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Evaluating Daylighting Effectiveness and Occupant Visual Comfort in a Side-lit Open-plan Office Building in San Francisco, California

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0. Abstract

The introduction of daylight to reduce electrical lighting energy consumption and to enhance Indoor Environmental Quality is one of the most common claims made for commercial office buildings promoted as "sustainable," "energy efficient," "green," or "high performance." However, daylit buildings are rarely studied in use to examine the impact of design strategies on visual comfort, or to examine how occupant modifications to the facade may reduce daylighting effectiveness and visual connection to the outdoors. This paper presents key findings from a post-occupancy study of a side-lit open-plan office building located in San Francisco, California. The study examines daylighting performance over daily and seasonal changes in sun and sky conditions in core and perimeter zones of the building. Daylighting performance is assessed through measurements of electrical lighting energy, observations of occupant modifications to the facade, and physical measurements of interior lighting conditions paired with occupant subjective assessments using novel desktop polling station devices. Results show a high frequency of visual discomfort responses at both perimeter and core workspaces and observations reveal a large percentage of facade glazing covered by interior shading devices. Despite the significant reduction in effective visible light transmission, occupants working in the perimeter zones generally considered the levels of available daylight to be sufficient, even when daylight levels were below recommended thresholds for daylight autonomy. Issues related to the daylighting design strategies are discussed in regard to improving the performance of future daylit buildings and refining daylighting design criteria.

Keywords: Daylighting, POE, glare, photocontrols, daylight autonomy

1. Background

In commercial buildings, decisions related to fenestration directly affect the major categories of energy consumption. Lighting represents the single largest electricity end use (35%), with the majority of use during daylight hours [1]. Space cooling represents another significant electricity end use (25%), one-third of which is due to electrical lighting and another one-third to solar heat gains through windows [2]. Thus, facade strategies that control solar loads while transmitting sufficient daylight to minimize the need for electrical lighting have the potential to significantly improve energy performance compared to conventional commercial office buildings. In addition to energy, a growing body of research demonstrates that the introduction of daylight into interior environments has implications for occupant comfort, health, well-being, and productivity [3,4,5,6].

Due to the potential energy and Indoor Environmental Quality (IEQ) benefits of daylighting, the use of daylight to reduce energy consumption and enhance IEQ is one of the most common efforts undertaken for commercial office buildings promoted as “sustainable,” “energy efficient,” “green,” or “high performance.” These efforts have led to a range of facade design strategies and building technologies aimed at balancing daylight transmission for energy and IEQ with solar control and visual comfort. Examples of fixed and movable exterior facade shading devices documented by (Olgay and Olgay [7] provide numerous building case studies demonstrating effective control of solar radiation and view of the solar disc for visual comfort. More recently, the International Energy Agency Solar Heating and Cooling program (IEA-SHC) published a comprehensive reference that describes and assesses both conventional and innovative systems for utilizing daylight in buildings according to their energy savings potential, visual characteristics, and control of solar radiation [8]. Laboratory studies have demonstrated the benefits of integrated facades (automated interior and exterior facade shading devices paired with photocontrolled electrical lighting) for reducing lighting energy consumption over static shading systems while maintaining (or improving) visual comfort and control of solar loads [9]. To ensure visual comfort is maintained in the field, the Lawrence Berkeley National Laboratory developed commissioning procedures for automated roller shades using High Dynamic Range imaging (HDR) to verify that window luminances did not exceed a threshold deemed uncomfortable based on prior human factors studies [10]. Despite this body of knowledge, claims of effective daylighting are often based on the use of large areas of facade glazing (without exterior shading), or the specification of photocontrols for electrical lighting systems without consideration for occupant use of shading devices. Claims may also be supplemented with results from lighting simulations that demonstrate compliance with green building rating system criteria (e.g. U.S.G.B.C. LEED Daylight EQ credit), or that predict a specific level of electrical lighting energy reduction from photocontrols. However, buildings are rarely studied in use to determine if the daylighting design strategies implemented achieve the intent of creating a sufficiently daylit and visually comfortable work environment from the perspective of building occupants, or how occupant behavior affects the level of daylight availability and electrical lighting energy reduction anticipated during design.

If the daylighting design strategies implemented in innovative new buildings are to be considered successful prototypes for future buildings, it is important to validate them through Post Occupancy Evaluation (POE). POEs are needed to provide feedback for two primary purposes: 1) To compare performance in use to design intent in order to validate design assumptions and to diagnose "what's working" and "what's not" regarding the specific daylighting design strategies and technologies implemented, and 2) To improve the design guidance and assumptions for comfort and satisfaction used in the design of future projects. Due to the limited consensus for how IEQ parameters such as daylight sufficiency, visual discomfort, and view should be measured, assessed, and relatively valued in dynamic daylit environments, it is important for POE methods to incorporate techniques for acquiring subjective feedback from building occupants, as arguably the end user is the most important indicator of performance.

The objective of this study was to compare the daylighting performance of a prominent [11,12,13] sidelit open-plan office building in use to design intent to examine the effectiveness of the daylighting design. In this study, daylighting performance was considered in regard to a project's ability to achieve target levels of daylight illuminance and electrical lighting energy reduction while simultaneously maintaining a visually comfortable work environment and a satisfactory level of visual connection to the outdoors for occupants.

The specific aims of this study were to:

(1) Evaluate the outcomes of specific daylighting design strategies on daylight availability, electrical lighting energy reduction and visual comfort over a range of daily and seasonal variation in sun and sky conditions.

(2) Examine the impacts of modifications to the building facade by occupants and management to address visual discomfort on daylighting effectiveness and visual connection to the outdoors.

(3) Demonstrate a method for collecting repeated-measures of occupant subjective assessments paired with physical measurements using a novel desktop polling station device.

(4) Identify guidelines to inform and improve the daylighting design practices implemented in the building evaluated.

Selection of the building for POE was based on the following criteria:

- Combination of open-plan perimeter zone and open-plan "core" workstations
- Large areas of high visible light transmittance (VLT) glazing implemented as a strategy to enhance daylight transmission to workstations in core zone
- Photo-controlled electrical lighting system implemented as an energy strategy
- Explicit target set for electrical lighting energy reduction

- Facades designed with exterior shading to provide solar control of direct sun
- Qualified for LEED Daylight and View EQ credits
- Recognized and promoted as a model of sustainable design

2. Method

2.1 Overview of the building

The building evaluated is a 605,000 gross sq. ft. LEED Silver office building completed in 2007 and located in the Market District of San Francisco (**Fig. 1**). As an early example of the General Services Administration's Design Excellence Program, the project was designed to serve as a benchmark for sustainable building design through the efficient use of natural energy sources [14]. Consequently, a multi-disciplinary approach was taken by the project team to integrate natural ventilation and daylighting in the tower section of the project to minimize the need for mechanical cooling and lighting [15]. The building massing consists of a slender (384 ft. by 68 ft.), 18-story tower along the northwest edge of the site, with a 4-story annex building located perpendicular to the tower along the western edge. **Fig. 2** shows a plan view diagram of the building orientation and **Fig. 8** shows a generic floor plan.

Fig. 1. Exterior view of the building evaluated.

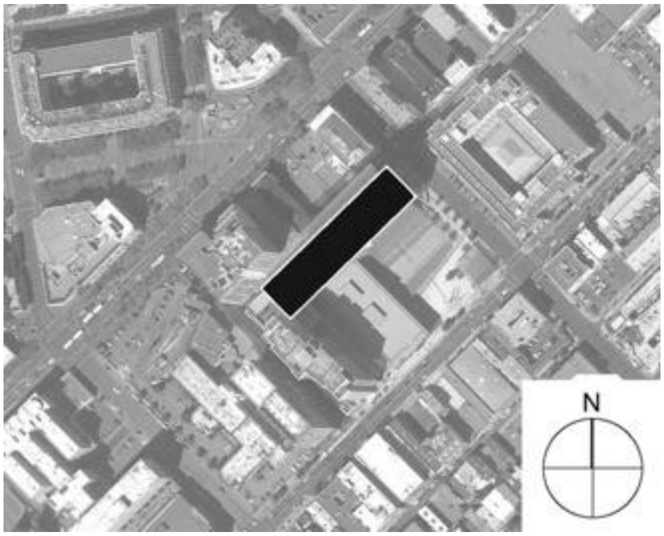

Fig. 2. Site plan diagram.

2.2 Electrical lighting system

The electrical lighting in the tower section consists of a combination of task and ambient lighting fixtures. The overhead ambient lighting consists of direct/indirect pendant luminaires with T-5 3500K 4-foot fluorescent lamps controlled by a lighting control system. During the study, overhead ambient lighting was turned on automatically in the morning at 6:00 AM and off in the evening at 7:00 PM DST each workday by the lighting control system. During daylight hours, each perimeter lighting zone was controlled by a single photosensor (closed loop control) that reduced luminaire output in response to available daylight. Core zones were not controlled by photosensors and were operated at full output throughout the day. Although wall-mounted dimming controls allowed occupants to switch off or adjust the lighting setpoint of a given lighting zone, the available wall controls were rarly operated by occupants. Based on predictions from energy simulations, the inclusion of photocontrols was anticipated to reduce electrical lighting energy consumption of the lighting zones in the tower by 25% [25].

2.3 Daylighting and solar control design strategies

Both the northwest (NW) and southeast (SE) facades are glazed from floor to ceiling with a spectrally selective glazing assembly that enables 67% Visible Light Transmission (0.67 VLT) while transmitting only 37% of solar heat gain (0.37 SHGC). Exterior shading devices were added to both glazed facades to control solar loads for occupant comfort and reduce internal cooling loads to a level sufficient to eliminate the need for mechanical cooling of the perimeter zones. On the SE facade (**Figs. 3** and **4**), perforated exterior metal panels were introduced to reduce direct beam solar radiation. The level of perforation results in an on-axis solar transmission of approximately 50%. On the NW facade (**Figs. 5** and **6**), vertical laminated glass and plastic fins oriented perpendicular to the facade were introduced to block direct-beam solar radiation during the afternoon hours when the sun would otherwise fall on the glazing simultaneous to the peak outdoor air temperatures [11]. Additionally, some panels in the vision zone are actuated mechanically with the intention of being controlled automatically by the Building Automation System (BAS). These panels are designed to tilt outward to reduce the level of obstruction for views to the outdoors.

The following is a summary of the strategies for daylighting and solar control:

1. Floor-to-ceiling high-VLT glass window wall system
2. Extended (13 ft.) floor-to-ceiling height window wall
3. Exterior facade solar control devices
4. Task / ambient split electrical lighting with ambient lighting dimmed by photocontrols
5. Shallow (68 ft.) floor plate depth
6. Interior layout of open-plan workspaces arrayed along the perimeter with low partition heights and cellular or open-plan workspaces in the core zones

Fig. 3. Interior view looking out through SE facade glazing, retrofit solar control film, and exterior perforated metal panels (with interior roller shades retracted).

