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Environmental Energy
Technologies Division

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Abstract

A prototype integrated, dynamic building envelope and lighting system designed to optimize daylight admission and solar heat gain rejection on a real-time basis in a commercial office building is evaluated. Office worker response to the system and occupant-based modifications to the control system are investigated to determine if the design and operation of the prototype system can be improved. Key findings from the study are: (1) the prototype integrated envelope and lighting system is ready for field testing, (2) most office workers (N=14) were satisfied with the system, and (3) there were few complaints. Additional studies are needed to explain how illuminance distribution, lighting quality, and room design can affect workplane illuminance preferences.

1. Introduction

Energy-efficient electric lighting, glazing, and daylighting control technologies hold the potential to significantly reduce peak demand as well as total electricity use of commercial buildings. To achieve these goals, these technologies need to be designed as integrated systems, supported by appropriate design tools. Since lighting and cooling in commercial buildings constitute the largest portion of energy use and peak electrical demand, promotion of such integrated systems could become a cost-effective option for building owners. As an additional significant benefit, although difficult to quantify, these integrated systems can provide higher quality work environments that are more comfortable for the occupants and provide owners with higher value space. Improperly designed buildings and room environments will lead to worker dissatisfaction and may result in a reduction in worker productivity.

Since 1991, a multi-phase research and development (R&D) program at Lawrence Berkeley National Laboratory (LBNL) [1] has focused on bringing together viable envelope, daylighting, and lighting solutions from traditionally disparate trades. As such, the approach differs substantially from much conventional research in that it cuts across traditional areas of basic research but also seeks to derive near-term practical solutions for commercial buildings. Initial prototype designs derived from R&D studies have been developed to meet more complex and realistic environmental and building conditions as the project has progressed: e.g., field tests have supplemented computer simulations, and in-situ building installations have followed physical scale-model testing.

Once developed, these new energy-efficient technologies must be proven before they are introduced to the building industry in order to ensure performance and to reduce real, as well as perceived, risk. In this paper, we evaluate a prototype integrated building envelope and lighting system in a commercial office building which is designed to optimize daylight admission and solar heat gain rejection on a real-time basis. We investigate office worker response to the system and occupant-based modifications to the control system to determine if the design and operation of the prototype system can be improved. Prior to discussing the data collection methodology and results, we first describe the innovative technology and control strategies that were the focus of this investigation.

2. Pilot Study Objectives, Test Environment, and Modes of Operation

In this section, we first present the objectives of the pilot study. After describing the test environment and the prototype system, we review the different modes of operation implemented in the pilot study.

2.1. Objectives

The pilot study represents one phase of a larger project whose objective is to design integrated building envelope and lighting systems that are energy-efficient, cost-effective, and practical. The systems should be comprised of commercially available components that operate reliably and are acceptable to users throughout the duration of the product life. Thus, this project recognizes the complex relationship between an energy-efficiency technology and issues related to its potential acceptance by the building industry, architects, owners, and users (e.g., comfort, cost and maintenance). Accordingly, this technology demonstration is both an R&D facility to help answer research questions and a limited proof-of-concept test, allowing practical "bugs" to be worked out of an innovative building system.[1]

This pilot study was designed to learn about building energy use and how people respond to both quantitative and qualitative aspects of the office environment. We were specifically interested in how the level of acceptance of this new environment was related to such factors as the movement of the blinds, window view, the amount and direction of daylighting, lighting distribution, glare from windows and ceiling lights, noise levels, and overall illuminance level. The information from the evaluation should be helpful to architects and space planners who design and plan office buildings elsewhere. The pilot study should also be relevant for other active shading systems now on the market today, and to state-of-the-art window systems yet to come (e.g., electrochromic glazings[2]).

2.2. Test Environment

An integrated, dynamic system was developed at LBNL for cooling-load dominated commercial buildings. Automated interior venetian blinds (functional precursors to switchable electrochromic glazings) were integrated with a dimmable electric lighting system to actively balance daylighting and thermal heat gains while addressing comfort issues. Two side-by-side office modules were built for full-scale measurement and verification of the dynamic system's performance at the Oakland Federal Building in Oakland, California. The rooms, each 3.71 m wide by 4.57 m deep (12.17 x 15 ft) and 2.68 m high (8.8 ft), were fully furnished with nearly identical building materials and furniture to provide a

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[1] The work presented in this paper is one small part of an extensive R&D project [1,4]. Other project activities included: simulation studies, reduced-scale field tests, showcase demonstrations, and design tools.

[2] An electrochromic glazing is a switchable glazing that changes reversibly from a clear to colored state with a small applied voltage.

commercial office-like environment (Figures 1 and 2). The 3.71 m wide x 2.3 m high (12.17 x 7.54 ft) windows, with 0.4 m (1.3 ft) window sills, faced southeast and had views of a high-rise built-up environment. Both test rooms were located in the southeast corner of a larger unconditioned, unfinished space (213 m^2, 2300 ft^2). Occupants sat typically at a dark wood desk 2.3 m (7.5 ft) from the window, facing the south side wall.

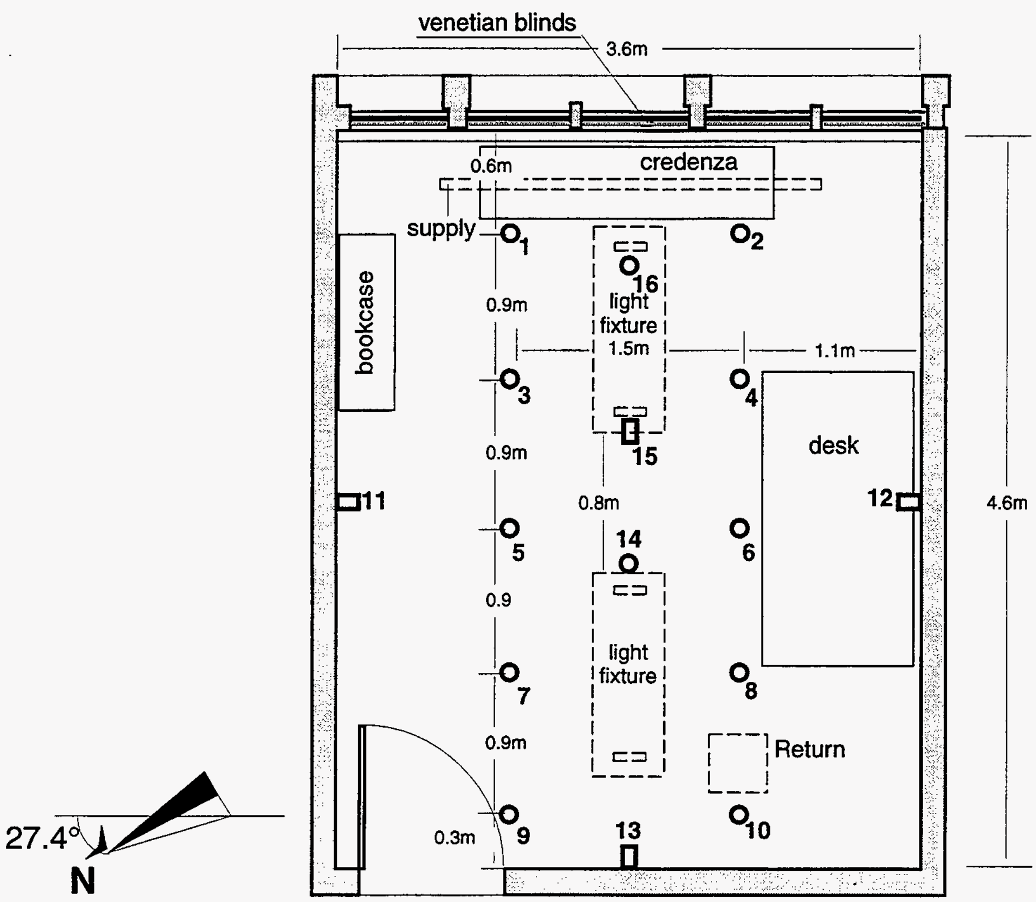
Each office had five sets of 1.27 cm (1/2 inch) wide, white interior blinds installed at the window. Each 0.6 m (2 ft) wide venetian blind was tensioned between the head and sill of the window and was non-retractable. The blinds were modified to incorporate a small modulated DC motor to activate the traditional manually operated slat positioning rod. The five blinds were synchronized to provide the same angle, where a positive blind angle is defined from the horizontal plane with slats inclined downwards for a ground view by the occupant. At 0^{o}, the slats are horizontal, allowing a relatively open window view; at 60^{o}, the slats are just touching; and at 68^{o}, the slats are squeezed shut to the mechanical limit of the venetian blind system. For stable solar conditions (e.g., clear sunny weather), the blinds often did not move for over an hour.

