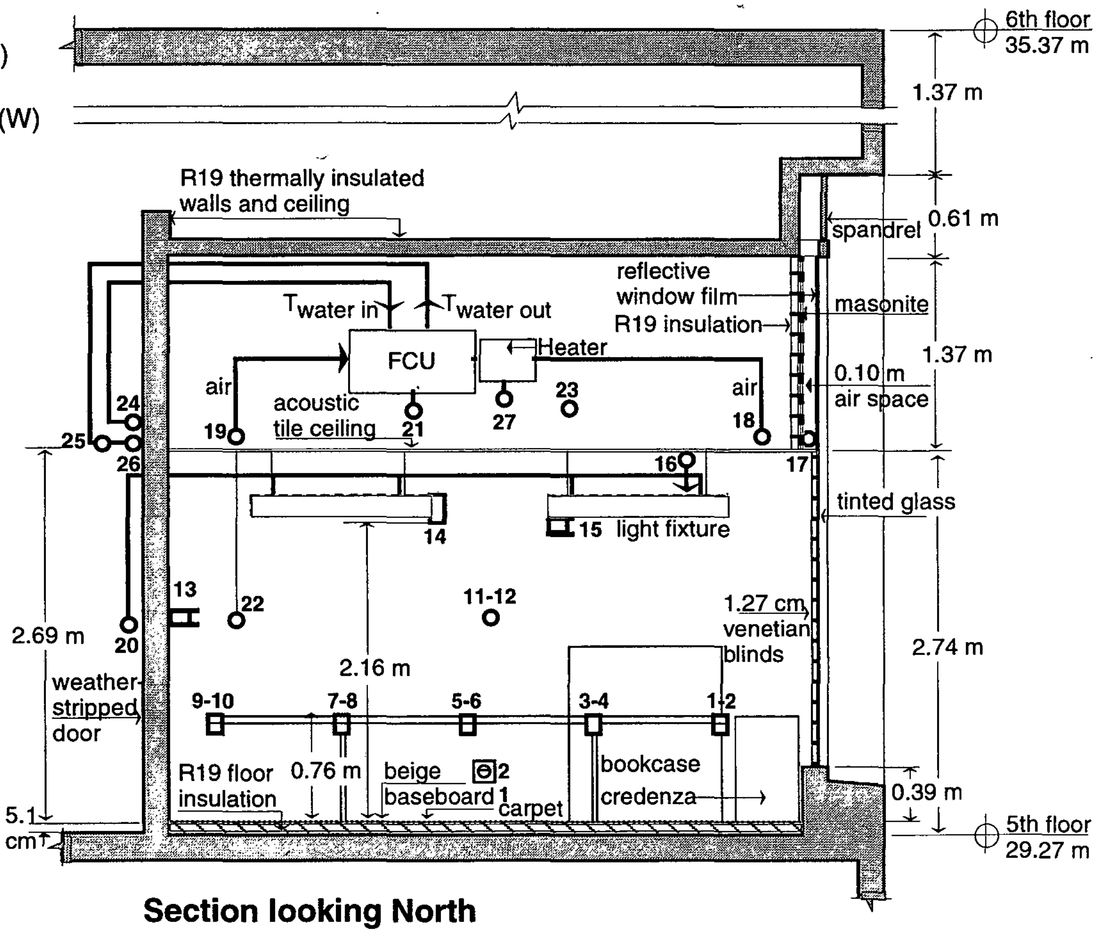
Fig. 1. Floor plan and section view of full-scale test room.