Fig. 4. Interior view looking out through SE facade showing view enabled by horizontal tilt of panels at seated eye level with interior roller shades retracted.

Fig. 5. Exterior view of the NW facade showing fixed exterior translucent vertical fins [16].

Fig. 6. View from catwalk within NW facade showing exterior vertical translucent fin shading devices. The partially transparent optical properties of the fins can be seen towards the bottom right of the image.

2.4 Prior facade shading retrofits

Following occupancy of the building, the NW and SE facades were retrofit with manually operated interior roller shades to address issues related to discomfort glare and solar overheating. Interior roller shades (color = grey, openness = 0.05, VLT = 0.14) were installed on the lower vision zone windows of the NW facade, and for floor 8, shades were installed on both the vision windows and upper daylight zone windows. On all floors, interior roller shades (color = grey, openness = 0.03, VLT = 0.07) were installed on both the lower vision windows and upper daylight zone windows on the SE facade. In addition, the glazing on the SE facade was retrofit with a (VLT = 0.24, SHGC = 0.25) solar control film. Additional personal modifications were observed in several workstations to further address issues of discomfort glare and solar control. These personal modifications are discussed in **section 3.5.2.1**.

2.5 Locations of the study

The study was conducted on the upper floors (8, 11, 14-16) of the tower section. Therefore, results reported in this study should be considered representative of the regions of the building evaluated, and not extrapolated to the performance of the entire building. **Fig. 7** shows a generic cross-section for a typical tower floor. Because depth-from-facade and facade orientation (e.g. NW vs. SE), were considered confounding variables in this study, data was collected from participants in groups based on location on the floor plate: NW perimeter, SE perimeter, and core (**Fig. 8**). Workstations along the perimeter zones are oriented so that occupants face the facade at a 45-degree angle. As a result of the building's orientation 45-degrees from north, (**Fig. 2**), north-facing or west-facing views result for participants on the NW perimeter zone, and east-facing and south-facing views for participants on the SE perimeter zone. Workstations located in the core generally face perpendicular to one of the facades, resulting in NW-facing views or SE-facing views.

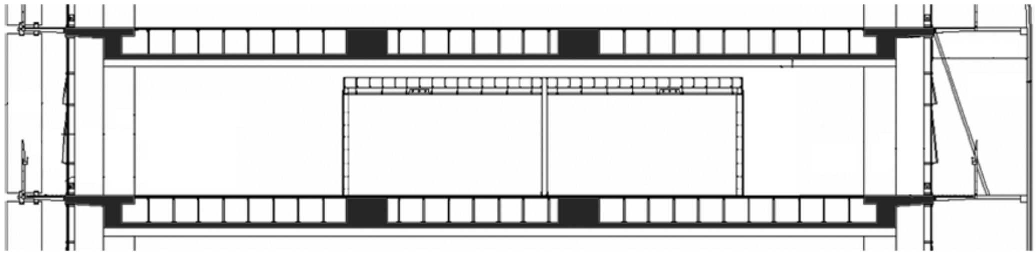

Fig. 7. Generic section through the tower section showing interior cabin workspaces [17].

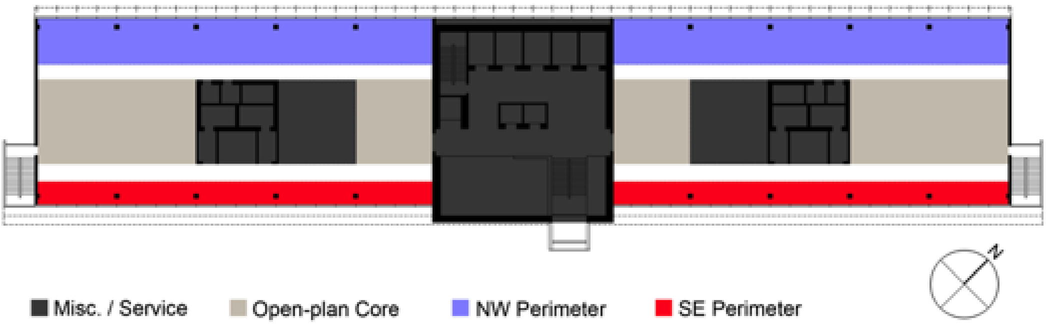

Fig. 8. Generic floor plan showing location of open-plan lighting zones studied.

2.6 Research design

A longitudinal, repeated-measures study design was chosen to sample subjective and physical measures across daily and seasonal changes in sun and sky conditions. During the study, no interventions were made to typical roller shade configurations or electrical lighting system control patterns. Daylighting performance was assessed by studying three fundamental and interrelated indicators: occupant shade control behavior, occupant satisfaction with IEQ factors of daylight sufficiency, visual comfort and view, and measured energy consumption of the overhead electrical lighting system. To examine these indicators, the study applied two primary methods. First, time-lapse imaging using a high dynamic range (HDR) image format was used to record occupant control of interior roller shades and measure interior luminances at each workstation. A detailed description of the HDR monitoring approach is documented in [18]. Second, a novel desktop polling station device was developed and implemented (**Figs. 9, 10**). The desktop polling survey method draws upon methods used in cross-sectional field studies that pair subjective response with physical measures but adapts them to a longitudinal, repeated-measures study design. Thirdly, overhead electrical lighting energy consumption was monitored at 15 minute intervals. Finally, on-site observations and an in-depth survey questionnaire were used. These methods are documented in detail in [18].

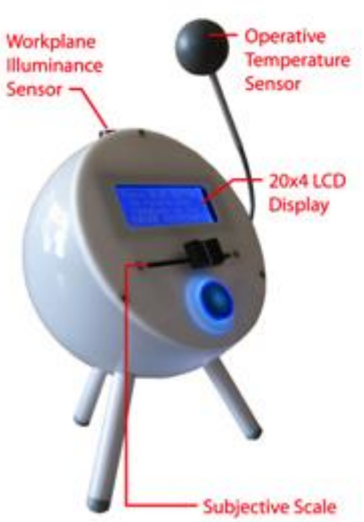

Fig. 9. Desktop polling station.

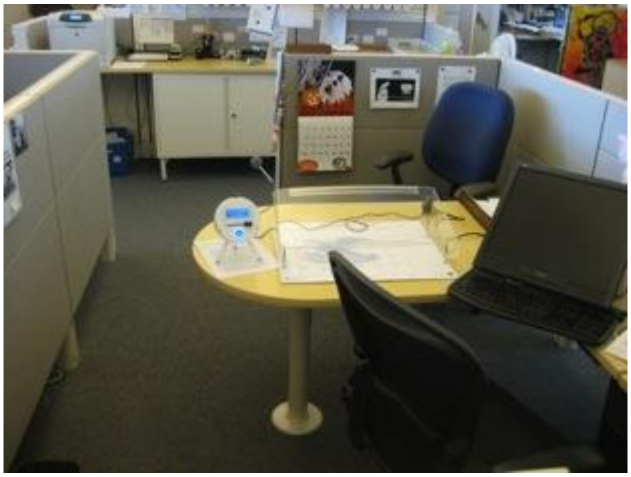

Fig. 10. Desktop polling station located on participant desk in open-plan core zone.

2.7 Participants

Subjective data were collected from 44 unique participants (38% male, 62% female) with an approximately equal number of participants recruited from each zone (NW perimeter: N=12, SE perimeter: N=18, core: N=14). Forty-three percent (43%) of participants were between the ages of 30-40, (36%) were between the ages of 40 and 50, and the remainder were above 50 (21%).

2.8 Monitoring schedule

The monitoring approach was designed around short-term (i.e. 2-3 week) monitoring phases for each group, strategically distributed across the year to allow inferences from short-term monitoring to inform an understanding of annual performance. As shown in **Table 1**, participants in each zone of the building (e.g. NW perimeter) were involved in two multi-week monitoring phases. During each phase, a polling station was located on each participant's desk and an HDR-enabled camera (Canon A570 with hemispherical fisheye lens) was affixed to the adjacent workstation partition.

Table 1. Schedule of monitoring phases. N indicates the number of participants.

						Sky Conditions (Days)		
Phase	Interval	Location	N	Wk.days	Solstice	Clr.	Dyn.	Ovr.
1	Jul. 12 - 29	NW Perimeter	11	14	summer solstice	9	2	3
2	Aug. 2 - Sep. 3	SE Perimeter	14	25	fall equinox	10	7	8
3	Oct. 4 - 15	Core	11	10	fall equinox	7	2	1
4	Oct. 18 - 29	NW Perimeter	13	10	fall equinox	6	2	2
5	Nov. 8 - 19	SE Perimeter	9	10	winter solstice	8	2	0
6	Dec. 6 - 17	Core	9	10	winter solstice	3	2	5

2.9 Procedure

Participants were instructed to use the polling station to input subjective feedback at any time throughout the day and were prompted with visual and audible cues if no response was recorded for more than two hours. Participants interact with the polling station by pressing the button to initiate a short (2-minute) IEQ survey and respond by recording their subjective response to a sequence of simple IEQ questions displayed on the device's LCD screen using the horizontal slide potentiometer. Subjective responses to questions of thermal comfort, thermal preference, daylight sufficiency, daylight preference, impact of shades on view, visual discomfort, and need for electrical lighting were paired with simultaneous measurements of global horizontal illuminance, globe temperature, and vertical luminance (acquired using HDR imaging). Daylight illuminance levels where calculated by subtracting the known contribution of the electrical lighting system from physical illuminance measurements. Analysis of frequency-of-use showed that, on average, participants responded approximately 4 times each day (**Fig. 11**) and that the responses were evenly distributed across each day (**Fig. 12**).

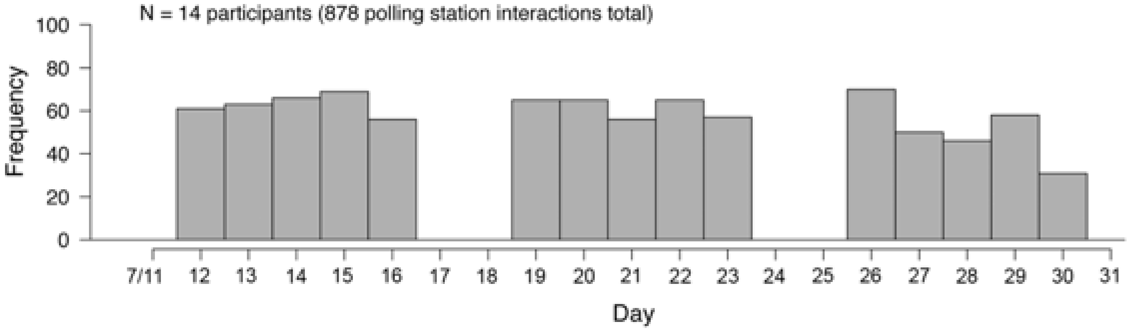

Fig.11. Frequency of polling station responses in aggregate during Phase 1 (by day).