The lighting system in each room was composed of two pendant direct/indirect luminaires, each with four T8 32W lamps and two 2-lamp dimmable ballasts. The dimming ballasts were rated to produce 10% light output for a minimum power input of 33%. The direct/indirect lighting system at 13 W/m^2 (1.35 W/ft^2) was selected for its improved lighting quality. The majority of the light (95%) was reflected upward by a half-elliptical reflector; the remainder filtered downward through a grid of small perforations in the reflector. Measured workplane illuminance levels (with electric lighting only) were ~540 lux at the back area of the room after 6 months of operation.

2.3. Modes of Operation

The motorized blinds and dimmable lighting controls in the prototype system were capable of being operated over a very wide performance range. We examined the performance of the system under three different modes of operation: (1) automatic, (2) auto user control, and (3) manual.

Figure 1. Floor plan of full-scale test room.

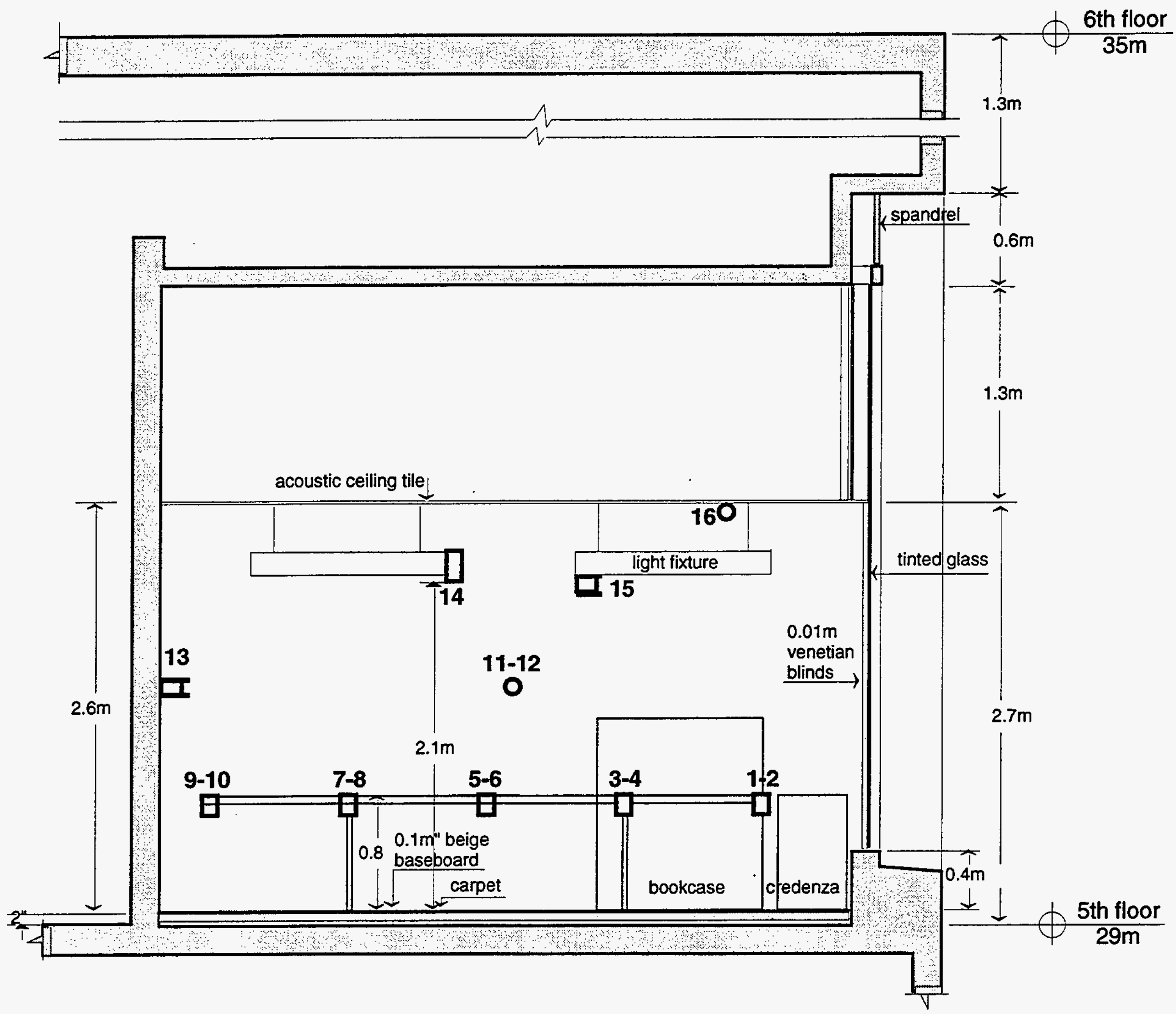


Monitored data:

1-10	Global illuminance - horizontal (lux)
11-12	Global illuminance - vertical (lux)
13	Global illuminance - window shielded (lux)
14	Photosensor signal (V)
15	Global illuminance - window (shielded) (lux),
16	Global illuminance - ceiling (lux)

Note: During occupant testing, sensors 1-10 were not present in the room. The total illuminance was determined indirectly using the signal from sensor 14 correlated to the average workplane illuminance measured by sensors 4 through 7. Fluorescent lighting illuminance was determined using a correlation between monitored power and the average workplane illuminance measured by sensors 4 through 7.

Figure 2. Section plan of full-scale test room.



Monitored data:

1-10	Global illuminance - horizontal (lux)
11-12	Global illuminance - vertical (lux)
13	Global illuminance - window shielded (lux)
14	Photosensor signal (V)
15	Global illuminance - window (shielded) (lux),
16	Global illuminance - ceiling (lux)

Note: During occupant testing, sensors 1-10 were not present in the room. The total illuminance was determined indirectly using the signal from sensor 14 correlated to the average workplane illuminance measured by sensors 4 through 7. Fluorescent lighting illuminance was determined using a correlation between monitored power and the average workplane illuminance measured by sensors 4 through 7.

2.3.1. Automatic mode

In the automatic mode, the envelope/lighting system was checked (and adjusted, if necessary) every 30 seconds to make sure the system was performing as designed:

(1) Direct sun may create visual discomfort if incident on the workplane and may cause thermal discomfort during the cooling season. The window control system was designed to block direct sun at all times throughout the day.

(2) Permitting just the right amount of daylight to offset the electric lighting can allow one to dim or turn off the electric lights. Admitting more daylight than the design level will impose an unnecessary solar heat gain load on the cooling system. The control system was designed to adjust the venetian blinds to meet the design level with daylight (540-700 lux). If there was insufficient daylight, the fluorescents were designed to "top-up" the daylight level to a design level of 510 lux.