Monitored data:

1-10	Evg horizontal (lux)
11-12	Evg vertical (lux)
13	Evg window-shielded (lux)
14	Photosensor signal (V)
15	Evg window-(shielded) (lux),
16	Evg ceiling (lux)
17	Photosensor at plenum (V)
18	Tair supply (°C)
19	Tair return (°C)
20	Lighting power (W)
21	Fan power (W)
22	Tair room (°C)
23	Tplenum (°C)
24	Twater in (°C)
25	Twater out (°C)
26	Flow (gpm)
27	Heater power (W)



Floor Plan



Section looking North

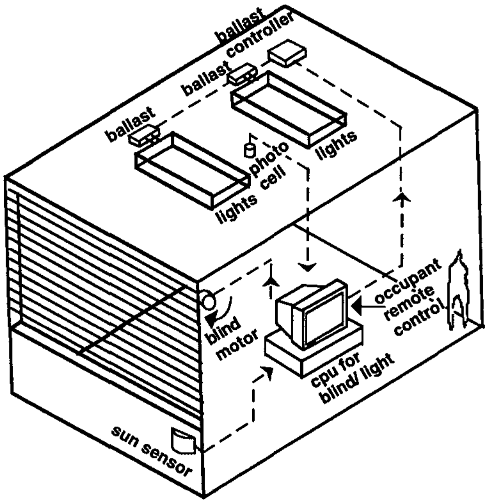


Fig. 2. Schematic of automated venetian blind/lighting system.