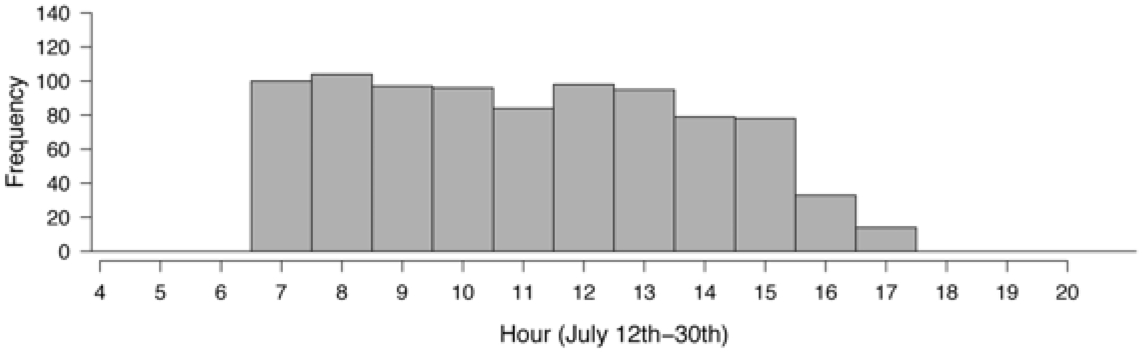

Fig. 12. Frequency of polling station responses in aggregate during Phase 1 (by hour).

3. Results and Discussion

This section presents and discusses key results from analysis of the indicators used to assess daylighting performance: occupant shade control behavior, measured daylight illuminance, electrical lighting energy, and occupant overall and "right now" subjective responses to IEQ factors of daylight sufficiency, visual discomfort and impact of shades on view. Results are compared to performance objectives and outcomes are discussed in regard to implications for the effectiveness of the daylighting strategies implemented.

3.1 Overall subjective assessments

Fig. 13 summarizes responses to the overall satisfaction survey which included questions regarding daylight availability, visual comfort, controllability of light sources, visual connection to outdoors, and satisfaction in general with personal workspace and the building recorded on a 7-point Likert satisfaction scale. For each question, the responses for the NW, SE, and Core zones are shown separately for comparison. In general, participants were satisfied with both their personal workspace and the building overall, with the lowest scores reported by the NW perimeter zone group for amount of daylight, visual comfort of daylight, and control of daylight.

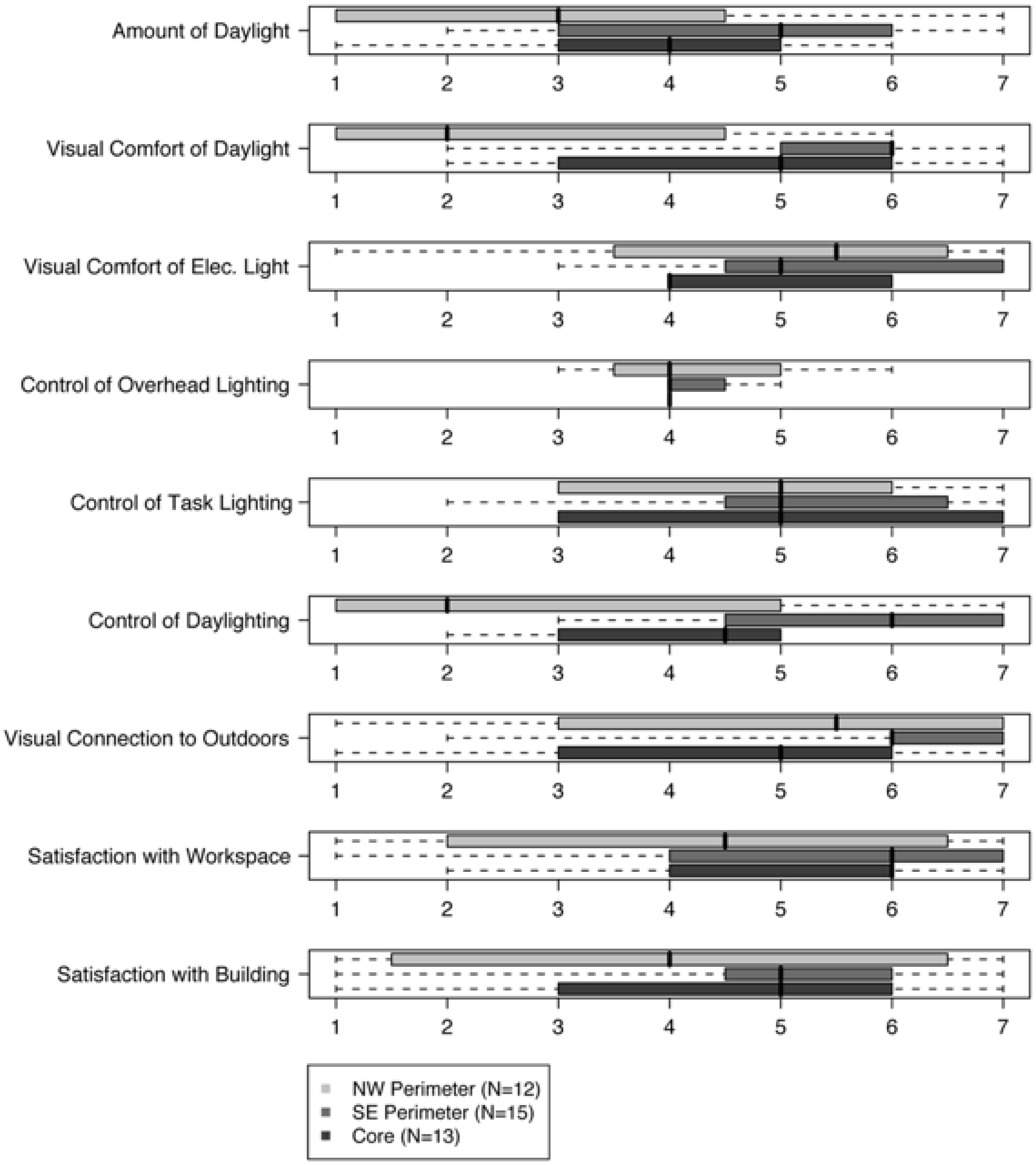

Fig. 13. Overall satisfaction ratings.

Fig.13 shows that participants were generally satisfied with their workspace and the building overall. However, responses for overall level of satisfaction with visual comfort showed that the majority of participants in the NW perimeter zone were dissatisfied. Comments from dissatisfeid study participants in the NW perimeter zones identified view of direct sun and glare from unshaded upper windows[1], neighboring building surfaces, the translucent exterior vertical fins themselves, and dynamic sky conditions as sources

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[1] On the NW facade where upper window shades were not installed (floors 15 and 16).

of visual discomfort. Participants in the SE perimeter identified sources of discomfort in terms of glare associated with a direct view of the sun and reflections of the solar disc off of the exterior perforated metal panels. Comments from participants located in the core zones generally agreed with comments from those in the perimeter zone who had the same visual orientation.

3.2 Occupant shade control behavior

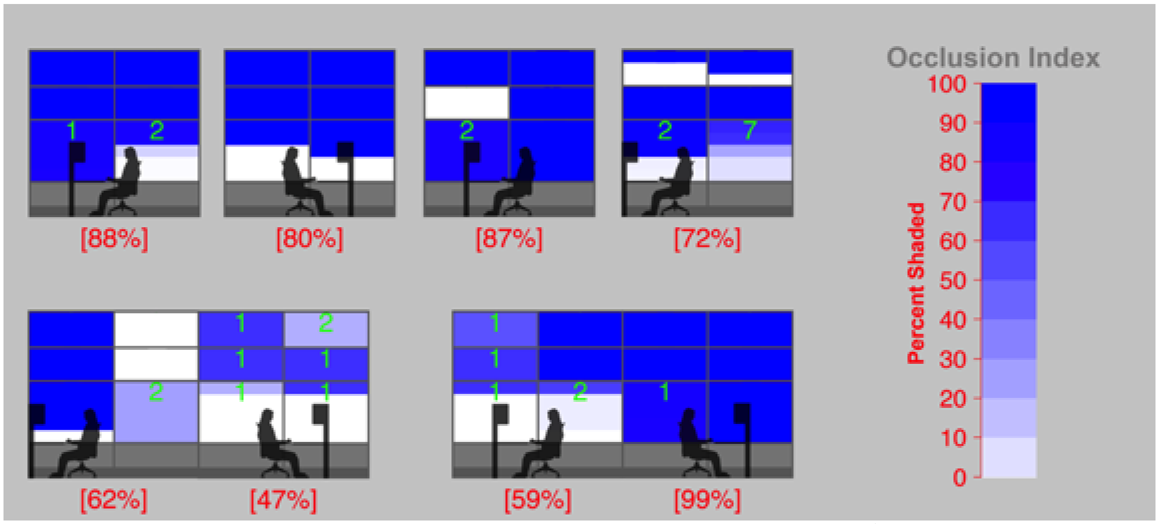

Fig. 14. Observed roller shade configurations on the NW facade (8th floor) during Phase 1 (N=8 facade sections). Numbers in green indicate the total number of adjustments made to a given roller shade during the monitoring phase. Grey indicates the lower row of windows occluded by office furniture. This row was not included in the assessment.

Table 2. Summary shade use data

				Percent Shaded			Number of Shade Operations			
Phase	Zone	Facade sections	Days	Upper win.	Lower win.	Facade	Upper win.	Lower win.	Total	Avg. per person per day
1*	NW	12	14	NA	73%	49%	NA	0	0	0.00
1	NW	8	14	80%	56%	74%	12	17	29	0.26
4*	NW	13	10	NA	66%	46%	NA	5	5	0.04
4	NW	5	10	50%	40%	56%	1	14	15	0.30
2	SE	26	25	63%	33%	58%	48	151	199	0.31
5	SE	14	10	45%	43%	55%	21	97	118	0.84

*Indicates facade sections where roller shades were not retrofit to the upper two row of windows

Facade sections were photographed using HDR images at 5-minute intervals from (6AM – 7PM PST) each workday and composited to visualize roller shade configurations over each monitoring phase. **Fig. 14** is a composite of interior elevations created from observation of time-lapse HDR imaging of the 8th-floor NW facade during Phase 1. The number shown in brackets below each facade section indicates the time-weighted and area-weighted average of glazed facade covered by roller shades (discounting the lower row of windows (in grey) which were generally occluded by office furniture and were not retrofit with roller shades). The roller shade configurations presented in **Fig. 14** are representative of the predominantly shaded conditions observed during each phase of the study. Because roller shades were not retrofit to the upper two rows of windows for floors 15 and 16 on the NW perimeter zone, these floors are summarized separately in **Table 2** and have lower levels of overall window shading. A total of 128 individual shades were observed on the NW facade and 240 individual shades on the SE facade. Analysis of facade showed that occupants located in the NW perimeter zones shaded between 66% and 73% (Phase 1 and 4 respectively) of the facade glazing where shades were installed and participants located in the SE perimeter zones shaded between 55% and 58% (Phase 2 and 5 respectively) on average. Because shades on both NW and SE facades were lowered adjacent to participant workspaces and rarely[2] adjusted, the effective VLT of the facade was significantly lower than the level enabled by the original design. For the NW facade, the effective VLT of shaded portions of the facade resulted in approximately 14% of the daylight transmission enabled by the high-VLT glazing (equating to approximately 9%[3] effective VLT). The effective VLT achieved by shaded portions of the SE facade combined with reductions from the retrofit solar control film was approximately 2% of the visible light enabled by the high-VLT glazing and exterior perforated metal screen. When considering the combined effect for all of the shading layers on the SE facade, the effective VLT equates to approximately 0.5%.