(3) For greater energy efficiency, the electric lights are turned off if there is sufficient and stable daylight,[3] after a 10-minute time delay. The delay reduces potentially annoying on/off cycling of the lights (from 11% light output to 0%) during variable daylight conditions.

(4) The window view can be obstructed by the slats of the venetian blind. For periods when there was insufficient daylight (overcast, early morning/late afternoon hours), or when there was no direct sun in the plane of the window, the slat angle is set to horizontal to permit a view. The venetian blind could not be retracted to allow a completely unobstructed view.

An example of this automatic control strategy is shown in Figure 3 for a clear sunny day, and is contrasted against a fixed blind scenario for the same day (July 2).

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[3] 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).

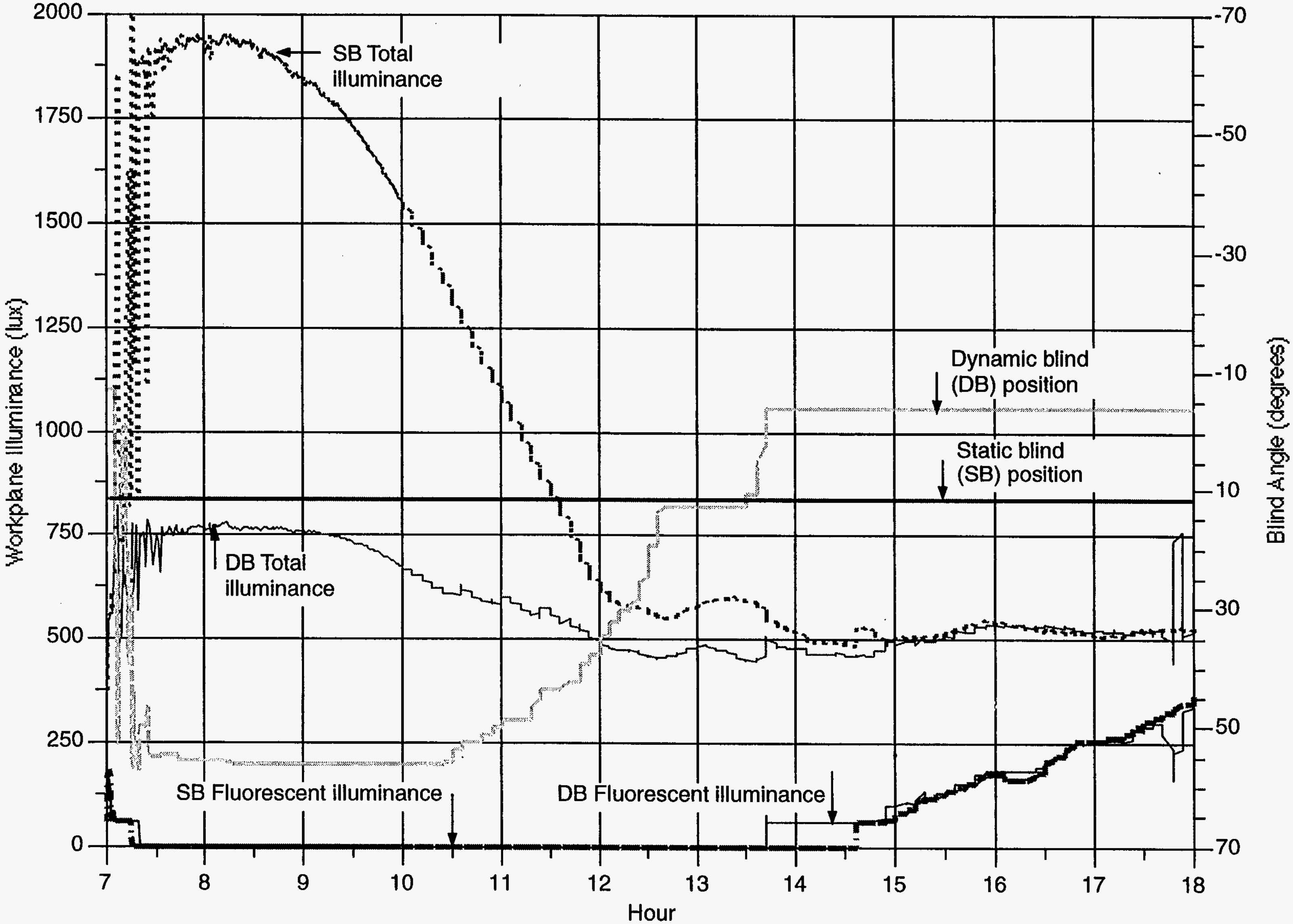

Figure 3. Blind angle, monitored fluorescent illuminance, and total (fluorescent + daylight) illuminance at a workplane area two-thirds towards the back of the room. Data are given for a 15° static blind (SB) and a dynamic blind (DB) over the course of a clear sunny day (July 2, 1996). Both systems have the same daylighting control system. Note how the total illuminance in the room with the static blind followed the pattern of outdoor daylight availability, reaching ~2000 lux when the morning sun was in the plane of this southeast-facing window, whereas in the room with the dynamic blind, interior illuminance levels were maintained within a range of 370-800 lux throughout the day. The electric lights were turned on nearly 1 hour earlier with the dynamic system, so daily lighting energy use (defined from 6:00 to 18:00) was 84 kW or 18% higher. However, the daily cooling load (not shown) was 1,118 kW (16%) lower and the peak cooling load was 479 W (21%) lower compared to the static blind.

2.3.2. Auto user control mode

Any automatic lighting control system, if it is to meet user approval, must allow for user adjustment of some of the control parameters.[4] Simultaneously, these adjustments must be few enough in number to be easy to use and not add unduly to the system's expense. The importance of providing users with accessible and personally adjustable controls, and the consequences of doing so, is the subject of ongoing discussion and debate. To explore these issues, the following user controls were built into a remote, small (3" x 4") console box that allowed occupants to set their preferences during the auto user control mode:

Illuminance level. A slider switch allowed the user to adjust the design workplane illuminance setpoint (electric and daylight). This allowed users to set the illuminance between 240 lux and 1650 lux. The system tries to meet this setpoint with available daylight, but does not allow direct sun admissions. At the beginning of the test environment, the slider switch was set to the mid-point of the range (~ 950 lux).

Delay time period before electric lights turn off. The "lights off" control gives the user the option of setting the time delay to 5, 10, or 20 minutes using a toggle switch: e.g., electric lights would be turned off after a 10-minute delay if there was sufficient and stable daylight to provide the design workplane illuminance level set by the slider switch. At the beginning of the test environment, the time delay was set to 5 minutes.

Horizontal (relaxed) blind position. When direct sun is not present and the workplane illuminance level is not excessive, the blind slats "relax" to a horizontal position to maximize view. The user can customize this position using a slider switch to tilt the blind upwards or downwards (± 0 to 35^{o}) to time their view or control glare, if present. At the beginning of the test environment, the blinds were set to the horizontal position.

A very responsive window system may meet all control objectives adequately, especially under transient conditions (partly cloudy skies). However, frequent blind movement may be unacceptable to users (noise, visual distraction) and may result in shortened product life. During transient conditions, the degree of slat angle adjustment required per interval of control can be large. The amount of

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4 See Ne'eman et al. [2] and Slater et al. [3] for studies showing the importance of controls to office workers. Studies conducted by the Building Research Establishment in the United Kingdom showed that high user satisfaction and high energy efficiency were associated with high levels of local control [3]. Conversely, where users had little or no control over the lights in their workspace, or low awareness of the proper use of controls, low satisfaction and energy wastage were common.

movement can be restricted by the user to a certain level for a given adjustment time by the following two control options:

Blind adjustment interval. The user has the option of setting how often the blind can move from 1 to 10 minutes. At the beginning of the test environment, the adjustment interval was set to 1 minute.

