Impact of Fixed Exterior Shading on Daylighting: A Case Study of the David Brower Center

By

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1. INTRODUCTION

Commercial buildings in the U.S. consumed 18% of primary energy and 36% of the nation's electricity in 2006 (U.S. Department of Energy, 2011). According to the 2003 Commercial Buildings Energy Consumption Survey (CBECS), heating, cooling and lighting account for 36%, 8% and 21%, respectively, of the total energy consumed in the commercial building sector (Energy Information Administration [EIA], 2008). In response to increasing concerns over global warming, a number of initiatives to reduce energy used by U.S. buildings have taken form over the course of the past decade, including the development of voluntary rating systems such as the Leadership in Energy and Environmental Design (LEED) rating system of the U.S. Green Building Council (USGBC) and the Energy Star rating system of the U.S. Environmental Protection Agency. Yet despite significant efforts on behalf of a range of public and government organizations progress has been slow (Scofield, 2009).

One of the essential components in low-energy buildings is the building envelope. Window systems are critical to occupant comfort and well-being, but frequently bring a high level of complexity to the design process due to the inherent difficulty of striking a balance between occupant comfort needs, building energy use, project budget and a range of other considerations. While windows provide a way to introduce daylight and views, fenestration design must be carefully assessed in terms of daylighting, visual comfort, heat gain and heat loss. A number of studies suggest that without proper solar and lighting control, occupants are likely to draw shades or blinds when visual or thermal comfort thresholds are exceeded (**Figure 1**) and that blinds are likely to remain closed for extended periods of time, negating the potential benefits of having the window in the first place (Galasiu & Veitch, 2006;

Inkarojrit, 2008). Automated controls provide a way to control facade systems, as is the case with automated shading, however they provide their own set of challenges – added operational complexity and cost, and the need for maintaining additional controls and components (Heschong Mahone Group [HMG], 2008; Zelenay, Perepelitza & Lehrer, 2011). In contrast, fixed window elements, such as fixed exterior shading, may offer less opportunity for selective control of daylighting and solar heat gain, however the risk of faulty system operation, experienced with automated systems that are improperly commissioned or maintained, is eliminated.

While exterior shading systems offer significant benefit in terms of solar control and occupant thermal comfort and are quite common in Europe, they are not typically implemented on U.S. buildings (Perepelitza 2010 Zelenay et al., 2011). The prevalence of exterior shading systems in Europe can be explained by higher energy prices, stricter

Figure 1 Highly-glazed office building in San Jose. View of west elevation, December 2009.
Photo credit: Charles C. Benton

building codes, and higher expectations regarding the quality of the working environment and construction (Yudelson, 2009). Owner and design team concerns about operation and maintenance of and high cost of systems are the main factors impeding the widespread adoption of these systems in the U.S. (Lee, Selkowitz, Bazjanac, Inkarojrit, & Kohler, 2002; Lee & Selkowitz, 2005; HMG, 2008; Zelenay et al., 2011).

In light of the fact that exterior shading is uncommon in the U.S., the question of why fixed exterior louvers were implemented at the David Brower Center, a four-story mixed-use building in Berkeley, California, is a compelling one (**Figure 2**). The building, situated in a dense urban neighborhood in downtown Berkeley (**Figure 3**), was designed by the San Francisco-based firm Daniel Solomon Design Partners (formerly Solomon E.T.C.) in collaboration with Tipping Mar + Associates (structural engineer), Integral Group (mechanical engineer formerly Rumsey Engineers), and Loisos + Ubbelohde (daylighting and facade consultant).