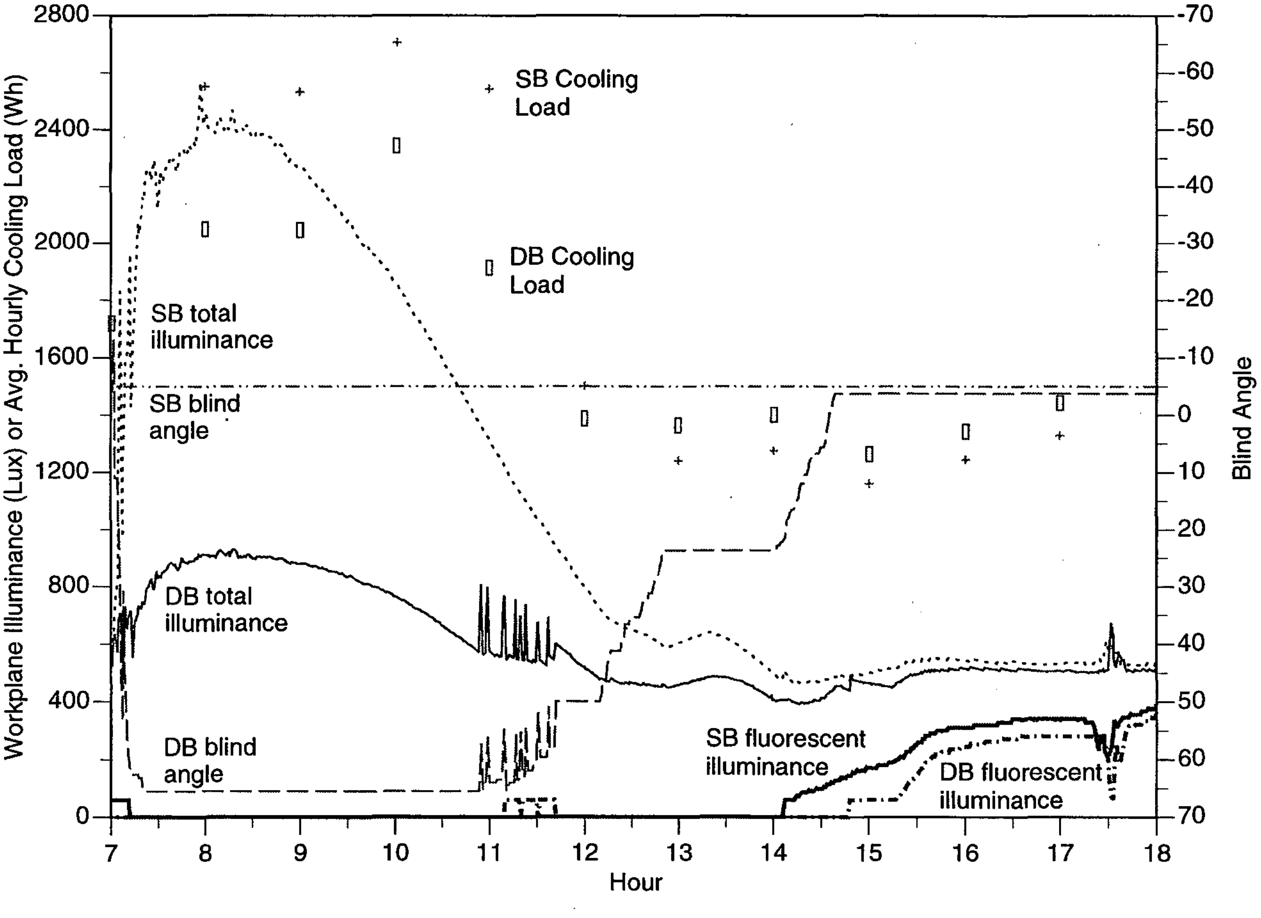


Fig. 3. Monitored total workplane illuminance, fluorescent lighting illuminance, and blind angle for the static horizontal blind (SB) and the dynamic venetian blind (DB), both with daylighting controls. Daily cooling load savings were 2917 W (21%). Peak cooling load reductions were 332W (13%). Daily lighting energy savings were 127 Wh (21%). Data are shown for southeast-facing offices in Oakland, California on a clear day, August 15, 1996.

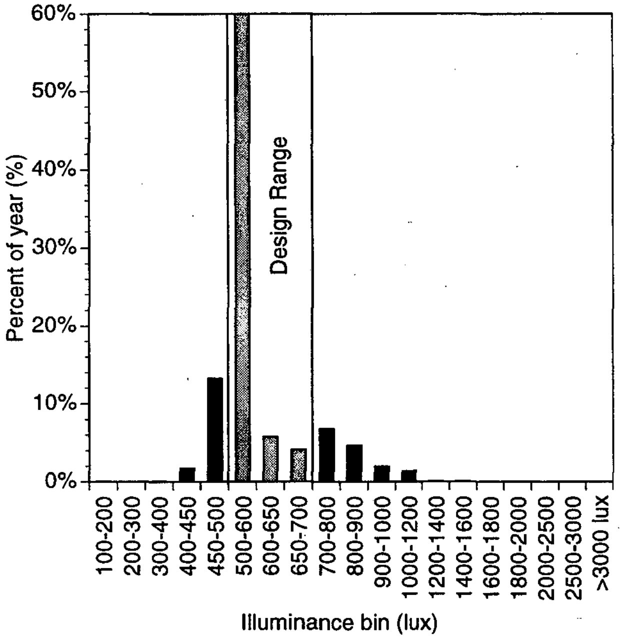


Figure 4. Binned monitored workplane illuminance data for the default 30-s-activated blind and lighting system. Data represents non-contiguous days within a monitoring period from June 1996 to June 1997.