3.3 Measured daylight illuminance in perimeter and core workstations

Performance in regard to daylight availability was assessed using the Daylight Autonomy (DA) metric [19]. Daylight Autonomy was chosen because it is the consensus-based indicator proposed for the latest draft of the LEED Daylighting EQ credit [20]. The credit requires that 75% of all occupied spaces “achieve a minimum DA value of 50%, based on an annual illuminance of 30 foot-candles” (i.e. 323 lux). Daylight Autonomy was calculated for each polling station by totaling the time-series measurements of horizontal daylight illuminance above the DA threshold recorded between (6:00 – 19:00 PST) and dividing by the total number of observations recorded over the multi-week monitoring phase. The time interval (6:00 – 19:00 PST) was chosen because it corresponds to the schedule for the electrical ambient lighting. Because this interval includes some periods without daylight, a less strict interpretation was also included which calculates DA based on the interval (sunrise – sunset). Results are presented in **Table 3**.

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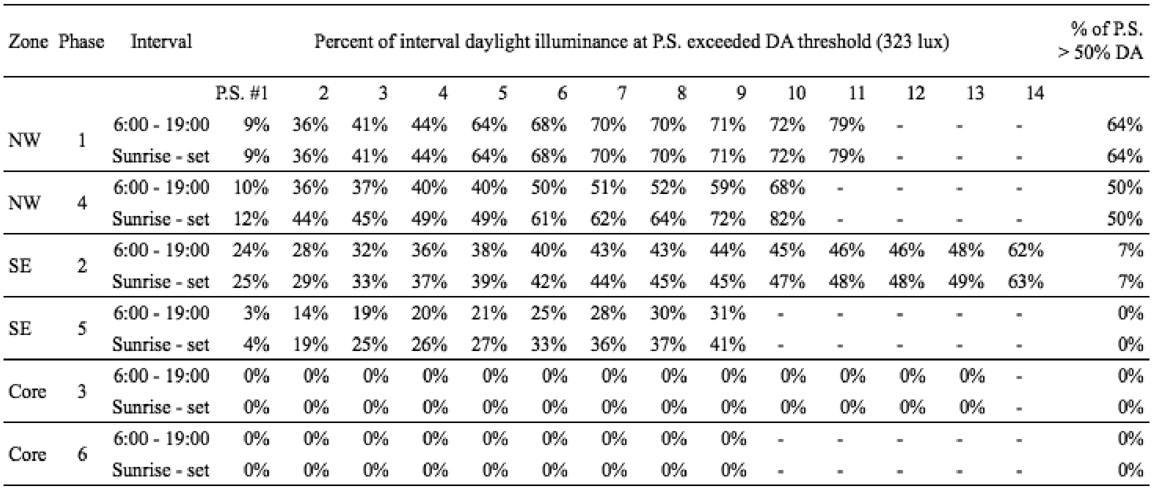
[2] Analysis of frequency of shade operation showed that many study participants made no adjustments to the shades adjacent to their workstation during the study, and those that did made, on average, one adjustment every 4 workdays.

[3] This assumption is based on multiplication of visible light transmission of the high VLT glazing (67%) by the diffuse light transmission of the shade fabric (14%).

Table 3 shows that no zone complied with the DA criteria using either interpretation of the DA interval. However, the NW perimeter zone comes relatively close during Phase 1, and several polling stations were very close to 50% DA during Phase 4. Similarly, many polling stations in the SE perimeter zone achieved DA of greater than 40% but less than the 50% required for compliance. The core zones did not meet the DA criteria and did not achieve daylight autonomy for any period of time during either phase.

Table 3. DA performance for the NW perimeter, SE perimeter, and Core zones.



Zone	Phase	Interval	Percent of interval daylight illuminance at P.S. exceeded DA threshold (323 lux)														% of P.S. > 50% DA
			P.S. #1	2	3	4	5	6	7	8	9	10	11	12	13	14	
NW	1	6:00 - 19:00	9%	36%	41%	44%	64%	68%	70%	70%	71%	72%	79%	-	-	-	64%
		Sunrise - set	9%	36%	41%	44%	64%	68%	70%	70%	71%	72%	79%	-	-	-	64%
NW	4	6:00 - 19:00	10%	36%	37%	40%	40%	50%	51%	52%	59%	68%	-	-	-	-	50%
		Sunrise - set	12%	44%	45%	49%	49%	61%	62%	64%	72%	82%	-	-	-	-	50%
SE	2	6:00 - 19:00	24%	28%	32%	36%	38%	40%	43%	43%	44%	45%	46%	46%	48%	62%	7%
		Sunrise - set	25%	29%	33%	37%	39%	42%	44%	45%	45%	47%	48%	48%	49%	63%	7%
SE	5	6:00 - 19:00	3%	14%	19%	20%	21%	25%	28%	30%	31%	-	-	-	-	-	0%
		Sunrise - set	4%	19%	25%	26%	27%	33%	36%	37%	41%	-	-	-	-	-	0%
Core	3	6:00 - 19:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-	0%
		Sunrise - set	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-	0%
Core	6	6:00 - 19:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	-	-	-	-	-	0%
		Sunrise - set	0%	0%	0%	0%	0%	0%	0%	0%	0%	-	-	-	-	-	0%

Figs. 15 -20 present the daily contribution of the overhead electrical lighting to the total illuminance measured at the polling stations on average over each multi-week monitoring phase for the NW, SE and core zones respectively. The daylight contribution and electrical light contribution to total workplane illuminance are shown as the median value among all polling stations at each time interval. The vertical grey bars are included to indicate the percentage of all polling stations where the daylight illuminance exceeds the DA threshold (323 lux) at each 15-minute interval throughout the day.

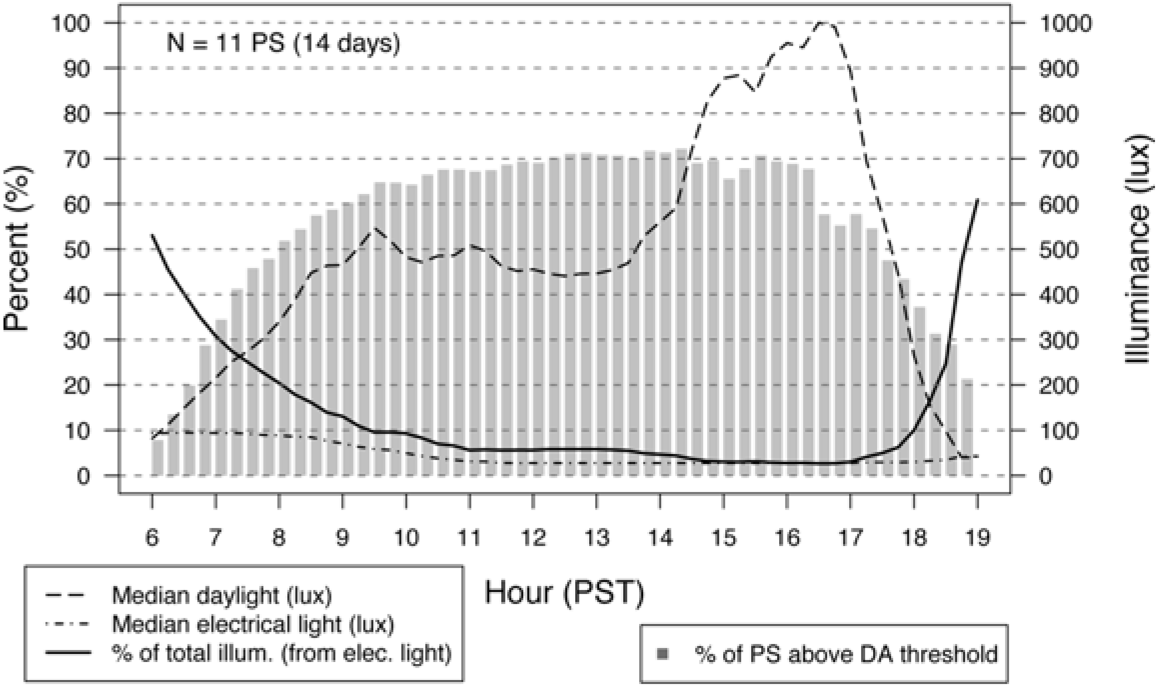


Fig. 15. NW perimeter zones: Daily contribution of the overhead electrical lighting to the total illuminance measured at the polling stations. Phase 1 (Jul. 12 – 29).