Figure 2 South elevation of the David Brower Center

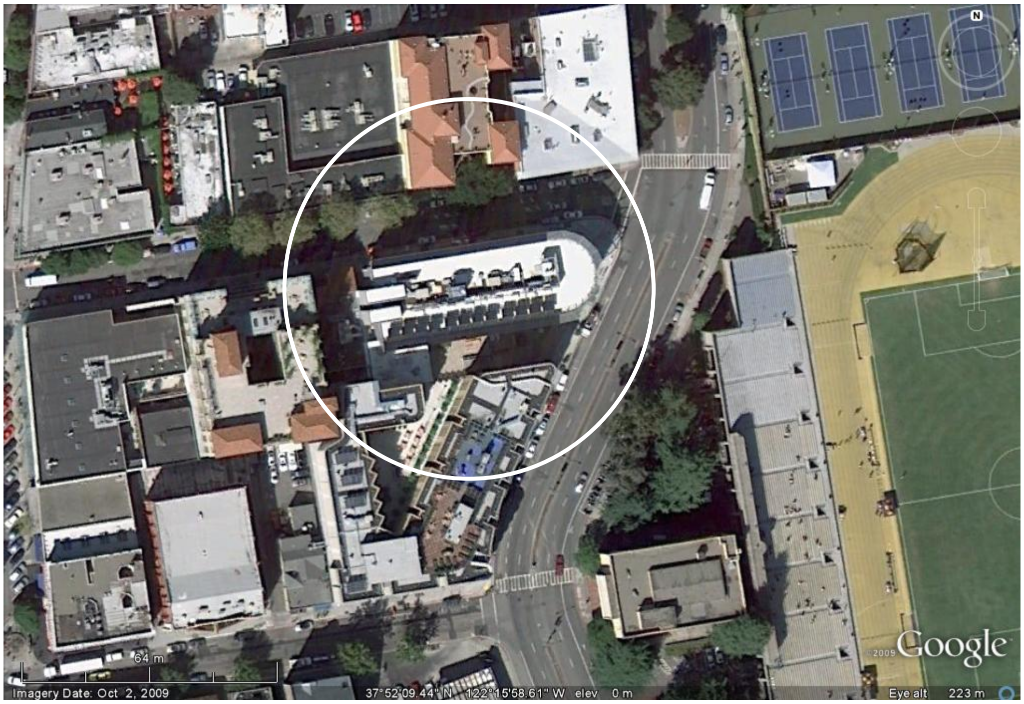

Figure 3 Site plan

Source: Google Maps

Figure 4 Northeast elevation of the David Brower Center

1.1. DAVID BROWER CENTER

As the first LEED Platinum-certified buildings in Berkeley and one of 40 LEED Platinum buildings in the San Francisco Bay Area, the David Brower Center incorporates a range of sustainable design strategies ranging from siting within close proximity to public transportation, use of sustainable materials, to an array of energy- and water-conservation measures (Meinhold, 2011). Named after David Brower, a prominent environmentalist and founder of the Earth Island Institute, the Center is home to a number of nonprofit organizations, among them the Earth Island Institute. In effect, the David Brower Center is more than just a building – it is an agglomeration of organizations and individuals who foster environmental and social change through community education (David Brower Center website, 2011). To this end, a portion of the program is dedicated to community educational events – an auditorium and conference center for community events, and a restaurant at ground level that serves sustainably grown food that is bound to satisfy the palette of even the most demanding food connoisseur. This landmark building is also home to the project's developer, Equity Community Builders.

In order to maximize building energy efficiency, the design team incorporated a range of passive design strategies, including proper building massing and solar orientation, a moderate window-to-wall ratio, thermal mass, natural ventilation, high-performance glazing, and fixed exterior shading (**Figure 7 - Figure 10**).[1] By implementing a number of passive building design strategies and carefully controlling internal loads, the design team was able to reduce peak cooling loads enough to enable the implementation of a cooling tower in

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[1] Window-to-wall ratio (WWR) by orientation: 41% (South), 54% (North), 51% (East), 6% (West), 2% (roof)

combination with a hydronic in-slab radiant cooling system – a more efficient alternative to standard variable air volume (VAV) systems and compressor-based cooling. Moreover, the coupling of a high-performance facade with a high-efficiency in-slab radiant heating and cooling system results in a 44% reduction in energy use relative to California's energy code, Title 24. A roof-mount photovoltaic system offsets approximately 50% of the electrical demand of the building (Zelenay et al., 2011).[2]

The following thesis will study the David Brower Center in more detail, focusing on the performance aspects of the facade and fixed exterior shading. The main question driving this investigation is the impact of the exterior shading on performance – in particular its impact on solar control and daylighting in the south-facing office spaces. Why did the design team implement fixed exterior louvers? Do the louvers enhance daylighting in the space and minimize the occupants' need to rely on interior shading to ensure visual comfort? These questions will be answered through a combination of interviews with design team members, survey of the building's occupants, field monitoring of a representative office space, and computer daylight simulations.

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[2] More detailed information on building energy use and electrical power generation can be found in *Appendix A*.