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," corresponding to a value of 10 and 1 movement, respectively, per adjustment interval.[5] At the beginning of the test environment, the blind movement was set to "unlimited".

2.3.3. Manual mode

In order to examine the preferences of office workers, we allowed occupants to manually control their environment when the automatic mode was turned off (i.e., the manual mode). During this period, occupants were able to adjust the blinds as they liked and turn the lights on (100% power) or off (0% power) with a wall switch, as they would do in their own office. At the beginning of the test environment, the blinds were set to the horizontal position and the lights were turned on.

3. Research Methodology

3.1. Questionnaire development and pretest

We developed a questionnaire to investigate how the level of occupant acceptance of the dynamic building envelope and lighting system was related to the quantitative and qualitative aspects of the

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[5] Thus, the user is given the option to set the venetian blinds' adjustment frequency (1-10 minutes) and amount of blind slat movement allowed per adjustment cycle (unlimited to limited). If the slider switch is set to 1 minute frequency with unlimited movement, the venetian blinds will be adjusted as much as is required every 1 minute, if necessary. For stable daylight conditions (e.g., clear sunny summer mid-mornings), the blinds will often not adjust for a 4-5 hour period. For unstable daylight conditions, the blinds may need to move every 1 minute. With unlimited movement, the blinds will be adjusted accordingly. If the slider switch is set to 1 minute frequency with limited movement, the blinds will be adjusted a smaller amount every one minute if necessary, until the control system is satisfied.

office environment described in Section 2.3.[6] Salient features of the questionnaire are described in Table 1. The questionnaire was based on a review of the literature, discussions with LBNL staff, and meetings with other experts in the field.

The questionnaire was pretested on four LBNL employees, using the same test procedure as in the full-scale test (Section 3.3). In the pretest, the respondents indicated that the questions in the questionnaire were understandable and easy to complete. Only minor changes were made to the questionnaire. The respondents noted where improvements in the operating system (including the type of adjustments that they could make) were needed.

3.2. Participant recruitment

We first contacted the U.S. General Services Administration (GSA) in the Oakland Federal Building to discuss the best method for recruiting volunteers to participate in the occupant evaluation. GSA distributed a letter to supervisors in the various federal agencies located in the building, encouraging them to notify their employees about participating in our project. We also attended a meeting of federal agency supervisors at the building. In addition to asking for their help in recruiting volunteers, we showed them the room where the employees would be working. We recruited 14 Federal government office workers: two-thirds were male, and over half were between 40-49 years old. About half were managers or administrators while the other half were professional or technical people. Although we do not believe the sample was biased, we would have liked a larger sample and probabilistic sampling, but project resources limited us to this sampling approach and number of volunteers.

3.3. Test procedure

The field test was conducted from July 9 to July 23, 1996 (predominantly clear sunny weather). Occupants spent three hours in the new office environment (e.g., either between 9:00 AM and Noon, or between 1:00 PM and 4:00 PM). During this time period, the occupants experienced three different control environments (Section 2.3), each for one hour (in random order): (1) automatic mode, in which the window and lighting system was operated, but occupants were not asked to make any modifications to the system; (2) auto user control mode, in which the window and lighting system was in operation, but occupants were able to adjust the settings of the system with an attached remote controller, with the

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[6] The questionnaire is available upon request.

design constraints set by the system; and (3) manual mode, in which the automatic mode was turned off, and occupants were able to adjust the blinds and turn the lights on or off as they liked.

At the start of the test period, each occupant was presented with an overview of the project, a description of the three different modes of operation, and a demonstration of the remote console box that allowed occupants to set their preferences (see Section 2.3.2). Each office worker was asked to perform office work tasks (reading, writing, and computer-related tasks[7]) that they normally do. After completing the initial part of the questionnaire at the beginning of the first hour, each employee was asked to respond to a set of questions regarding the room at the end of each hour. At the end of the third hour, each respondent completed a final list of questions regarding their overall experience with the window/lighting system and specific strengths and weaknesses of the system (open-ended questions).

4. Survey Findings

All of the interviewees believed that it was important to have pleasant physical surroundings at work, and that it was difficult to work when they were physically uncomfortable. Prior work difficulties were related to noise distractions (78%) and glare (57%). However, only half of the sample believed it was important to control environmental conditions in their workplace. During the three hour period, about 75% of the sample spent their time reading and writing, often facing the desk in the room. Working on a computer was done by the other 25% of the sample. Each office worker experienced the same three operational modes as in the pretest, in random order.

4.1. Overall survey findings

In this section, we present the survey responses of the participants in this study. In a later section, we examine the lighting and blind measurements to corroborate the reported impressions. In the survey findings reported below, a rating made by 7% of the subjects represents 1 person out of the 14 office workers.

[7]Although a computer was not provided, some participants brought their own portable (laptop) computer.

In general, most of the volunteers 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. Respondents were also generally satisfied with their ability in controlling the blinds for adjusting the amount of light and for adjusting the direction of the light. With respect to other conditions in the room, most people were satisfied with ventilation and the level of noise. While a few people were dissatisfied with the window view, most dissatisfaction was related to the "cool" temperature (20.5-21.7°C [69-71°F]) in the room. 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).

4.2. Findings by modes of operation

We analyzed the occupant data for each of the three different modes of operation experienced by each of our volunteers (one for each hour) (Table 1). 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 (where the computer alone optimizes the building envelope and lighting system), almost 75% of the sample preferred more daylighting; (2) in the auto user control mode (where occupants are able to manually set the conditions in which the computer operates), more people were comfortable with the lighting and experienced less discomfort with dimness and lighting distribution; and (3) in the manual mode (where the computer was turned off), 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, in contrast to the other lighting environments, 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%). We examine the different lighting environments in more detail below.

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[8] In this paper, "lighting" includes both daylighting and electric lighting, unless otherwise specified.

[9] In this paper, we do not present tests of significance due to the small sample size (14). Thus, the findings are illustrative, and statistically significant differences will need to be determined on larger samples.

Table 1. Selected Survey Findings
(Sample size = 14)

	Strongly Disagree (%)	Disagree (%)	Neither Agree Nor Disagree (%)	Agree (%)	Strongly Agree (%)	N/A (%)
Overall lighting comfortable						
Automatic	0	29	14	57	0	0
Auto user control	0	21	0	71	7	0
Manual	0	7	7	64	21	0
Lighting uncomfortably bright for tasks						
Automatic	43	50	7	0	0	0
Auto user control	21	71	7	0	0	0
Manual	29	71	0	0	0	0
Lighting uncomfortably dim for tasks						
Automatic	21	21	29	29	0	0
Auto user control	7	71	14	7	0	0
Manual	14	79	7	0	0	0
Lighting poorly distributed						
Automatic	21	36	7	36	0	0
Auto user control	21	57	7	14	0	0
Manual	21	64	7	7	0	0
Lighting caused deep shadows						
Automatic	21	50	29	0	0	0
Auto user control	21	57	14	7	0	0
Manual	29	71	0	0	0	0
Reflections from light fixtures hindered work						
Automatic	36	43	7	0	0	14
Auto user control	36	50	14	0	0	0
Manual	21	64	7	0	0	7
Lighting fixtures too bright						
Automatic	29	50	7	0	0	14
Auto user control	36	57	0	0	0	7
Manual	14	64	0	14	0	7
Glare from ceiling lights bothersome						
Automatic	29	43	7	0	0	21
Auto user control	43	43	7	0	0	7
Manual	14	71	0	7	0	7
Glare from windows bothersome						
Automatic	21	71	7	0	0	0
Auto user control	36	57	7	0	0	0
Manual	8	69	8	15	0	0
Preferred more daylight for tasks						
Automatic	0	21	7	64	7	0
Auto user control	0	29	21	43	7	0
Manual	14	29	29	21	7	0