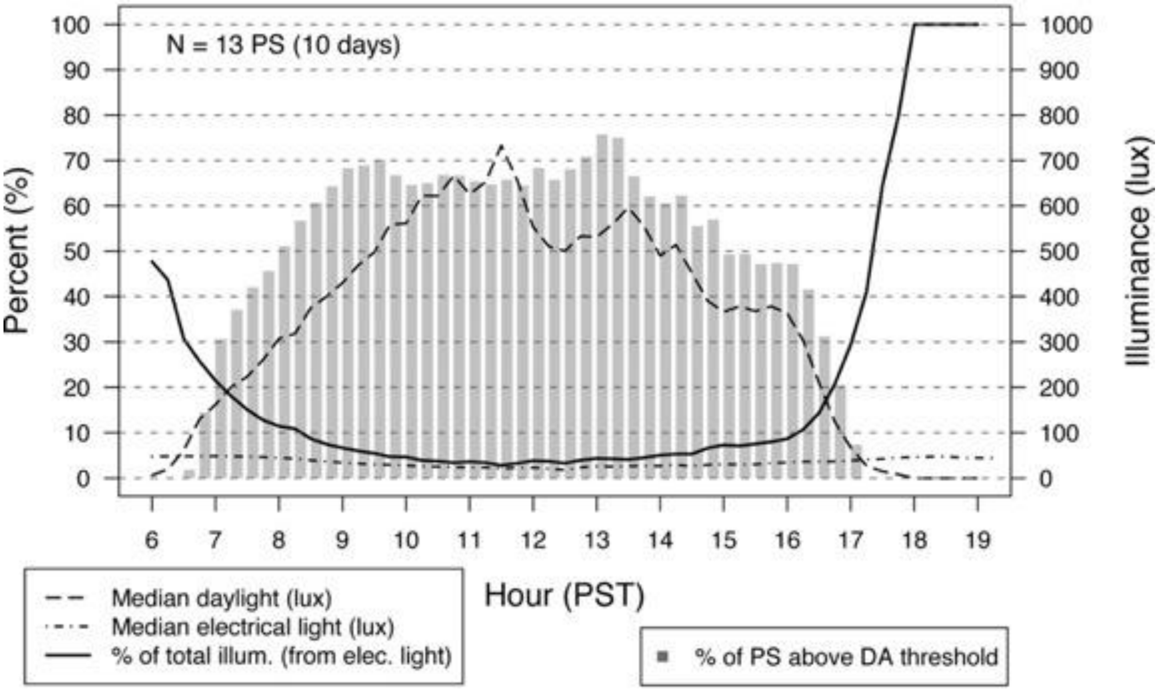


Fig. 16. NW perimeter zones: Daily contribution of the overhead electrical lighting to the total illuminance measured at the polling stations. Phase 4 (Oct. 18 – 29).

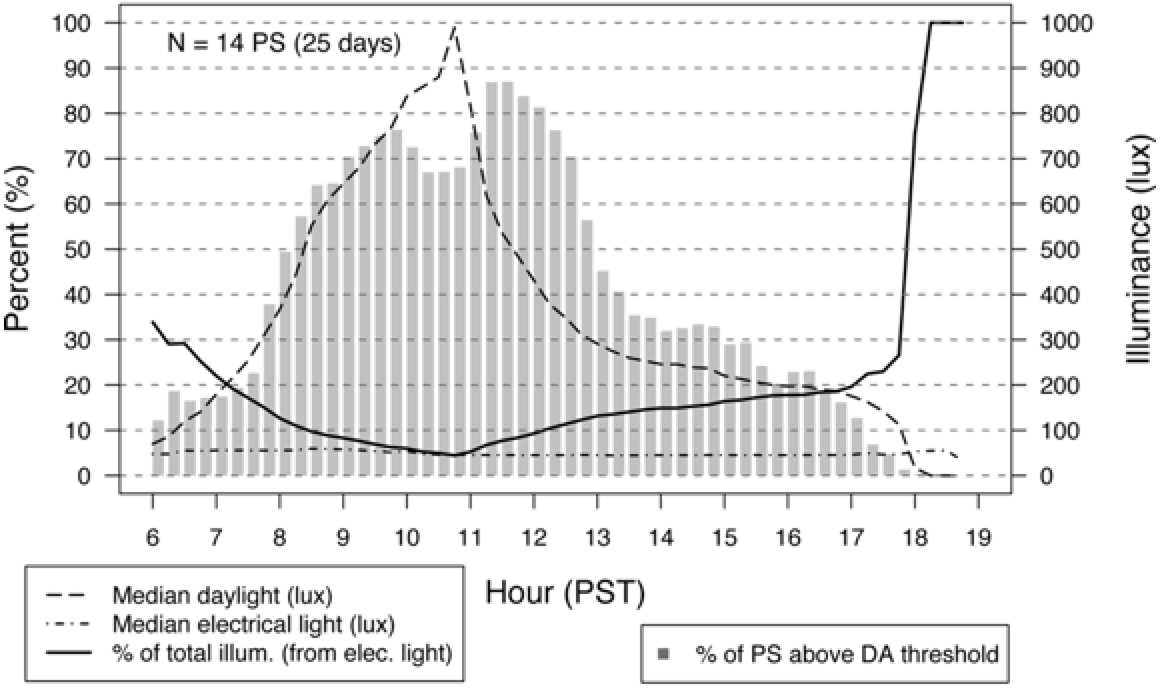


Fig. 17. SE perimeter zones: Daily contribution of the overhead electrical lighting to the total illuminance measured at the polling stations. Phase 2 (Aug. 2 – Sep. 3).

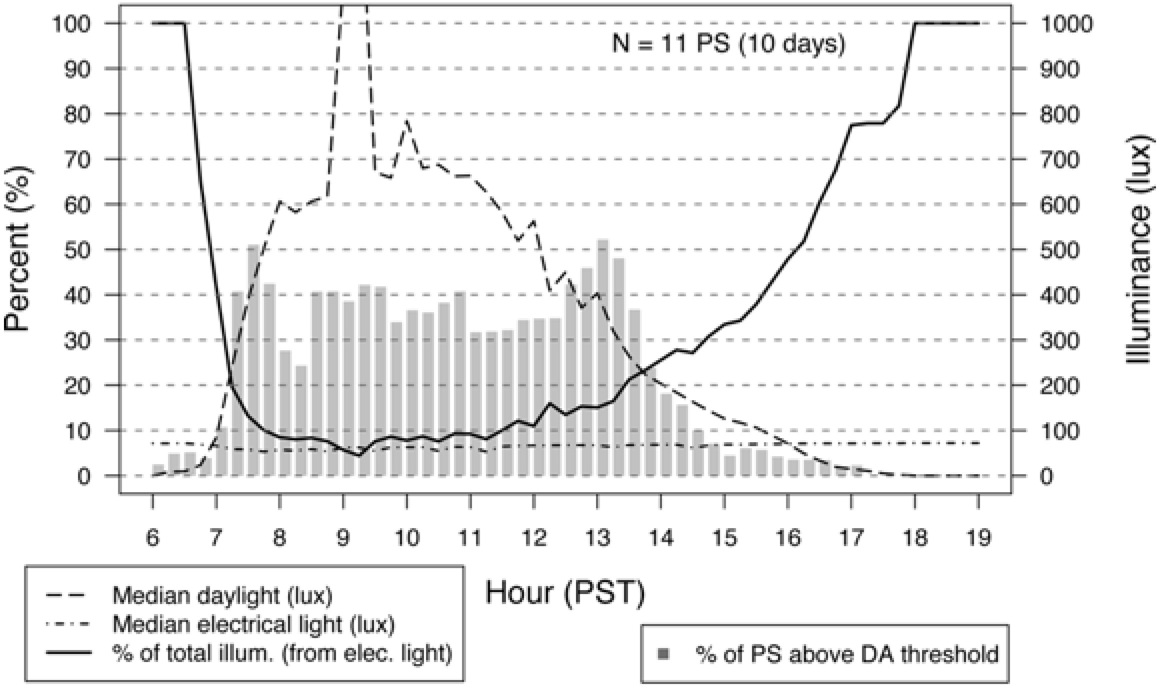


Fig. 18. SE perimeter zones: Daily contribution of the overhead electrical lighting to the total illuminance measured at the polling stations. Phase 5 (Nov. 8 – 19).

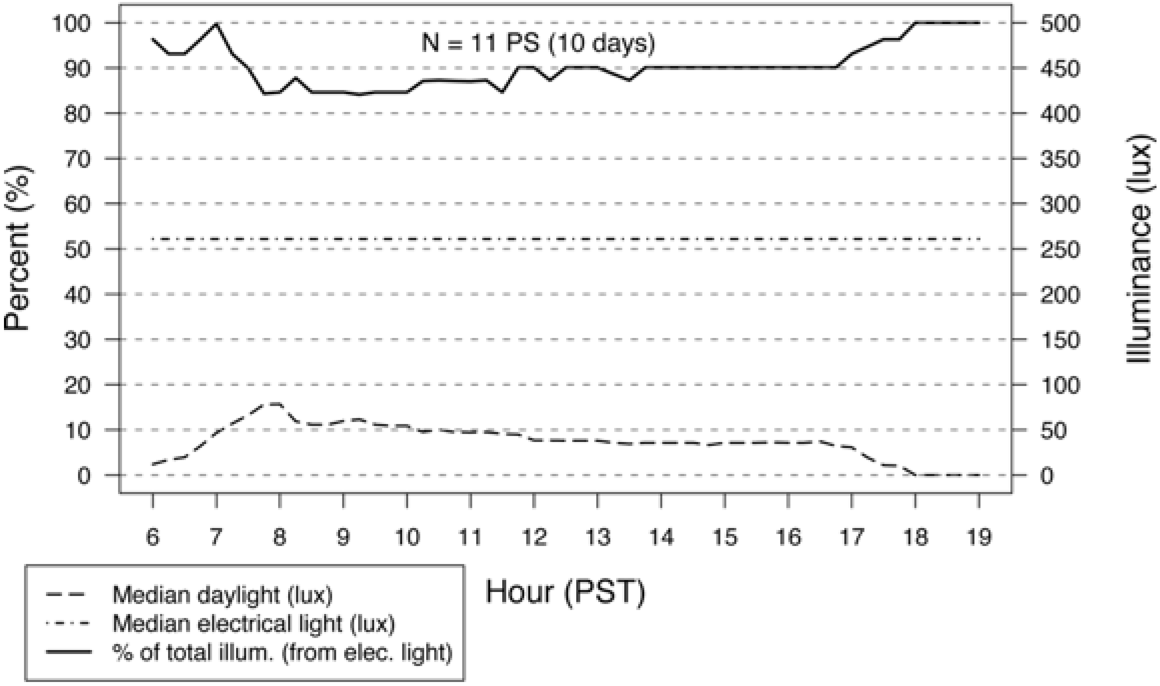


Fig. 19. Core zones: Daily contribution of the overhead electrical lighting to the total illuminance measured at the polling stations. Phase 3 (Oct. 4 – 15).