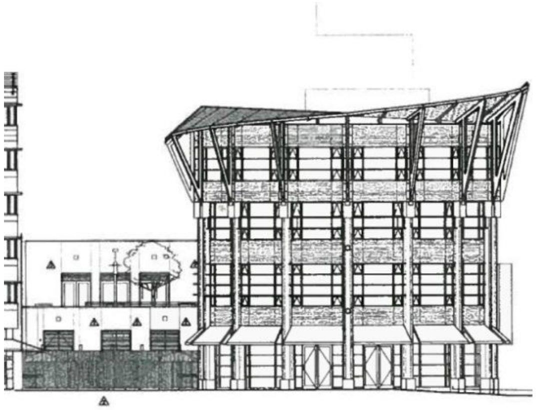

Figure 5 West elevation

Image credit: Daniel Solomon Design Partners

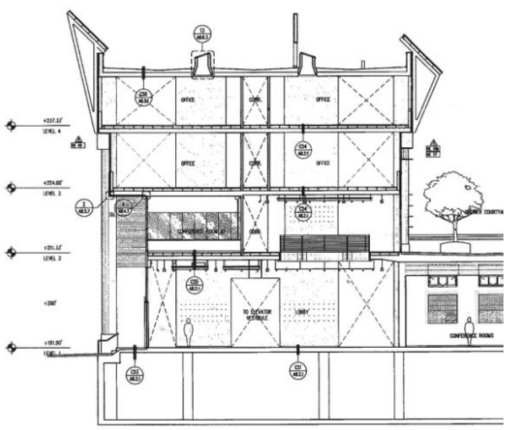

Figure 6 Cross section

Image credit: Daniel Solomon Design Partners

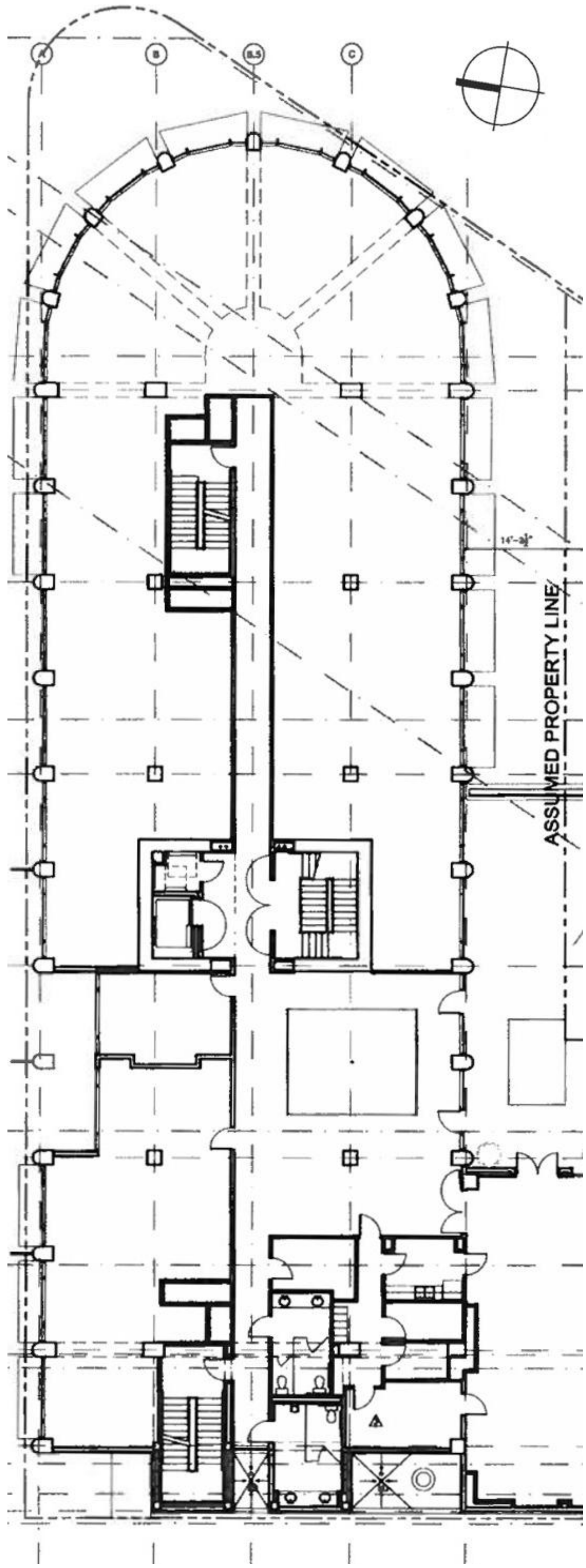

Figure 7 Third floor plan (right)