Table 1 Continued. Selected Survey Findings

	Strongly Disagree (%)	Disagree (%)	Neither Agree Nor Disagree (%)	Agree (%)	Strongly Agree (%)	N/A (%)
Amount of daylight sufficient for work without additional electric lighting						
Automatic	0	50	14	21	14	0
Auto user control	0	43	7	21	29	0
Manual	0	21	29	29	21	0
Dimming of lights bothersome						
Automatic	7	21	21	21	0	29
Auto user control	7	43	21	7	7	14
Manual	14	29	21	0	0	36
Preferred more artificial lighting for tasks						
Automatic	14	29	29	29	0	0
Auto user control	7	43	21	29	0	0
Manual	21	36	43	0	0	0
Lights being turned on and off not bothersome						
Automatic	0	21	21	29	7	21
Auto user control	0	14	29	36	7	14
Manual	0	7	14	29	7	43
Sound from the movement of the blinds bothersome						
Automatic	0	64	21	14	0	0
Auto user control	7	36	29	21	0	7
Manual	7	57	21	14	0	0
Intermittent opening and closing of the blinds bothersome						
Automatic	7	64	7	7	0	14
Auto user control	7	29	50	0	0	14
Manual	7	29	29	7	0	29
By controlling the blinds, able to satisfactorily adjust the <u>amount</u> of light for work.						
Automatic	0	7	7	7	0	79
Auto user control	7	21	7	29	14	21
Manual	0	7	0	57	21	14
Important to adjust the amount of light for work by controlling the blinds						
Automatic	0	0	21	43	36	0
Auto user control	0	7	7	50	36	0
Manual	0	0	7	64	29	0
By controlling the blinds, able to satisfactorily adjust the <u>direction</u> of light for work.						
Automatic	0	0	7	7	0	86
Auto user control	14	21	21	7	14	21
Manual	0	14	21	50	7	7

4.2.1. Automatic mode

Most interviewees (57%) felt the overall lighting to be comfortable — not too bright, no deep shadows, not impacted by reflections, and not bothered by glare from ceiling lights. Some people (29%) felt the lighting to be uncomfortable — perhaps due to the light levels being too dim (as reported by 29% of the entire sample) and/or poor lighting distribution (36%). Almost 3/4 of the sample (71%) preferred more daylighting, and 64% felt daylighting was not sufficient for their work without additional electric lighting (that's probably why 29% preferred more fluorescent lighting).

The dimming of lights was bothersome for 21% of the sample, and 21% thought the lights being turned on and off to be bothersome. Only a few people were bothered by the operation of the envelope system: 14% thought the sound from the movement of the blinds was bothersome, and 7% felt the intermittent opening and closing of the blinds was bothersome.

With respect to other conditions in the room, most people were satisfied with ventilation (86%) and level of noise (86%). A few people were dissatisfied with the window view (14%). Most dissatisfaction was related to the temperature (being too cool) (42%) in the room.

4.2.2. Auto user control mode

In contrast to the automatic mode, more people (78%, compared to 57%) felt the overall lighting to be comfortable. Dimness was a problem for only one person (7% of the sample, compared to 29% in the automatic mode), and poor distribution was a problem for 14% of the sample (compared to 36%). While one-half of the sample preferred more daylight, this percentage was less than in the automatic mode (71%) — although 43% felt daylighting was not sufficient for doing their work without additional electric lighting.

The dimming of lights was bothersome for 14% of the sample, and 14% thought the lights being turned on and off to be bothersome; these percentages were lower than in the automatic mode (21%). Only a few people were bothered by the operation of the system: 21% thought the sound from the movement of the blinds was bothersome, and nobody felt the intermittent opening and closing of the blinds was bothersome.

Respondents expressed diverse opinions in their ability to control the blinds for adjusting the amount of light and for adjusting the direction of the light. For example, 43% were satisfied with the former (i.e., amount of light), while 28% were dissatisfied; similarly, 21% were satisfied with the latter (i.e., direction of light), while 38% were dissatisfied.

With respect to other conditions in the room, most people were satisfied. Most dissatisfaction was again related to the temperature (28%) in the room, followed by window view (14%).

4.2.3. Manual mode

In the manual mode, most (85%) of the sample felt the overall lighting to be comfortable, a higher percentage than the other two operational modes (78%, 57%). Accordingly, there were very few complaints related to brightness, dimness, shadows, or lighting distribution. However, in contrast to the other modes of operation, relatively more people in the manual mode were dissatisfied with specific sources of brightness and glare: lighting fixtures were too bright (14%), glare from ceiling lights (7%), and glare from windows (15%).

Only 28% of the sample preferred more daylight and none preferred more artificial lighting, although only 40% felt the amount of daylight was sufficient for their work without additional electric lighting. People were satisfied in their ability to control the blinds for adjusting the amount of light (78%) and the direction of light (57%) for their work. Over 90% of the occupants found the manual mode to be just right. With respect to other conditions in the room, most people were satisfied. Most dissatisfaction was temperature related (28%).

4.3. Confounding environmental influences

In this pilot study, office workers may be reacting to both the innovative technology and the room environment, making it difficult at times to separate the influences of the technology from the room environment. For example, several workers reported that what they liked best about the room was related to the prototype system: "maximizes use of sunlight," "able to control artificial lights according to the amount of natural light from the window," and "blind manual controls." Similarly, some volunteers noted that what they liked least about the room was related to the system: "not enough direct control over amount of natural light into room," "windows shielded too much light at times," and "blinds are a little noisy when adjusting."

In contrast to these technology-specific responses, some workers responded in a way that had very little to do with the integrated building envelope and lighting system: for example, some volunteers reported "no disturbances," "solitude," "carpet", "desk space," "chair with some lumbar support," and "light-colored walls and ceilings" as the best things about the room. And for what they liked least about the room, volunteers noted the following: "all the wires," "whiteness - overall lack of contrast," "new building fumes," and "the view is of artificial sights rather than natural ones." We suspect that some of these factors may have indirectly affected their responses to questions regarding the prototype system. Thus, if this technology were to be demonstrated in other buildings, care should be given to the entire room environment, making sure it is as pleasant as possible to the occupant.

Similarly, the reactions to the technology and the room environment may have been influenced by the existing office situation of the office workers. Although we did not investigate this issue, informal comments by the volunteers indicated that their existing office environment may affect their responses to the demonstration environment. For example, the demonstration room was too cool for a worker who said that he had a warm office: he tried to adjust the blinds in the demonstration room to admit more sun to stay warm. In another case, the demonstration room was very cheerful and bright for a worker who said he lived in a "cave environment" with dark painted walls, direct light fixtures, and small windows.

5. Lighting and Blind Measurements

Extensive lighting and blind measurements of the offices were taken during the pilot study. In this section, we compare these measurements with occupants' preferred settings and their impressions about the different hourly modes of operation. In Table 2, we show the one-hour averages for respondents by mode of operation and by time of day for selected variables. The first two analyses are for the automatic mode in the morning and in the afternoon. As expected, total illuminance (daylighting plus electric lighting) is within the design range of 510-700 lux. These measurements contrast strongly with the manual mode where respondents could create their own lighting environment: on average 1493 ± 653 lux in the morning and 1030 ± 248 lux in the afternoon, indicating that they preferred higher light levels than those set by the automated control system, as confirmed by the survey findings noted above.[10]

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[10] Preferences for higher illumination among office workers have been reported in other studies [5-9].