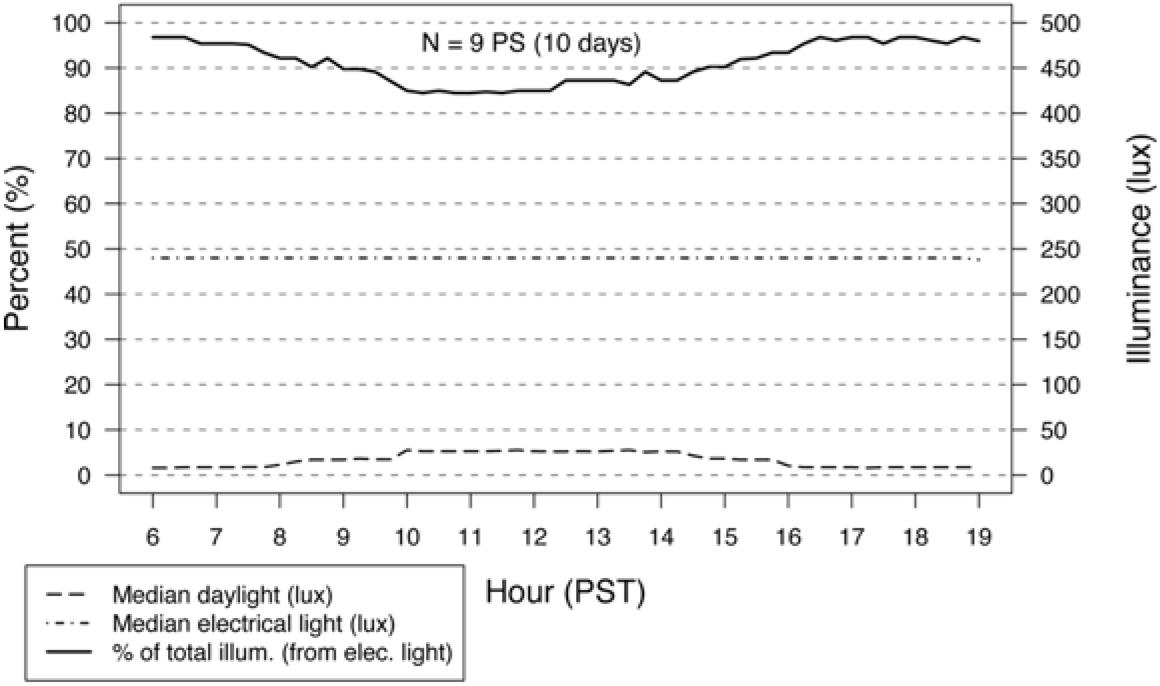


Fig. 20. Core zones: Daily contribution of the overhead electrical lighting to the total illuminance measured at the polling stations. Phase 6 (Dec. 6 – 17).

The decisions to design both the NW and SE facades as floor-to-ceiling high VLT glass window walls, extend the floor-to-ceiling height to 13 ft., limit the depth of the floor plate to 68 ft., and create open-plan workspaces with low partition heights were all influenced by the objective of achieving sufficient levels of daylight transmission and views for workspaces located in the core. Therefore, the physical and subjective data from the core zones are perhaps the most appropriate indicators of the success or failure of the overall daylighting concept. Subjective data are dealt with in **section 3.5**.

The level of daylight transmission in the core zones was often found to be insufficient based on the subjective responses from study participants as well as from analysis of physical measures. Daylight contributed to less than 15% of the total illuminance measured in the core zones during occupied hours and resulted in a median daylight illuminance of 44 lux (SD = 60 lux) and 17 lux (SD = 23 lux) respectively for Phase 3 and Phase 6. This result is significantly lower than the levels of daylight transmission anticipated by the 2% daylight factor prediction used for compliance with the LEED v. 2.1 EQ Daylight credit. For comparison, under a CIE overcast sky of 10,000 lux, a 2% daylight factor corresponds to an interior daylight illuminance of 500 lux. The median daylight illuminance achieved in the core zones during Phase 3 and Phase 6 corresponds to roughly 9% and 3% respectively of this target value.

3.4 Electrical lighting energy reduction from photocontrols

During the study, lighting power data recorded by the lighting control system for lighting zones on floors (8, 11, 14 - 16) were analyzed to examine the effectiveness of photocontrols in reducing electrical lighting energy consumption. **Table 4** shows the average lighting energy reduction from photocontrols for the NW and SE perimeter lighting zones during the phases of the study. As noted in **section 2.2**, core lighting zones were not controlled by photosensors and, although occupants could dim overhead lighting with wall-mounted dimmer switches, data showed that the core lighting zones were operated at full output throughout both monitoring phases.

Table 4. Electrical lighting energy reduction from photocontrols

		LPD (W/ft2)		% Reduction	
Zone	Phase	Max	Average	Phase	Combined
NW Perimeter	(1) Jul. 12 - 29	1.2	0.60	50%	51%
	(4) Oct. 18 - 29	1.2	0.57	53%	
SE Perimeter	(2) Aug. 2 - Sep. 3	1.3	1.08	17%	18%
	(5) Nov. 8 - 19	1.3	1.05	19%	
Core	(3) Oct. 4 - 15	2.0	2.00	0%	0%
	(6) Dec. 6 - 17	2.0	2.00	0%	

As shown in **Fig. 21**, whole-floor overhead electrical lighting energy reduction was less than the 25% reduction anticipated during design [21]. For a single floor, the maximum reduction achieved by photocontrols was (18.4%) and the average daily (6:00 AM – 7:00 PM DST) lighting power reduction was 12.6%.

Fig. 21. "Whole-floor" effective LPD for the overhead electrical lighting for one workweek (July 26 – 30, 2010) for the 16th floor. Average and minimum effective LPD are calculated from data acquired between 6:00 AM – 7:00 PM DST. The peaks at the end of each day indicate the energy consumed when the cleaners entered and switched on the lighting.

3.5 Occupant subjective assessments

3.5.1 Perception of daylight sufficiency

Table 5 summarizes responses to the 3-point polling station question (Q7): *"Could you work comfortably with the electric lights turned OFF right now?"* The question (Q7) is worded in a way that suggests a relationship between the state of the electrical lighting and occupant satisfaction with the ability to work comfortably. Although this wording is problematic as it could influence responses, the approach was developed in response to interviews with perspective study participants prior to the study who indicated the perception that the perimeter zones achieved sufficient daylight to not require supplemental ambient lighting for much of the day. The repeated measures question, (Q7), was thus introduced to quantify and model the physical conditions associated with this perception. As shown in **Table 5**, the majority of subjective responses recorded for the perimeter zone groups (65% to 75%) indicated that participants perceived sufficient levels of daylight to work comfortably with the electrical lighting turned off. In contrast, the majority of responses from the core zones indicated the perception of insufficient levels of daylight.

Table 5. Perception of daylight sufficiency

		Responses	Daylight perception (% of responses)		
Zone	Phase	(N)	Insufficient	Neutral	Sufficient
NW Perimeter	(1) Jul. 12 - 29	861	11%	14%	75%
	(4) Oct. 18 - 29	280	21%	12%	67%
SE Perimeter	(2) Aug. 2 - Sep. 3	1036	19%	6%	75%
	(5) Nov. 8 - 19	332	31%	4%	65%
Core	(3) Oct. 4 - 15	754	55%	22%	23%
	(6) Dec. 6 - 17	231	75%	14%	11%

To examine the physical lighting conditions associated with perceptions of daylight sufficiency, subjective responses were compared to concurrent measurements of workplane illuminance for all data in aggregate from the perimeter zones (**Fig. 22**). This method could be considered problematic in that it compares a subjective assessment of daylight sufficiency to a physical measure that includes both daylight and overhead electric lighting. However, nearly all daylit commercial open-plan offices include a mix of daylight and electrical lighting, and it was an objective of this study to not intervene in the typical operation of the building systems or conditions experienced by the occupants. In addition, as shown by Figs. 15 – 20, the contribution of the dimmed direct/indirect overhead luminaires was relatively low in the perimeter zones (from <1% to 20% of total illuminance) during daylight hours. Therefore, assessments indicating sufficient daylight can be attributed primarily to effective side-lighting. ,This approach was considered acceptable for analysis of subjective assessments recorded in the perimeter zones. Because the core zones were rarely considered to be sufficiently daylit, the potential contribution of electrical lighting to perceptions of daylight sufficiency is not a concern.

In **Fig. 22**, data are divided into illuminance "bins" in increments of 25 lux, where the responses to the polling station question (Q7) are shown as a percentage of the total number of (YES, NO) responses ("neutral" responses were omitted from the histogram). Vertical lines are drawn on each figure indicating common workplane illuminance thresholds of 300 and 500 lux. The percentages of "YES" and "NO" responses for each subset of illuminance levels (0-300, 300-500, >500 lux) are shown with light grey for "YES" responses and dark grey for "NO" responses. "N" indicates the number of unique study participants, followed by the total number of responses (in parenthesis). **Fig. 22** shows that the majority (67%) of responses recorded at workplane illuminance levels below 300 lux in the perimeter zone indicated the perception of sufficient daylight to work comfortably without supplemental electrical lighting and (86%) of responses at workplane illuminances of 300 – 500 lux.

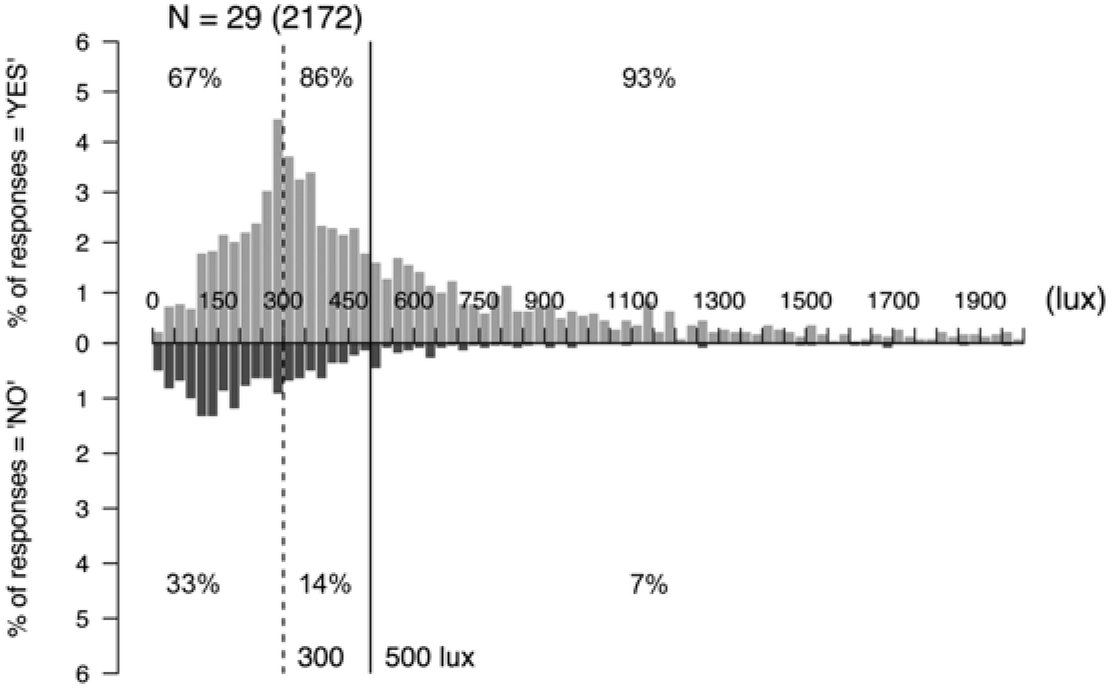


Fig. 22. Distribution of daylight sufficiency responses by horizontal illuminance for all (N=29) perimeter zone study participants in aggregate (Phases 1,2,4,5).