Image credit: Daniel Solomon Design Partners

Figure 8 South elevation

Figure 9 Detail of aluminum louvers

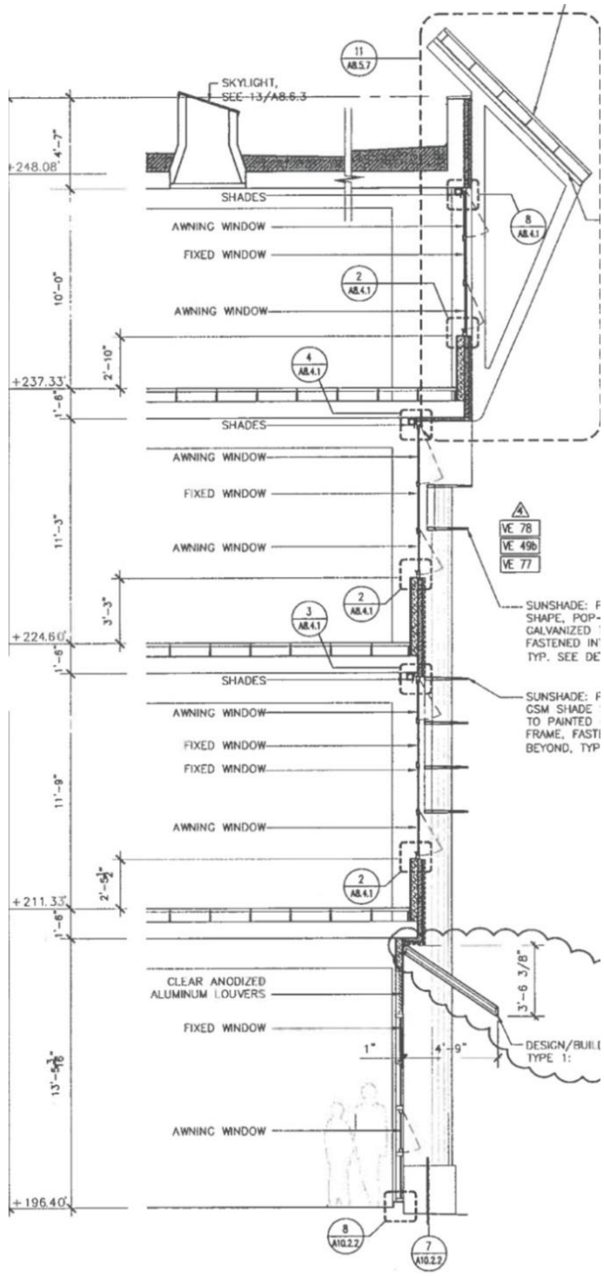

Figure 10 Section through south facade

Image credit: Daniel Solomon Design Partners

2. BACKGROUND

2.1. FENESTRATION DESIGN CONSIDERATIONS

The impact of fundamental facade design strategies such as orientation, window-to-wall ratio (WWR), glazing type, and fixed exterior shading on annual energy use and peak cooling loads has been thoroughly studied over the past several decades (Carmody, Selkowitz, Lee, Arasteh & Willmert, 2004, Carmody & Haglund, 2006; Hausladen, de Saldanha, & Liedl, 2007; Johnson et al., 1983; Lee & Selkowitz, 2009; Perepelitza, 2010). These studies reveal that window design has a significant impact on performance in terms energy use and occupant comfort. While increased insulation levels and smaller fenestration area can minimize the need for heating and cooling, windows play a central role in providing daylight and views to occupants. In office spaces, where adequate daylight is important for visually-demanding paper- and computer-based tasks, careful design of windows is especially important. However, as discussed in the introduction, proper solar control is critical to minimizing building energy demand and maintaining occupant comfort. Direct beam radiation can significantly increase energy use and peak cooling load, and result in both visual and thermal discomfort. In colder climates winter heat loss through the windows is a concern and needs to be addressed; typically through high-performance glazing and thermally-broken framing.