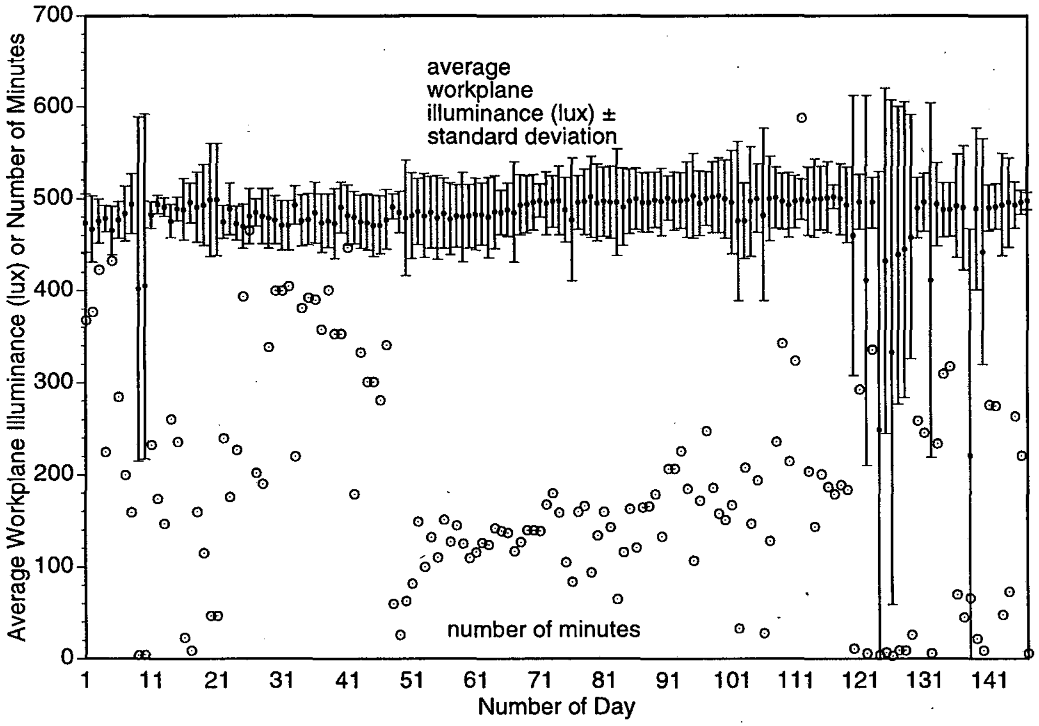


Figure 5. Daily average and standard deviation of the monitored average workplane illuminance for the cases when the design illuminance level was not met by daylight and fluorescent lighting, and the number of minutes in a 720-min (12-h) day when this occurred. Default envelope/ lighting operation. Data represents non-contiguous days within a monitoring period from June 1996 to June 1997.

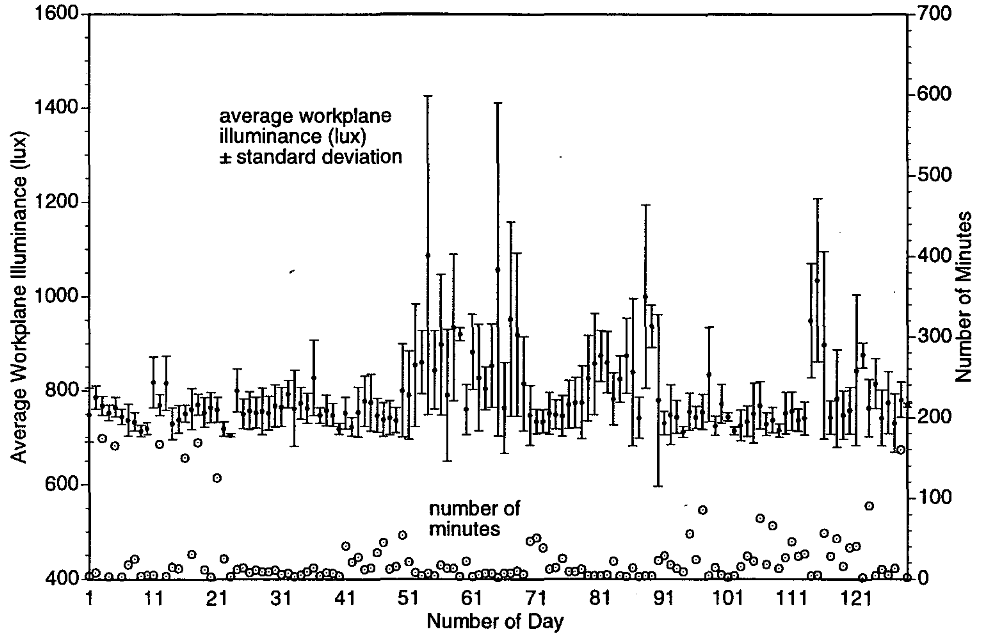


Figure 6. Daily average and standard deviation of the monitored average workplane illuminance for the cases when the design illuminance level was exceeded by daylight and fluorescent lighting, and the number of minutes in a 720-min (12-h) day when this occurred. Default envelope/ lighting operation. Data represents non-contiguous days within a monitoring period from June 1996 to June 1997.