Table 2. Lighting and Blind Data Hourly Averages for Each Respondent by Mode

Mode (Occupant number, Time of day, and Sky Conditions)	Estimated Daylight (lux) (1)	Monitored Electric Lighting (lux) (2)	Total Illuminance (lux) (3)	User Set Illuminance Setting (lux) (4)	User Set Light Delay (minutes) (5)	Monitored Blind Position (6)	User Set View Angle (7)	User Set Blind Adjustment (minutes) (8)	User Set Blind Motion (8)
AUTOMATIC - AM									
#1, 8-9, overcast	404	132	536	n/a	n/a	-7	n/a	n/a	n/a
#4, 9-10, sunny	618	9	628	n/a	n/a	58	n/a	n/a	n/a
#6, 10-11, sunny	572	25	597	n/a	n/a	63	n/a	n/a	n/a
#9, 10-11, cloudy	600	22	622	n/a	n/a	0	n/a	n/a	n/a
#12, 10-11, sunny	574	27	601	n/a	n/a	55	n/a	n/a	n/a
#13, 8-9, sunny	681	10	691	n/a	n/a	66	n/a	n/a	n/a
#14, 8-9, cloudy	169	341	510	n/a	n/a	-7	n/a	n/a	n/a
Average	517	81	598	n/a	n/a	37	n/a	n/a	n/a
St. Deviation	175	122	60	n/a	n/a	28	n/a	n/a	n/a
Maximum	681	341	691	n/a	n/a	-7	n/a	n/a	n/a
Minimum	169	9	510	n/a	n/a	66	n/a	n/a	n/a
AUTOMATIC - PM									
#3, 13-14, sunny	478	61	539	n/a	n/a	-4	n/a	n/a	n/a
#5, 13-14, sunny	531	17	548	n/a	n/a	22	n/a	n/a	n/a
#7, 12-13, ~sunny	597	7	604	n/a	n/a	36	n/a	n/a	n/a
#10,13-14, ~sunny	603	23	626	n/a	n/a	-6	n/a	n/a	n/a
#11, 13-14, ~sunny	606	10	616	n/a	n/a	31	n/a	n/a	n/a
#15,14-15, cloudy	583	10	593	n/a	n/a	15	n/a	n/a	n/a
Average	566	21	588	n/a	n/a	17	n/a	n/a	n/a
St. Deviation	51	20	36	n/a	n/a	48	n/a	n/a	n/a
Maximum	606	61	626	n/a	n/a	-6	n/a	n/a	n/a
Minimum	478	7	539	n/a	n/a	36	n/a	n/a	n/a
AUTO USER CONTROL- AM									
#1, 9-10, cloudy	536	12	548	469	5	61	39	1	10
#4, 8-9, sunny	916	5	921	821	8	46	43	1	9
#6, 9-10, sunny	863	60	923	765	6	n/a	20	4	6
#9, 8-9, cloudy	282	317	599	631	5	-4	40	1	6
#12, 9-10, sunny	852	12	864	836	5	48	26	3	10
#13, 9-10, sunny	655	8	663	272	5	66	33	2	9
#14, 10-11, cloudy	569	56	625	593	10	-6	47	5	9
Average	668	67	735	627	6	39	35	3	9
St. Deviation	227	113	162	205	2	31	10	2	2
Maximum	916	317	923	836	10	-6	47	5	10
Minimum	282	5	548	272	5	66	20	1	6
AUTO USER CONTROL - PM									
#2, 14-15, sunny	491	323	814	845	10	-6	44	1	10
#3, 12-13, sunny	652	31	683	691	5	10	42	1	10
#5, 14-15, sunny	461	170	631	663	18	-6	45	1	10
#7, 13-14, sunny	612	124	736	752	7	3	49	9	3
#10, 12-13, ~sunny	645	120	765	780	9	12	42	2	10
#11, 14-15, sunny	445	171	616	636	5	-31	66	9	3
#15, 12-13, cloudy	629	27	656	611	5	25	39	1	10
Average	562	138	700	711	8	1	47	4	8
St. Deviation	92	100	74	84	5	48	9	4	3
Maximum	652	323	814	845	18	-31	66	9	10
Minimum	445	27	616	611	5	25	39	1	3

See legend on next page

Table 2 Continued. Lighting and Blind Data Hourly Averages for Each Respondent by Mode

Mode (Occupant number, Time of day, and Sky Conditions)	Estimated Daylight (lux) (1)	Monitored Electric Lighting (lux) (2)	Total Illuminance (lux) (3)	User Set Illuminance Setting (lux) (4)	User Set Light Delay (minutes) (5)	Monitored Blind Position (6)	User Set View Angle (9)	User Set Blind Adjustment (minutes) (8)	User Set Blind Motion (8)
MANUAL - AM									
#1, 10-11, ~sunny	485	0	485	n/a	n/a	59	59	n/a	n/a
#4, 10-11, sunny	1636	584	2220	n/a	n/a	-13	-6	n/a	n/a
#6, 8-9, sunny	1417	552	1969	n/a	n/a	34	36	n/a	n/a
#9, 9-10, cloudy	648	582	1230	n/a	n/a	-27	-27	n/a	n/a
#12, 8-9, sunny	1263	580	1843	n/a	n/a	36	42	n/a	n/a
#13, 10-11, sunny	1877	21	1897	n/a	n/a	-16	-16	n/a	n/a
#14, 9-10, cloudy	229	576	805	n/a	n/a	13	15	n/a	n/a
Average	1079	414	1493	n/a	n/a	15	17	n/a	n/a
St. Deviation	627	276	658	n/a	n/a	34	34	n/a	n/a
Maximum	1877	584	2220	n/a	n/a	-27	-27	n/a	n/a
Minimum	229	0	485	n/a	n/a	59	59	n/a	n/a
MANUAL - PM									
#2, 13-14, sunny	343	583	926	n/a	n/a	44	46	n/a	n/a
#3, 13-14, sunny	604	585	1189	n/a	n/a	10	10	n/a	n/a
#5, 12-13, sunny	555	578	1133	n/a	n/a	34	37	n/a	n/a
#7, 14-15, sunny	419	130	549	n/a	n/a	-7	-7	n/a	n/a
#10, 14-15, sunny	418	577	995	n/a	n/a	10	15	n/a	n/a
#11, 12-13, ~sunny	765	558	1323	n/a	n/a	-33	-34	n/a	n/a
#15, 13-14, cloudy	651	445	1096	n/a	n/a	-44	-44	n/a	n/a
Average	536	494	1030	n/a	n/a	3	5	n/a	n/a
St. Deviation	150	168	248	n/a	n/a	36	34	n/a	n/a
Maximum	765	585	1323	n/a	n/a	-44	-44	n/a	n/a
Minimum	343	130	549	n/a	n/a	44	46	n/a	n/a

n/a = not applicable

1. Estimated daylight is determined by the correlation between the ceiling sensor photosensor and the measured average workplane illuminance towards the back of the room and can be off by as much as plus or minus 100 lux. Illuminance sensors were taken out when there were occupants in the room.

2. The electric lighting workplane illuminance levels were also defined by correlations and are accurate to within plus or minus 10 lux. If the lights are off, then illuminance = 0 lux; if the lights are on, then illuminance = 580 lux; any value between 0 and 580 indicates that the lights are being turned on and off during that hour.

3. Total illuminance is the sum of daylighting and electric lighting.

4. To calculate the preferred illuminance range, add 160 lux to the preferred setting; e.g., if the preferred setting = 500 lux, then the preferred range = 500-660 lux.