Spectrally-selective glazing coatings – coatings that transmit some wavelengths of energy but reflect others, are a widely used design strategy for maximizing transmitted daylight while minimizing heat gains and losses through glazing. While glazing with a solar control coating can significantly reduce solar heat gain with a relatively small impact on transmitted daylight, a reduction in the *solar heat gain coefficient* (SHGC) is always accompanied by at least some reduction in the *visible light transmittance* (VT) of the glazing. The *light-to-solar-heat-gain ratio* (LSR), calculated by dividing glazing VT by its SHGC, serves as an indicator of how well glazing can block solar heat gain while maximizing the transmitted daylight. Presently, the best-performing coatings have an LSR just over 2.[3] For projects seeking to minimize external solar gains while maximizing daylight (e.g. most office buildings in cooling-dominated climates), glazing with a high LSR should be selected. However, projects seeking some solar heat gain, e.g. many buildings in cooling-dominated climates, will use glazing with a higher SHGC, and the LSR in these cases will be lower.

Yet high-performance glazing alone is generally not sufficient to meet occupant comfort needs since it does not effectively control direct sun. While interior shading can be used to block direct sun from reaching the occupant, it is not effective in blocking solar heat gain. Moreover, research has shown that once interior shading is lowered by the occupant it often remains lowered for extended periods of time. The implications of this are discussed in greater detail in section 2.3 *Daylight and visual comfort*. In light of these limitations, there is a need to consider alternative technologies for managing daylight while minimizing solar heat gain, such as fixed or automated exterior shading and advanced glazing technologies.

While advanced glazing and shading technologies can offer significant performance benefits, (see section 2.4 *Exterior shading and solar control*), they are considerably more expensive than glazing with a spectrally-selective coating. Indeed, higher design fees and construction costs present major barriers to the widespread adoption of advanced

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3 Performance for a coating applied to surface #2 of an insulated glazing unit with two 6 mm clear lites.

technological solutions in buildings. Due to lower energy costs and different cultural expectations in terms of construction quality in the U.S. (Yudelson, 2009), U.S. developers and building owners may have little incentive to invest in the development of high-performance envelopes.

2.2. Benefits of Daylight and View

Light refers to the visible part of the electromagnetic spectrum (~380–780 nm) (Webb, 2006), and daylight is defined as the visible part of global solar radiation (Illuminating Engineering Society of North America [IESNA], 1999). While daylight or electrical lighting in buildings is commonly perceived as a means for meeting the visual needs of occupants, the role of light in the life of building occupants extends beyond a purely functional or aesthetic role. Daylight in particular has been shown to have a profound impact on humans; it is essential to human health and well-being. While electrical lighting is usually more than sufficient for the completion of daily tasks, it is typically quite different from daylight in terms of its spectral distribution, intensity and variation throughout the day and seasons (Stevens & Rea, 2001; Boyce, Hunter, & Howlett, 2003).

2.2.1. Occupant Health and Well-Being

Light has been shown to strongly affect the circadian rhythm, a physiological process which has been shown to affect mood and behavior. Mediated by the hormone melatonin, secreted mainly by the pineal gland, the process is strongly linked to the light-dark cycle (Veitch, 2006). Short-wave ultraviolet (UV) radiation (280 – 380 nm) plays an equally important role in the regulation of physiological processes. While harmful to human health in high amount, UV radiation in the UVB band (280 – 315 nm) is required in the synthesis of vitamin D, a pre-hormone vital to the development, growth, and maintenance of a healthy body (Webb, 2006). However, indoor environments typically exclude the majority of ultraviolet (UV) light, since much of UV light is blocked by glazing (Baker & Steemers, 2002).[4]

The non-visual biological response to daylight is governed by the amount of light entering the eye rather than illuminance levels inside the space (van Bommel, 2006), however the two are often related. Insufficient exposure to daylight results in the deregulation of the circadian rhythm, which can lead to daytime drowsiness and a variety of other symptoms (Baker & Steemers, 2002). Past studies of shift workers have shown that decreased exposure to daylight is strongly correlated with an increased risk of health problems, including higher risk of accident, cardiovascular disease, and gastrointestinal problems (Webb, 2006). Studies of stress levels among people working indoors indicate that workers working under daylight have considerably lower stress levels than those working under artificial lighting (van Bommel, 2006). In a year-long study of 90 Swedish elementary students in classrooms with and without windows, Küller & Lindsten (1992) found differences in cortisol levels among children in classrooms with and without windows. The authors conclude that the difference in cortisol levels affects child sociability, stress, and ability to concentrate, and that windowless classrooms should be avoided.