3.5.2 Visual comfort

To assess the frequency and subjective magnitude of visual discomfort for each monitoring phase, polling station subjective data were examined by phase and by zone. **Fig. 23** and **Fig. 24** show the responses of participants to the polling station question (Q6): “Please rate your level of visual discomfort from windows right now.” Results indicate significant periods of time where windows were a source of some level of visual discomfort. For the perimeter zones, the most severe conditions were recorded during the monitoring phase where each zone received greater exposure to low-angle sun. For example, during Phase 1 (July 12-29, for the NW) and during Phase 5 (November 8 – 19 for the SE), 70% and 60% of all responses indicated discomfort from windows and 18% and 20% of all responses rated the level of discomfort from windows as “very uncomfortable.” This outcome is particularly notable given the significant level of attenuation in VLT resulting from the exterior perforated metal panels, solar control film, and roller shades.

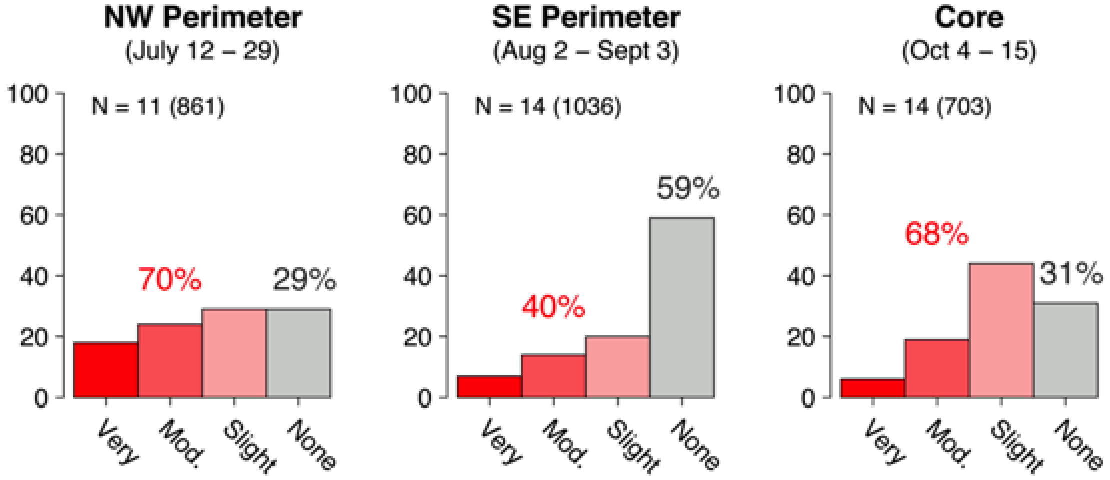


Fig. 23. Summary of occupant subjective responses to (Q6) for Phases 1, 2, 3. “N” indicates the number of participants, followed (in parenthesis) by the total number of responses recorded for the group.

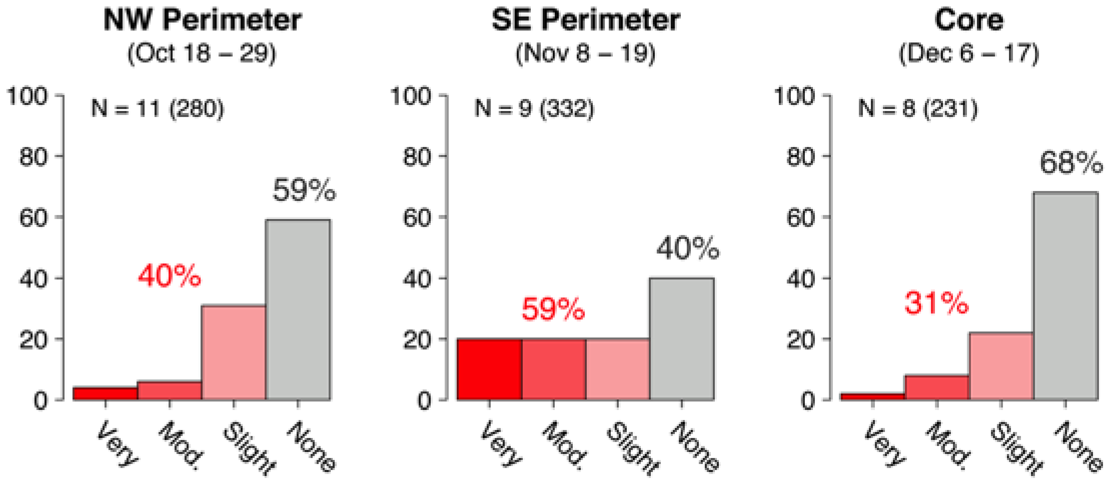


Fig. 24. Summary of occupant subjective responses to (Q6) for Phases 4, 5, 6.

3.5.2.1 Exterior solar control devices and visual comfort

The roller shade positioning and visual discomfort conditions observed in the building are strong indicators that the exterior solar control devices on the NW and SE facades do not provide an acceptable level of glare control for occupants. On the NW facade, a central issue with the vertical glass fins is that they do not continuously block direct sun penetration during occupied hours. An additional, and perhaps more significant issue is that the translucent fins themselves become a source of visual discomfort when they intercept direct sun. As shown in **Fig. 25**, an unshaded view of the exterior fin was observed to produce luminance levels in excess of 22,500 cd/m^2, approximately twice the luminance of a bare, 34 Watt T-12 fluorescent light bulb (~10,000 cd/m^2). In addition, when the NW facade received direct sun, the surface of the fins was observed to reflect the image of the solar disc to the field of view of occupants who were facing away from the sun and would not otherwise have been affected.

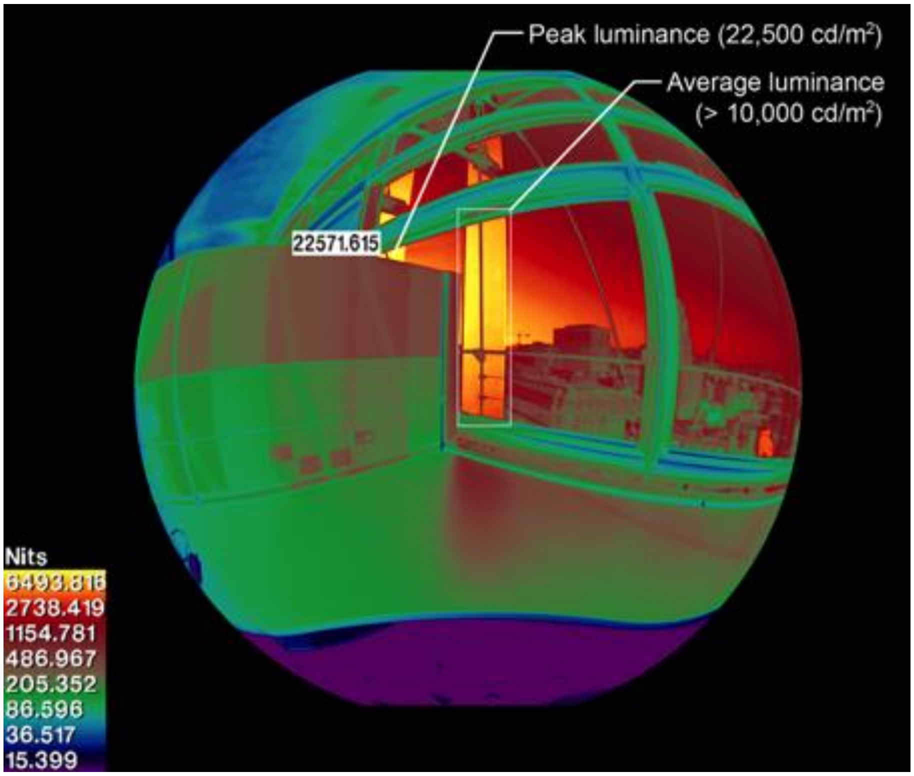


Fig. 25. HDR image of exterior glass fin showing peak luminances in excess of 22,500 cd/m^2 and average fin luminance in excess of 10,000 cd/m^2.

The central architectural feature of the SE facade is an exterior layer of perforated metal panels. The retrofits made to the SE facade, the observed position of roller shades, and the subjective assessments of occupants present a number of implications for this “filtering” approach to balancing daylight transmission and view with solar and glare control. As shown in **Fig. 26**, the combined effect of the shading layers (e.g. exterior perforated metal panels, high performance glazing, solar control film, and shade fabric) remains inadequate for controlling the luminance of the solar disc.

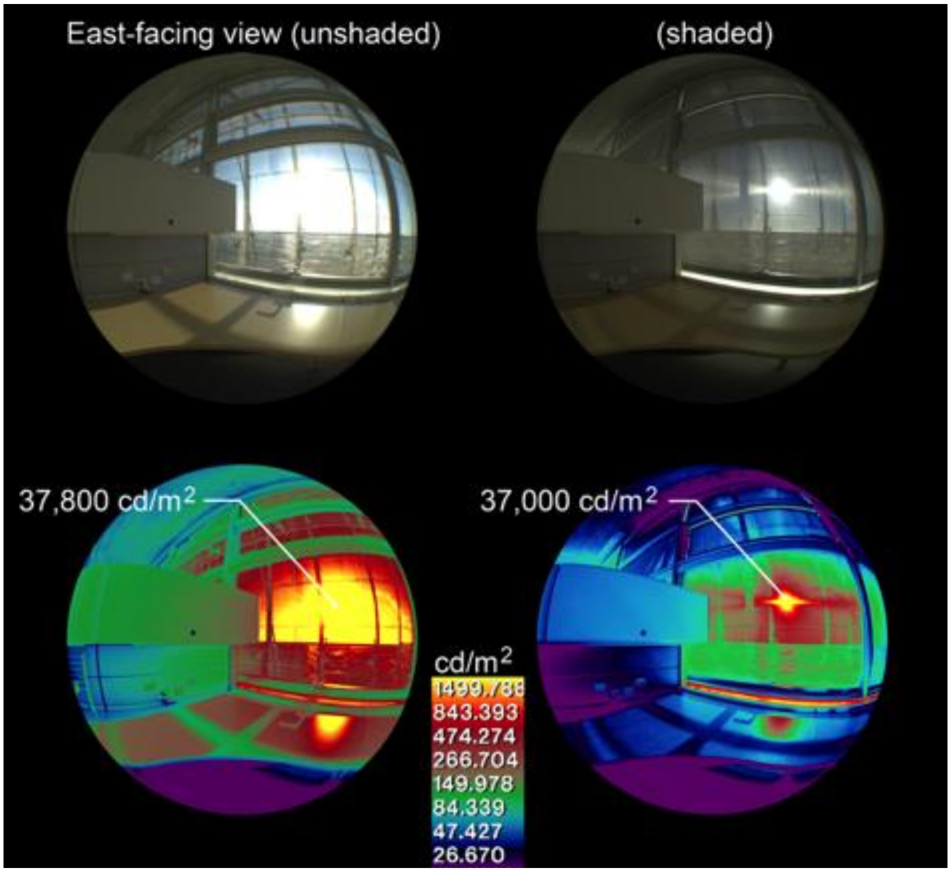


Fig. 26. Generic viewpoint for east-facing workstation orientation showing unshaded (left) and shaded (right) luminance conditions recorded using HDR imaging[4]. Image on left acquired at 9:10AM ST on 11/12/2010. Image on right acquired at 9:10 AM ST on 11/17/2011. Luminance values are represented with a falsecolor log-scale where yellow indicated values above 2000 cd/m^2.