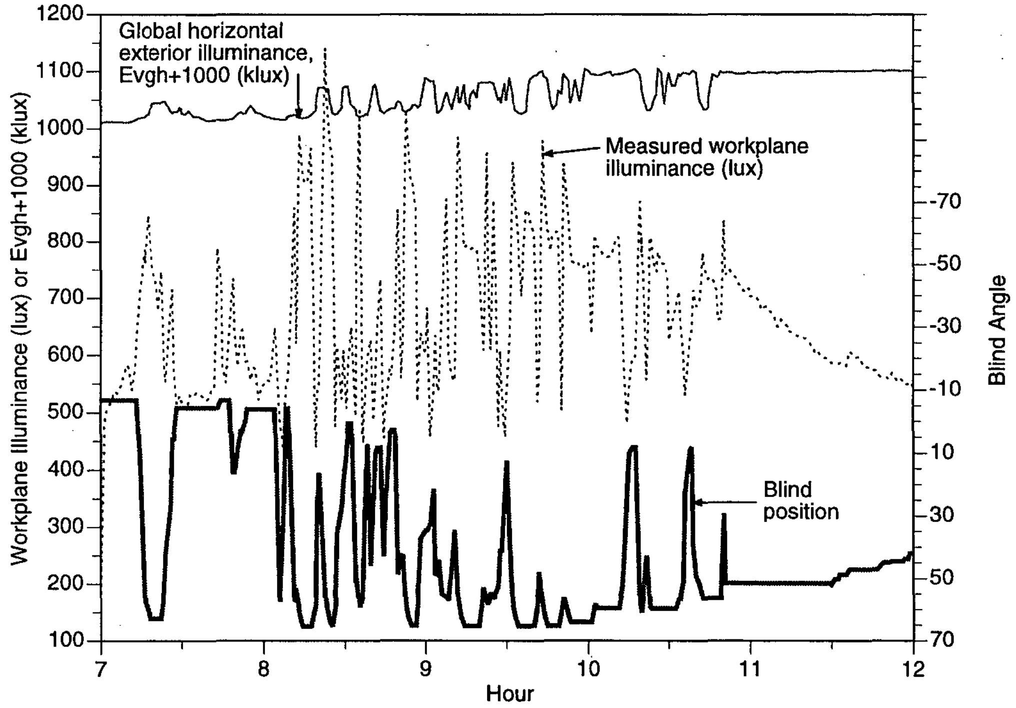


Figure 7. Total workplane illuminance exceeds the upper 700 lux range under partly cloudy conditions with the 30-s-activated blind and lighting system. Data are shown for August 27, 1996.