5. The light delay represents the option of setting the time delay to 5, 10, or 20 minutes using a toggle switch: e.g., electric lights will be turned off after a 10-minute delay if there is sufficient daylight to provide the design workplane illuminance level.

6. Monitored blind position is the measured angle of the venetian blind slats: when the blind position is 0, the slats are horizontal; when 68 to 60, the slats are closed; and when -30, the slats are tilted up, so that the occupant has a view of the sky.

7. User set view angle is the preferred slat angle for view. If the sun is out of the plane of the window or if there is no direct sun, and if the preferred illuminance level is not exceeded, then the user can tune the view angle to slightly upwards for a sky view or downwards for a ground view (± 35°).

8. In the "auto user control" mode, the user is given the option to set the venetian blinds' adjustment frequency (Blind Adjustment) (1-10 minutes) and amount of blind slat movement (Blind Motion) allowed per adjustment cycle (unlimited (10) to limited (1)). If the slider switch is set to 1 minute frequency, unlimited movement, the venetian blinds will be adjusted as much as is required every 1 minute, if necessary. For stable daylight conditions (e.g., clear sunny summer mornings), the blinds will often not adjust for a 4-5 hour period. For unstable daylight conditions, the blinds may need to move substantially to meet control objectives. With unlimited movement, the blinds will be adjusted accordingly. If the slider switch is set to 1 minute frequency, limited movement, the blinds will be adjusted a smaller amount every one minute if necessary, until the control system is satisfied. For unstable daylight conditions, it may take longer to satisfy the control parameters.

9. In the "manual" mode, the user can set the blinds to any angle, as in a regular non-automated venetian blind. The "user set view angle" is this preferred slat angle and is virtually the same as the data in the column titled "monitored blind position."

Workers preferred both more daylight and electric lighting (also noted in the survey responses). For some, the desire for more light did not necessarily mean that workers needed more light for seeing or performing tasks: in one case, a volunteer wanted more light to stay alert. As discussed below, there is a need for investigating how illuminance distribution, lighting quality, and room design affect workplane illuminance preferences. And it also may be desirable to raise the lower bound of the design illuminance range from 510 lux to, for example, 560 lux, although this may slightly increase cooling loads.

While the trend toward higher preferred illuminance levels is shown clearly between the automatic and manual modes, this trend is partially confirmed by the auto user control mode. Whereas 57% of the workers in the automatic mode were comfortable with the overall lighting at an average illuminance of 593 lux, 71% of the workers in the auto user control mode were comfortable with the overall lighting at 683 lux (13% higher). With the auto user control mode, 6 out of 14 (43%) occupants were comfortable with the overall lighting with an average illuminance of 590 lux in the morning and 693 lux in the afternoon, while 4 out of 14 were also comfortable but preferred either more daylight (3 occupants) or more electric light – average illuminances for this mode were 793 lux in the morning and 696 lux in the afternoon. The remaining 4 subjects were uncomfortable with the overall lighting environment and preferred more electric and/or more daylight. For this mode, the average illuminance level was 803 lux.

Note that the stated desire or preference for more light versus the behavior of the occupants as indicated by their preferred settings on the remote control device were somewhat contrary. Between the eight subjects desiring more light (whether comfortable with the overall lighting or not), all could have set the illuminance slider switch to a higher level of preferred illuminance and would have been provided with either more daylight or electric light. One occupant set the illuminance slider switch to 272 lux, received 663 lux (in some cases, a lower illuminance level could not be provided by the system because the outdoor direct sun conditions were too bright to be controlled below the preferred illuminance level), and was moderately comfortable. This may indicate that this component of the remote control device was not well understood by workers in this mode.

Very few respondents reported any problems with glare in the survey. This was confirmed by the monitored data from which glare calculations (ranging from 0 to 4) were computed for the survey period.[11] The average glare rating for the subject facing the window (the "worst case") varied from 1.65

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[11] Several glare formulas were examined in this study, ranging from standard formulas such as DGI, UGR, and CGI, to a recently developed estimate for subjective ratings, SR (see Osterhaus [10]). All

for automatic mode to 1.75 for manual mode, which is slightly above the border of the "just noticeable and just disturbing" glare range (1.5), and none were greater than 2.2 (approaching the "just disturbing to just intolerable" border of 2.5). As discussed below, only two workers complained about glare, and these problems only occurred during the manual mode. In both cases, the office workers were reading and writing and facing the desk. In sum, the glare calculations and the survey results suggest that the automatic and auto user control modes reduced the potential for glare slightly (by 0.14, where a difference of 1.0 is statistically significant).

In Table 2, under the auto user control mode, we show the blind settings for view that were measured ("monitored blind position") as well as set by the workers ("user set blind position"). On clear sunny mornings, these preferred blind view settings are not relevant for this period in July since direct sun is present and the "view" control objective is overridden by the "block direct sun" and "optimize illuminance" control objectives. For example, respondent #13 set the preferred controls to blind view position at 13^{o}[12] and illuminance at 272 lux, but because there was direct sun, the monitored blind position was 52^{o} and the monitored illuminance was 663 lux. In the afternoon and on overcast mornings, the user set preferences are relevant. On average, the preferred and monitored blind view position was from 1^{o} to -11^{o}. Note on clear sunny afternoons, the outdoor view can get very bright since the opposing 10-story buildings reflect direct sun. Yet again, very few respondents reported any problems with glare. Two users preferred an upwards sky view (blind angle set to -15^{o} and -45^{o}), and one other user preferred a slightly downwards ground view (3^{o}).

In the auto user mode, most people preferred to have the fluorescent lights turned off after a 7-8 minute delay, on average, if there was sufficient daylight. One notable exception was one subject who set the average time delay to 19 minutes. This subject may have been responding to the previous hour's automatic mode where the fluorescent lights were turned off once after a default delay of 10 minutes, then 45 minutes later turned on when daylight illuminance levels dropped. Note that the fluorescents never turned off during this auto user control hour where the delay was set to 19 minutes.

Throughout the day, four out of fourteen workers distinctly preferred less blind movement with two subjects having explicit reasons. In one case (#14), the user thought that the noise was bothersome and set the blind activation rate to 5 minutes with nearly unrestricted movement per cycle (9). This same user found this rate activation too frequent, perhaps not knowing how to set the remote control device to less frequent movement. For this user in the previous hour's automatic mode, the blinds did not move for

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the formulas correlated well in terms of their relative rankings. The results for SR are described in this paper.

[12] The blind is horizontal and allows the worker a relatively open window view when the blind angle is 0^{o}; the blind is closed when the blind angle is close to 60^{o} (from 48^{o} to 68^{o}).

the entire hour. In the second case (#6), the worker found the blinds to be not frequent enough, citing "other" reasons (besides weather and frequently changing tasks — the worker preferred more light from the window) for why the blind movement was unsatisfactorily slow (toggles set to 4 minute activation and somewhat limited (6) movement). The measured data show that throughout this hour the blinds were erroneously exhibiting hysteresis due to the tensioning on the blind (oscillating between slightly closed and slightly open ~ 55^o and 65^o). The blind noise has since been quieted and the hysteresis problem has been solved.

Finally, it is important to note that some, but not all, of the lighting conditions and measurements occurred during partly cloudy days (unstable daylight conditions). During certain periods of the day, the lighting and survey data indicated that lighting levels may have been low at times and the system might be adjusting frequently, resulting in 7-14% of the occupants wanting more light and bothered by "noisy blinds" and lights being turned on and off. In one case, the occupant felt the system was not responding quick enough and noted that "control delays were frustratingly slow" and he just "gave up on them." However, in general, most people were satisfied with blind adjustments. Concerns with system frequency could not be matched with the frequency of blind adjustments (every minute) or the number of adjustments per interval (e.g., 10 per interval).