Despite the significant reduction in daylight transmission resulting from the layers of shading, a high proportion of subjective responses recorded in the SE perimeter zones indicated visual discomfort from windows and a preference for less daylight. The occurrence of discomfort responses when the facade was in a predominantly shaded state conflicts with the assumption that the provision of fabric shading devices, (that have a level of openness to preserve a partial view), will enable sufficient control over the solar disc. Consequently, a number of informal workspace modifications were made to “supplement” the level of solar control available from the facade shading layers and were principally implemented to completely block direct view of the solar disc. An example is shown in **Fig. 27**.

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[4] It is important to note that HDR imaging is not suitable for accurate measurements of the luminance of the sun, as the CCD sensor will “saturate” above a threshold determined by the exposure bracketing established for compositing HDR images from low dynamic range (JPEG) images.

Fig. 27. Example of personal workspace modification on the SE facade to block direct view of the solar disc.

3.5.3 Subjective assessment of visual connection to outdoors

The intent of the LEED View EQ credit, stated in [22], is to: “provide for the building occupants a connection between indoor spaces and the outdoors through the introduction of daylight and views into the regularly occupied areas of the building.” Further, the requirements state that the design should: “achieve a direct line of sight to the outdoors via vision glazing for 80% of all regularly occupied spaces.” To examine the impact of solar control film and roller shade retrofits on occupant satisfaction with visual connection to the outdoors, view was assessed by two measures: 1) Overall level of satisfaction with visual connection to the outdoors, and 2) Repeated-measures assessments of satisfaction with impact of roller shades on visual connection to outdoors. **Fig. 13** shows that, overall, occupants were generally satisfied with their level of visual connection to the outdoors, despite the significant fraction of the facade covered by roller shades, with slightly greater levels of satisfaction recorded in the perimeter zones compared with the core. Sources of dissatisfaction, reported on a branching question from the survey, were primarily associated with visual discomfort (e.g. high luminance contrasts) rather than obstructions to view or distance-from-facade.

Fig. 28 compares the results to the polling station question (Q5): “How satisfied are you with the impact of shades on your view to the outdoors right now?” to the percentage of vision window adjacent to perimeter zone study participants covered by roller shades. As shown in **Fig. 28**, greater levels of vision window shading (> 50% shaded) were associated with dissatisfaction, where the majority of satisfied responses to (Q5) where found for levels of vision window shading ranging from 0% shaded to approximately 30% shaded. The majority of dissatisfied responses were recorded when the vision windows were observed to be fully shaded (median of dissatisfied responses = 100% shaded), with the remaining responses recorded at levels exceeding approximately 60% shaded. This result supports observations (e.g. **Fig. 14**) showing that occupants often positioned the vision window shades in a partially lowered position to preserve an unobstructed view.

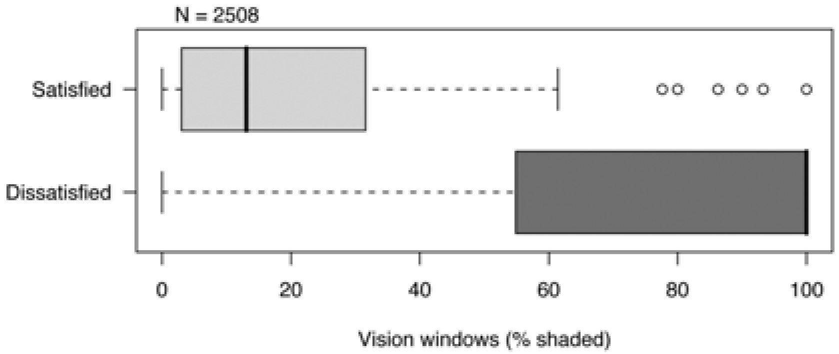

Fig. 28**.** Distribution of satisfied and dissatisfied responses to (Q5) by lower window occlusion level. (100% = completely shaded).

4. Conclusions

In the case of the building evaluated, efforts were made to maximize the physical level of daylight transmission to the interior via a narrow (68 ft.) floor plate, high VLT facade glazing, and by extending the floor-to-floor height (13 ft.), while controlling solar loads with perforated metal panels as exterior shading devices. Analysis of physical measurements, occupant behavior, and subjective assessments collected form study participants reveal the following summary conclusions:

First, both the NW and SE exterior solar control devices were ineffective in providing sufficient glare control for occupants, leading to significant areas of high VLT facade glazing that were covered by interior roller shades throughout daily and seasonal changes in sun and sky conditions (66% to 74% where shades were installed on the NW facade and 55% to 58% for the SE). The high levels of roller shade use and solar control film added to the SE facade diminish the design intent of the high VLT facade to maximize available daylight. Moreover, the effective VLT of shaded portions of the facades (9% for the NW, 0.5% for the SE) raises questions for the applicability of simple estimates of daylight availability based solely on window-to-wall ratio (WWR) and glazing VLT, particularly for perimeter zones where occupants must routinely operate shading devices for solar and glare control. For such cases, such estimates are likely to overestimate the daylight availability of projects in use.

Second, HDR images taken from workspaces along the SE facade showed that interior roller shades (3% openness) combined with (0.24 VLT) solar control film and 50%

perforated exterior metal panels remained insufficient to control discomfort glare at perimeter workspaces caused by direct view of the solar disc (disc luminance exceeded 37,000 cd/m^2 when viewed though all available shading layers). Therefore, for facades that receive significant hours of direct sun, operable shading devices should be provided that enable occupants to completely block direct view of the solar disc.

Third, because a large portion the upper daylight zone windows adjacent to occupied workspaces were covered by roller shades, the contribution of the extended floor-to-floor height to increasing daylight penetration to the core workspaces was substantially diminished. This result raises questions for the applicability of a common daylighting assumption that increasing the window head height will increase the depth of useful daylight penetration. This assumption typically predicts a daylight zone that extends into the building a distance from 1.5 to 2.5 times the window head height [23, 24, 25, 26]. However, observations of shading configurations show that occupant behavior is a far more significant determinant of the daylighting zone, and highlight the need for validated shade control models describing the environmental and contextual conditions associated with occupant shade use in order to better-predict daylight availability.

Fourth, despite the significant reduction in facade VLT, daylight availability in the perimeter zones was considered sufficient by occupants for the majority of daylit hours during the study and was sufficient for photocontrolled perimeter electrical lighting to generally meet or exceed the anticipated lighting energy reduction target of 25%. Further, occupants working in the perimeter zones (where electrical lighting output was dimmed) frequently perceived daylight to be sufficient when measured workplane illuminances were below common thresholds for daylight autonomy (67% of responses at horizontal illuminances < 300 lux, 86% at 300 – 500 lux). Therefore, additional electrical lighting energy savings could be achieved by implementing lighting controls capable of switching off (rather than dimming) ambient lighting in zones where daylight illuminance levels routinely exceed either of these thresholds.

Fifth, the daylight levels achieved in the perimeter zones were often achieved at the expense of occupant visual comfort in both core and perimeter zones, with the greatest frequency of visual discomfort responses recorded in the SE perimeter zone. The high frequency of visual discomfort responses and the history of facade retrofits presents strong evidence for the importance of incorporating glare analysis into the design process to achieve effective daylighting in use.

Sixth, despite the frequent subjective responses of visual discomfort from widows, occupants in the perimeter zones generally left a portion of the vision window unshaded to maintain visual connection to the outdoors. And, although multiple shading layers often partially screened direct views to the outdoors, study participants in both core and perimeter zones were generally satisfied with their visual connection to the outdoors.

Finally, the combined layering of glare and solar control devices led to daylight illuminance levels in the open-plan core zones that were substantially below commonly used thresholds for daylight autonomy and were rarely considered sufficient by occupants to work without overhead electrical lighting. And, because lighting in the core zones was not automatically dimmed or switched off in response to daylight (and never adjusted by occupants), no reduction in electrical lighting energy was achieved. Therefore, the potential daylighting benefits of the narrow (68 ft.) floor plate depth and low workstation partition heights were not fully realized in the open-plan core zones evaluated.

5. Recommendations

The following are recommendations for improving the daylighting performance of future projects that seek to emulate the building evaluated in this study:

- Provide exterior shading devices that completely block direct view of the solar disc from both core and perimeter zone workspaces. Perforated or screen-like exterior shading devices should have sufficient depth (or overlap) in section to achieve a solar cut-off angle sufficient to completely block direct-beam radiation to the interior for the majority of occupied hours while preserving partial view.

- Ensure that visual conditions regularly experienced by occupants comply with consensus-based guidance for visual comfort, e.g. [27]. For designs where visual conditions are anticipated to deviate from guidelines, conduct human-factors evaluations with project stakeholders in a daylighting mockup to verify that design conditions are acceptable.

- Consider the optical properties of exterior shading devices and avoid highly reflective, transmissive, or specular materials for surfaces that will be in view from occupant workspaces.

- Where the facade is subdivided into a lower vision zone and upper daylight zone, use a static or dynamic daylight redirecting device for the upper zone such as a horizontal louver system with a specular top surface to intercept and redirect daylight to the ceiling and a dark bottom surface to reduce the luminance of the upper window.

- Consider highly reflective, diffuse interior surface finishes to optimize daylight redirection to interior workspaces and reduce the luminance contrast of window views.

- Provide workstations that enable occupants to easily adjust their primary task view in response to daily and seasonal changes in sun position and sky conditions. Provide access to interior shading devices that are easy to control and capable of completely blocking view of the solar disc.

- For task-ambient split electrical lighting, provide granular control of the overhead electrical lighting such that occupants have the ability to independently control ambient lighting at their workspace and ensure that the position and light output of task lighting can be easily adjusted. Where photocontrols are used, avoid control of large lighting zones by a single photosensor or wall controls.

- For automated lighting controls, consider installing ballasts capable of completely switching off (rather than dimming) ambient electrical lighting in perimeter lighting zones where the daylight contribution routinely exceeds 300 lux.

- Incorporate shade control behavioral models and indicators of discomfort glare into simulations of annual daylighting performance early in design to develop a broad assessment of the range of potential energy and comfort outcomes.

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