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4 A single 4 mm pane of glass transmits 50% of total UV radiation at 0° angle of incidence, 80% of wavelengths above 350 nm, but only a small portion (7%) of wavelengths below 320 nm. The UVB band (280-315 nm) not only has lower transmission rates than the UVA band (320 – 380 nm), but in contrast to UVA, it is more affected by angle of incidence. Total UV transmission rates for double glazing, which is more common in U.S. buildings, are considerably lower than for single glazing (Baker & Steemers, 2002).

Reduced exposure to daylight during the first half of the day and higher exposures to electrical lighting at night can impact the body's physiological function by altering the circadian rhythm. A shift in the circadian rhythm can result from even modest exposure to electrical lighting at night (500 lux) if there is limited exposure to daylight during the day (Boyce et al., 2003). While humans are most sensitive to daylight in the morning when they get up and before they arrive at work, and their sensitivity gradually decreases throughout the first half of the day, Cawthorne (1994) has shown that it is difficult to meet the daily requirement for daylight without adequate daylighting in the workspace (Baker & Steemers, 2002, p. 181). Morning daylight exposure in the workspace is thus an important consideration in the design of the space, especially during winter months in higher latitude climates (Baker & Steemers, 2002; Webb, 2006).

Studies show that occupants prefer daylight to electrical lighting (Boyce et al., 2003, Galasiu & Veitch, 2006). A survey of building occupants by Heerwagen & Heerwagen (1986) found that daylight is perceived considerably better for physiological comfort and health, and somewhat better for work performance. However occupants are willing to give up daylight if visual and thermal comfort needs are not met (Boyce et al., 2003). Post-occupancy evaluations of U.K. office workers by Leaman & Bordass (1999) revealed that provision of individual controls is a key variable in ensuring occupant satisfaction; windows need to be fitted with some form of solar control mechanism in order to ensure occupant comfort needs are met.

Designers can ensure that indoor spaces promote healthy biological processes by providing a relatively shallow plan space layout with high ceilings to allow for daylight penetration deep into the space. In fact, post-occupancy evaluations by Leaman & Bordass

(1999) have revealed that the depth of the floor plan is a major factor influencing occupant satisfaction in U.K. offices.

2.3. DAYLIGHT AND VISUAL COMFORT

While daylight can be used to offset electrical lighting use and has a positive impact on occupant well-being, a number of studies suggest that without proper solar control, occupants are likely to draw blinds when visual or thermal comfort thresholds are exceeded and that these blinds are likely to remain closed for some time, negating the potential benefits of having the window in the first place (Galasiu & Veitch, 2006; Inkarojrit, 2008, Inoue, Kawase, Ibamoto, Takakusa, & Matsuo, 1988; Reinhart & Voss, 2003). As a result, the impact of daylighting on visual comfort in office spaces has been an area of much study in recent years.

IESNA describes visual discomfort as a "sensation of annoyance produced by light in the visual field that is significantly higher than the luminance to which the visual system is adapted" (IESNA, 1993, p. 519). Ensuring that surface brightness in office spaces is balanced is critical to visually-demanding tasks such as office work, since large variations in luminances can results in poor transient adaptation – the ability of the eye to adjust to changes in brightness, and disability glare – glare resulting from diminished contrast of an image due to stray light within the ocular media (IESNA, 1993). A number of field studies have been conducted over the past few decades in an effort to understand occupant visual comfort preferences and to develop visual comfort metrics that can be used in the design of daylit environments (Galasiu & Veitch, 2006; Sutter, Dumortier & Fontoynont, 2006; Wienold & Christoffersen, 2006). Select metrics are discussed in section 2.5 *Daylight* *performance indicators*. Many of the visual comfort studies are focused on the development of occupant behavioral models that can be applied in building simulation software to predict the effect of occupant blind and shade control on lighting energy use (Inkarojrit, 2008; Reinhart, 2004). The development of more accurate algorithms for blind and shade operation would allow for an improved understanding of energy savings afforded by automated shading systems.