6. Case Studies of Dissatisfaction

We examined the measured data in detail where individuals expressed specific complaints about the system. In most cases, the monitored data "confirmed" the survey findings. For example, in the automatic mode, one worker reported that the overall lighting was not comfortable and the lighting too dim and poorly distributed. During this time, the measured data showed that indeed the blinds were closed and there was very little electric lighting (9 lux); the daylight level was 618 lux — well within the design illuminance range. Nevertheless, this person desired more daylight and artificial light. Because the blinds were closed, this person was also not satisfied with the window view. This same office worker had a similar negative attitude in the auto user control mode, even though the daylighting levels had reached an average of 916 lux. This person preferred more daylight and artificial lighting (electric lighting was little — 5 lux). Even though the blinds were half open, the window view was still not considered satisfactory. In the "manual" mode, all of these person's problems evaporated: during this time, the blinds were open and the lights were on, and there was lots of electric lighting and daylighting, resulting in a total illuminance of 1636 lux!

In the two cases where workers complained about glare, the glare problem occurred in the manual mode. In the first case, the volunteer reported glare from the ceiling lights (95% indirect, 5% direct).

However, the glare calculations (for facing window) indicated that this person was not experiencing an unusual glare situation (average glare rating of 1.7). The daylight (419 lux) and electric light (130 lux) were also similar to the auto user control mode where the person did not complain about glare. In the second case, the calculated glare index was higher than average and near the "just intolerable" range (average glare rating of 1.9). Total illuminance levels were also high: the daylight level was 1263 lux and the electric lighting level was 586 lux, and the blinds were 1/3 open. Thus, in this case the lighting conditions were very bright and the measured glare was high (in contrast to the first case, where total illuminance was not very high and there were no measured glare problems).

We found only one case where a person did not understand the control system. This person wanted more daylight in the auto user control mode, but had set the blind position to be nearly closed. As a result, he complained that he did "not have enough direct control over the amount of natural light in the room;" not surprisingly, he used the most electric lighting and had the most total illuminance for that particular lighting environment.

7. Suggested Improvements to Design and Operation of the System

Based on the responses to our survey and the lighting and blind measurements, we recommend that the following improvements be made to the design and operation of the prototype system.

First, the remote controller needs to provide, at a minimum, instantaneous feedback to the office worker; otherwise, delays in feedback will create an erroneous impression that the system is not working. For example, a green light could go on indicating that the requested preferences or options were received by the computerized system. Additional information, indicating the response of the system to the commands of the user (i.e., a "smart response"), would also be helpful.

Second, the slider switch (allowing the user the ability to adjust the design workplane illuminance) may need to be modified to incorporate higher illuminance levels. Before making any changes, one should probably conduct more evaluations (see below): for example, the sample in our study was composed of mainly older people (who are known to require more light) and of workers whose tasks were primarily reading and writing (where higher light levels are more comfortable for reading). Another study sample (e.g., young people working on computers) might have preferred lower illumination levels. Furthermore, before changing the design illuminance range of the system, one might want to modify the quality and distribution of the lighting environment by providing more light on the walls and task lighting.

And third, the researchers should consider adding more control options to the remote controller to give workers a stronger sense of control over their environment. It is interesting to note that only 2 of the 14 workers did not believe that it was important for them to control the environmental conditions in their workplace, and these two people expressed the least complaints about the system. In other words, if one were to generalize from our sample, most workers believe it is important for them to control their workplace environment, and the more controls the better [2,3]. This finding must be balanced with the need to keep the user control interface simple enough for the average user who does not want to study the details of the system. A single, multiple position selector that could modify a number of parameters at once would satisfy this requirement. The purpose of this selector would be to adjust the activity level of the control system to the preferences of the occupant(s). This control could bundle together parameters such as: blind adjustment interval, magnitude of blind motion, and electric light turn-off delay.

8. Conclusions

Based on the responses to our survey and the lighting and blind measurements, we were able to draw several conclusions about both the prototype system and future research needs. From the perspective of new technology development, we believe that the prototype integrated envelope and lighting system is ready for field testing. Because most workers were satisfied with the system and there were very few problems or complaints, the system could be installed in a variety of commercial buildings.

The pilot study raises a number of interesting issues with respect to occupant responses and preferences in daylighted environments. It provides some answers and stimulates a number of questions. First, most workers appeared to prefer greater illuminance levels (i.e., more daylight and electric lighting) for their office space, even though they could see well enough to perform their tasks. The higher illuminance levels may indicate the preference of office workers for more daylight, for a less-obstructed view out, for balancing the illuminance from daylighting[13], for more electric lighting to brighten the sides and back of the room, or for electric overhead lights. These preferences would lead to a higher illuminance. As one expert in the field noted: "'How high is enough?' is a question that we can answer easily if we only consider visual performance, but not so readily if our criteria are to maximize satisfaction or preference, or to consider the suggestions of psychobiologists" [11].

[13]Begemann et al. reported that office workers wanted more artificial light when given more daylight [6].

Hence, we believe additional studies are needed for investigating how illuminance distribution, lighting quality, and room design affect workplane illuminance preferences. For example, it may be possible to provide more daylighting to other areas of the room (in addition to the workplane surface), so that the occupants are satisfied with their "natural" lighting environment. In addition, it may be desirable to raise the lower bound of the design illuminance range from 510 lux to, for example, 560 lux. However, significant increases in workplane illuminance and room surface luminance levels could reduce VDT visibility and increase the annual energy cost of the lighting system. A large increase in lighting levels could also increase cooling loads and thermal discomfort.

Second, the automated system performed well and has a generally high level of acceptance by users. When occupants were offered the ability to manually control some or all of the system operation, most workers were able to use the manual controls for adjusting the operation of the lighting and envelope system. However, future modifications to the control system may be made to provide more feedback and control to the user. Prior to implementing the system on a wider basis, materials should be developed for educating and training people about the proper use of the controls and the nature of the feedback system.

Third, we have assumed in this study that office workers prefer relatively stable lighting conditions over time, even in the face of dynamic exterior conditions. Given a larger sample (see below), we could investigate: (1) what kinds of people need to control their lighting environment, (2) how this control may influence their reactions to the lighting environment, and (3) what proportion of the population prefer lighting conditions that change over time, corresponding to changes in external conditions.

Fourth, this study should be seen as a snapshot ("work in progress") of occupant acceptance; it is not a long-term evaluation of occupant acceptance of and preferences for the dynamic envelope/lighting system. For example, since the pilot study, tests have already been conducted on a modulated blind motor that is designed to produce a more smooth, quiet blind motion. Further refinements in hardware and software have been implemented in order to enhance the perceived acceptability of its operation by the occupants. Accordingly, as additional changes are made to improve the prototype system (e.g., including retractable blinds), additional evaluations of the system are warranted (see below).

Fifth, future evaluations of this system should include the following: a larger sample size, more diversity in work tasks, and probabilistic sampling. Our ability to generalize the results from this pilot study with any degree of confidence is limited because the sample was small and the sampling approach was accidental rather than probabilistic. For this reason, readers should consider the findings as suggestions for further study and consideration, rather than as a conclusive fact. Furthermore, a large-scale evaluation of the system should be considered where, for example, funds are available to pay for people to participate in the study for longer periods of time (e.g., 1 day or 1 week, or two 1-week periods, one in summer and one in winter, etc.). Similarly, the system could be installed in an existing work environment and monitored for 6-12 months. During this longer study, illuminance levels, tasks, and sitting arrangements would vary, and data on a variety of performance measures would be collected and analyzed.

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