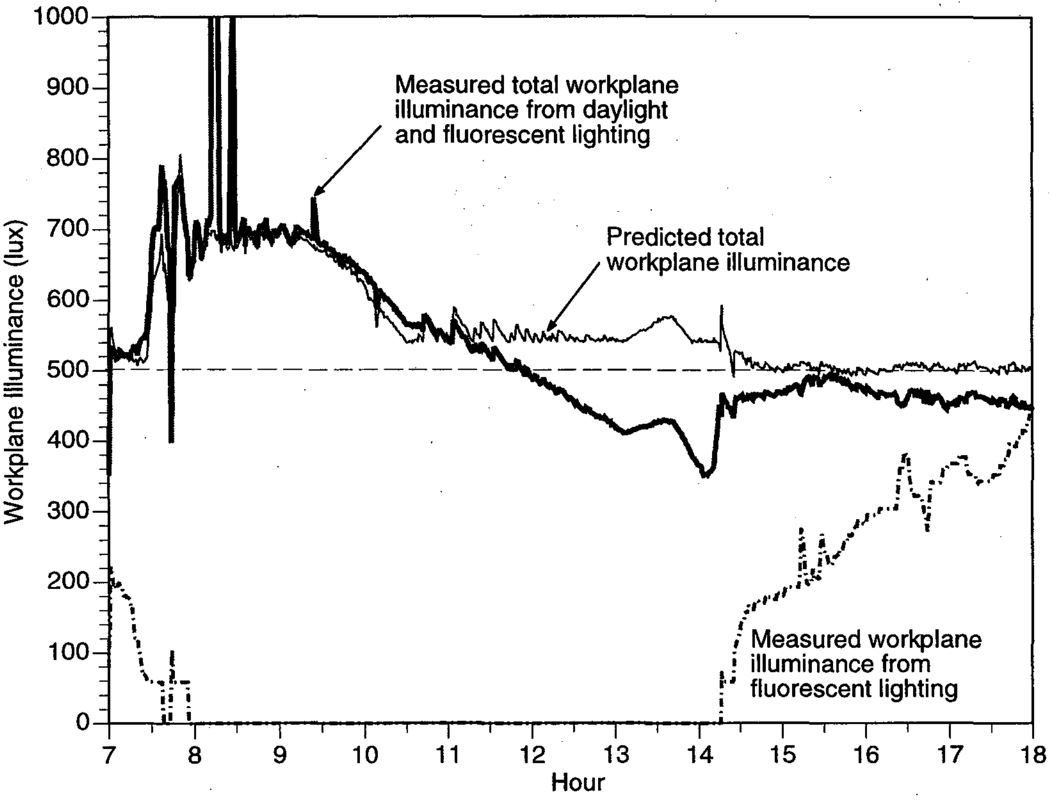


Figure 8. Predicted and monitored workplane illuminance from daylight and electric lighting. Data are shown for a southeast-facing private office in Oakland, California on a clear day, September 10, 1996.

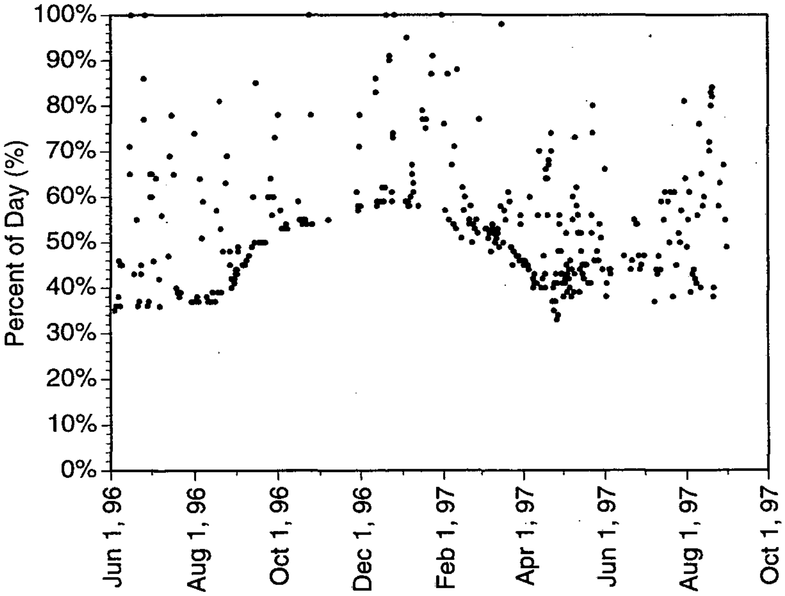


Figure 9. Percent of day when view, defined by blind angles between +2° and -35° from horizontal, was possible. Default venetian blind/lighting operation for a southeast-facing window in Oakland, California.