While relative brightness uniformity is generally desirable for physiological reasons, especially for adequate visual performance in office type settings, absolute uniformity from a psychological standpoint is not desirable as it can result in a lack of focus (Dubois, 2001). Small areas exceeding the luminance ratios limits recommended by IESNA (discussed in section 2.5.3), are “desirable for visual interest and distant eye focus for periodic relaxation throughout the day” (IESNA, 1993, p. 519). Lam (1992) differentiates between glare (light interfering with our perception) and “sparkle,” an “attractive brilliance” that ought to result from design intent. A sparkling element in the visual field can be “a desirable and natural focus for a space” (p. 53). Field studies in office environments by Loe, Mansfield & Rowlands (1994) and Newsham & Veitch (2001) show that visual interest is strongly correlated with the maximum-to-minimum luminance ratio within the field of view. Subjects rated scenes with higher luminance ratios more visually interesting, however the increase in interest leveled off at luminance ratios of 1:20.

2.4. EXTERIOR SHADING AND SOLAR CONTROL

As discussed previously, spectrally-selective glazing is not a sufficient means for controlling direct sun, which can lead to increased solar gain and occupant visual discomfort.

Supplementation with an additional form of solar control is generally needed, and while interior shading systems are quite effective in controlling glare, they do not block solar heat gain. Exterior shading systems, on the other hand, are considerably more effective because they block radiation before it can enter the space. Automated shading systems provide the opportunity to block solar heat gain while maximizing daylight through dynamic shading adjustments in response to outdoor and indoor conditions. The performance benefits of automated shading systems are discussed in more detail in the following section.

2.4.1. Performance benefits

Fixed shading systems. Fixed exterior shading elements such as horizontal overhangs or vertical fins can enrich the architectural vocabulary of the facade, create variable shading effects inside the space that vary throughout the day and throughout seasons, reduce energy use and improve occupant comfort (Baker & Steemers, 2002; Carmody et al., 2004; Carmody & Haglund, 2006). By blocking direct sunlight before it reaches the window, fixed exterior shading can minimize solar heat gain and overcome the issue of continuously deployed interior shading by eliminating potential visual and thermal discomfort in sunlit perimeter spaces. Exterior shading is typically supplemented with manually-operated interior shading because even in the absence of direct sunlight means for managing visual discomfort due to reflections on the computer screen and view of bright exterior surfaces or sky are needed.

The exact impact of fixed exterior systems on performance varies widely depending on climate, facade orientation, window size and geometry, glazing system, and the depth and geometry of the shading itself (Carmody & Haglund, 2006). Horizontal shading elements are especially effective in controlling high altitude sun, however their impact is limited on the east and west building elevations where it is difficult to control low incident sun angles. Vertical shading elements can be used to manage low-angle sun somewhat more effectively but can substantially obstruct the view to the outside. While supplemental interior shading systems can help meet occupant visual comfort needs irrespective of sun position, they are not effective in controlling solar gain (Lee & Selkowitz, 2009).

Automated shading systems. Active facade technologies – technologies that actively adjust in response to ambient conditions, occupant preferences and building energy management control system (EMCS), can overcome some of the limitations of fixed exterior shading. Technologies such as automated shading systems, switchable electrochromic and thermochromic glazings can more effectively manage daylight while minimizing solar gain (Lee et al., 2002). The coupling of an automated exterior shading system with moderate- to large- window areas provides comparable savings in thermal loads as those attained by simply downsizing the window, but with the added benefit of more daylight (Lee & Selkowitz, 2009). While the applicability of automated shading systems is limited to low- and mid-rise buildings,[5] these systems can outperform fixed shading systems on account of the fact that their position can be automatically adjusted in response to ambient and/or indoor conditions. Similar to fixed shading systems however, the impact of automated shading systems on energy use can vary widely depending on the climate, window area and glazing, orientation, shading control strategy, and lighting system design. For example, in a 9-month field study of the New York Times facade mockup, which entailed testing and

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[5] Wind loads preclude the use of these systems on tall buildings since systems need to retracted at wind velocities of 30 mph or higher (Lee & Selkowitz, 2009).