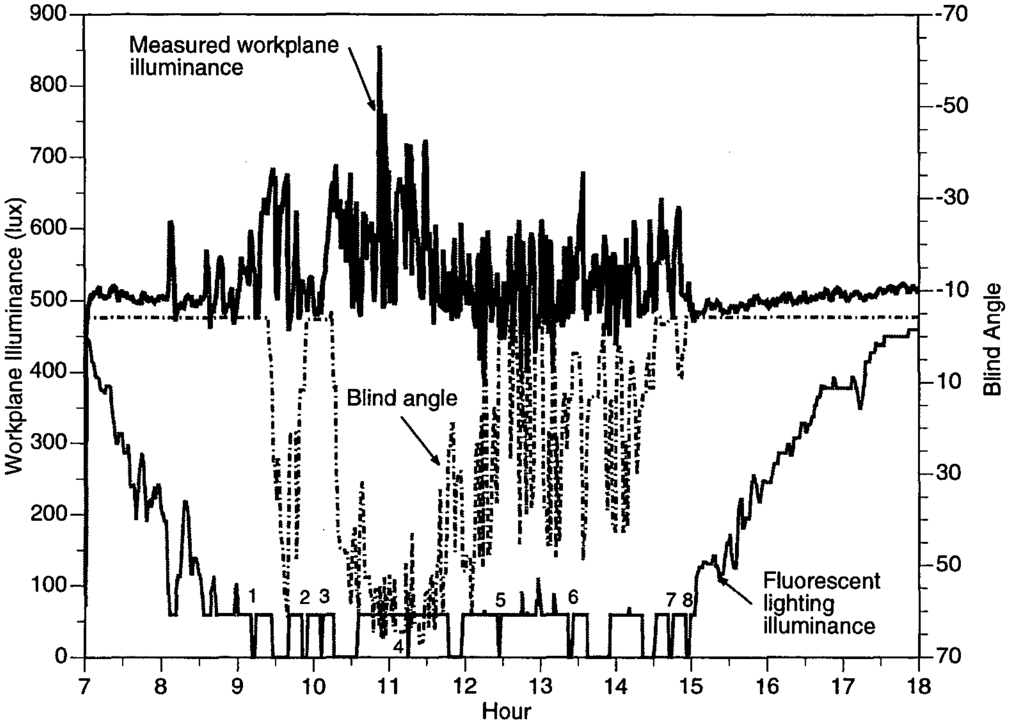


Figure 10. The fluorescent lighting turns on within 5 min of having been shut off a total of 8 times throughout this worst case, partly cloudy day (August 5, 1996). The fluorescent lights were designed to shut off if there was sufficient daylight after a 10-min delay.

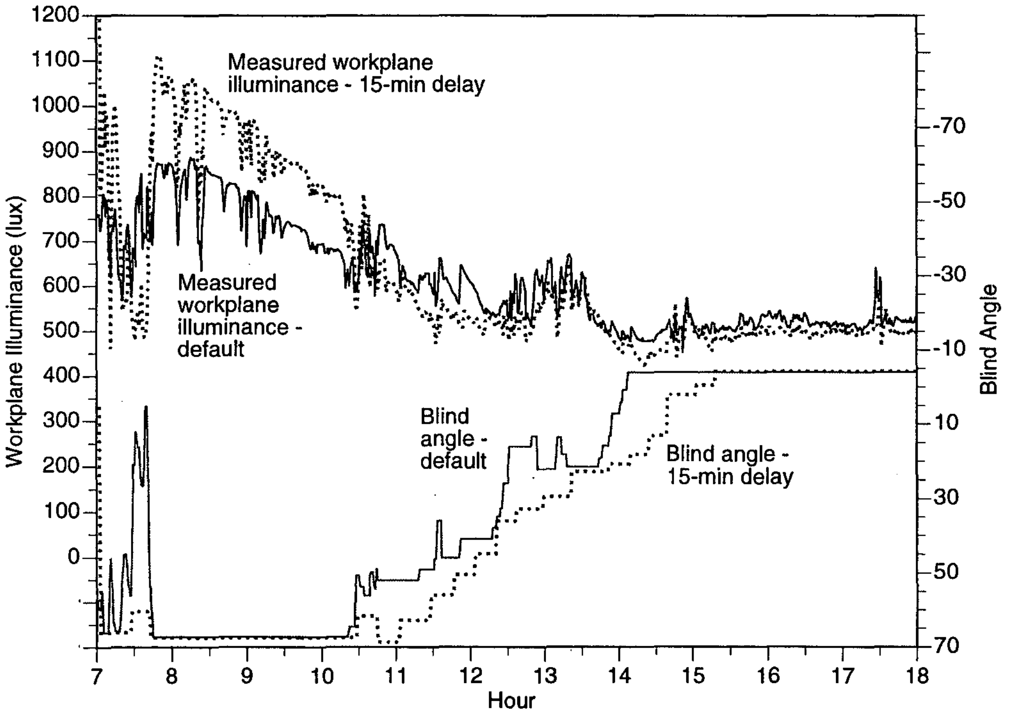


Figure 11. Venetian blind operation with default 30 s activation with unlimited movement versus operation with a 15-min delay on blind movement (unlimited movement when activated). Total workplane illuminance data are also shown for this sunny day, April 26, 1997.

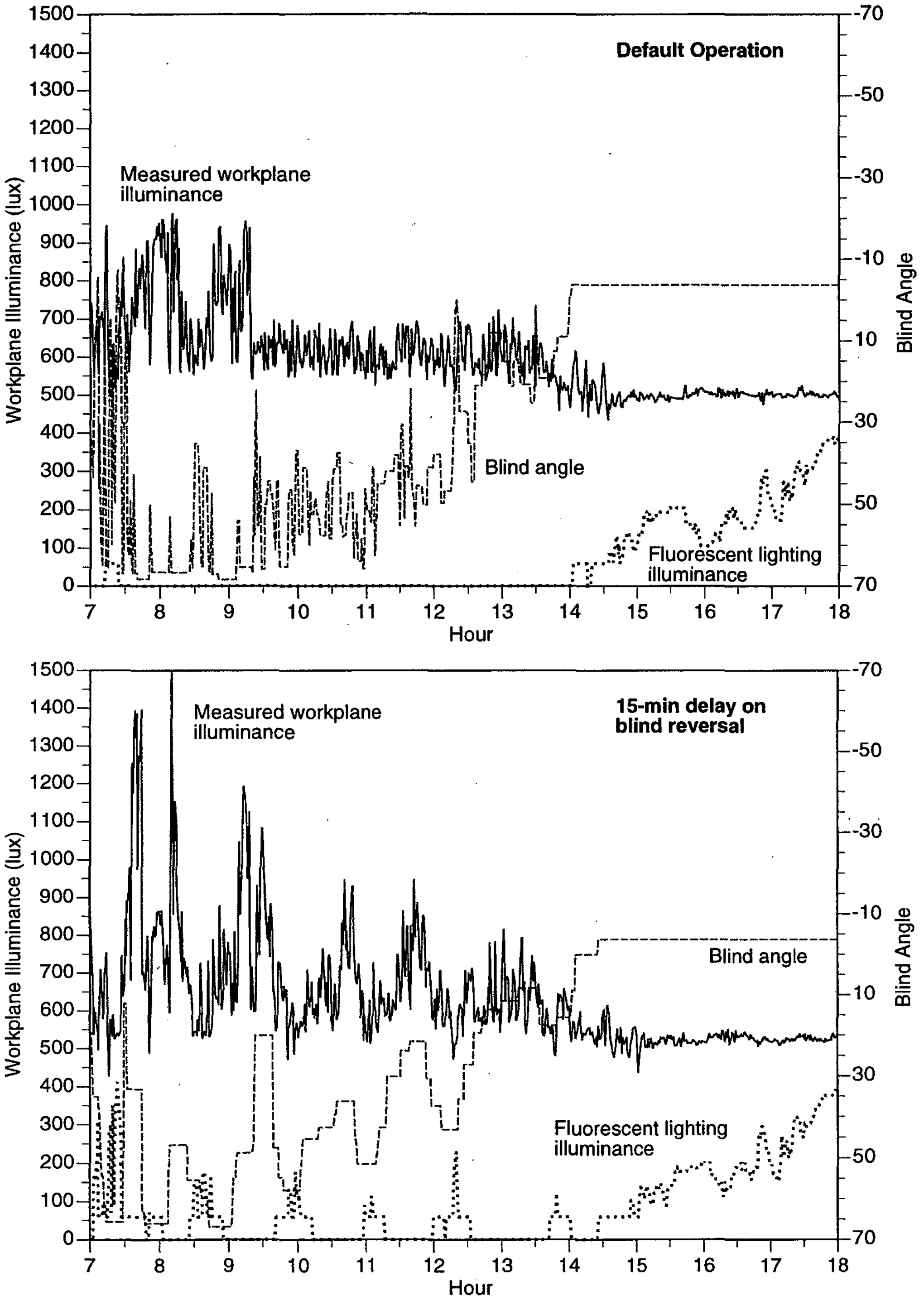


Figure 12. Venetian blind operation with default 30 s activation with unlimited movement versus operation with a 15-min delay on reversal of blind movement (unlimited movement when activated). Total workplane illuminance and fluorescent lighting illuminance data are also shown for this partly cloudy day, May 2, 1997.

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