commissioning of a state-of-the-art automated interior shading and daylight dimming system, researchers from Lawrence Berkeley National Laboratory (LBNL) found that lighting energy savings are closely linked to the interior shading control algorithm (Lee & Selkowitz, 2006). More stringent glare control, and thus more frequent lowering of interior shades, results in reduced daylight levels and an increase in electrical lighting use. Newer closed-loop shading control systems incorporate more environmental variables, making it possible to further optimize for energy use in terms of two or more variables, or to balance energy requirements with visual comfort requirements (Guilleminn & Morel, 2001; Lee & Selkowitz, 2006). In practice however, automated systems require more maintenance than fixed systems, and when they are not commissioned properly or adjusted throughout the building operation phase, system performance may fall short of the design intent (Lee et al., 2002; Lee & Selkowitz, 2006; HMG, 2008; Zelenay et al., 2011). These issues are discussed in more detail in section 2.4.2 *Practical considerations.*

As part of a multi-year project focusing on the performance of advanced glazing systems, the Windows and Daylighting group at LBNL has been conducting ongoing testing of emerging interior and exterior shading technologies in an effort to accelerate the adoption rate of these systems in the U.S. market (**Figure 11**). The goal of these studies is to demonstrate to building owners and designers that properly commissioned systems yield reliable performance, and to provide feedback to system manufacturers regarding the optimization of systems with respect to cost and performance (Lee & Selkowitz, 2009).

In a six month, solstice-to-solstice full-scale field study in Berkeley, California, LBNL tested a range of innovative fixed and automated shading systems in terms of their impact on performance in a south-facing zone with a large window area and dimmable lighting controls (Lee & Selkowitz, 2009). Six interior and six exterior shading systems were tested in LBNL's windows testbed facility consisting of three separate south-facing zones (**Figure 11**).

Figure 11 Lawrence Berkeley National Laboratory windows testbed facility

The results of the field study show that the interior automated shading systems were considerably more effective in managing visual comfort than the manually-controlled systems (**Table 1**).[6, 7, 8] With daylight dimming in place, the electrical lighting energy use

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[6] The reference case for comparisons consisted of a single-zone fully lowered venetian blind system with a conventional white 1″ slat. Slat was seasonally adjusted (three times over the course of the 6-month test period) to block direct sun.

[7] Manually-adjusted interior systems included one single- and two dual-zone venetian blind systems (one with a low-e coating on the underside of the slat) and a fabric roller shade with a 3% openness factor (OF). The venetian blind systems were always lowered and seasonally adjusted

(continued on next page)

savings for the manually-controlled and automated interior systems was comparable, averaging 62-69%, however the automated system offered superior visual comfort performance. The impact of interior shading systems on average cooling load savings was considerably smaller (up to 22% reduction) than for the exterior shading systems (78 – 94% reduction) (Lee & Selkowitz, 2009, p. 53 and 67).[9, 10] However, the exterior venetian blind systems with a conventional semi-gloss white slat failed to meet the visual comfort criteria (maximum window luminance of 2000 cd/m^2) for 20-30% of the monitored days (**Figure 12**). The high luminance of the underside of the slat was the main factor contributing to the reduced visual comfort performance of the system.

Interestingly, average cooling load savings from a three-zone, static venetian blind system with an optical V-shaped slat (88% reduction) were comparable to those for the automated exterior venetian blinds (84-87%), while the window luminance for the fixed system exceeded the threshold for only 6% of the time (Lee & Selkowitz, 2009, p. 67). The improved visual comfort of this system as compared to the automated system with the conventional slat can be explained by the more closed position of the slat (**Figure 13**). The

(three times over the course of the 6-month test period) to block direct sun. The roller shade was lowered so that the bottom edge was 30″ above the floor.

[8] Automated interior systems included two single- and one dual-zone venetian blind systems and an interior roller shade (3% OF). Venetian blinds were always lowered and only slat angle was adjusted (in either two to four steps or continuously) to block direct sun. The roller shade was lowered incrementally in 1-inch steps in the presence of direct sun.

[9] Manually-adjusted exterior shading systems included a single- and dual-zone venetian blind with a conventional semi-reflective slat and an optical V-shaped three-zone venetian blind system with a matte light-gray underside. The venetian blind systems were lowered; they are meant to be positioned at a fixed slat angle and adjusted seasonally to block direct sun using a crank.

[10] Automated exterior systems included a single and dual-zone venetian blind with a conventional semi-reflective white slat and a fabric roller shade (3% OF). The slat angle of the venetian blind systems were controlled in two to four steps to block direct sun. The roller shade was lowered incrementally in 1-inch steps in the presence of direct sun.

minimal operation associated with this system – seasonal slat adjustments to block direct sun, makes it a more robust alternative to the automated exterior systems.

Table 1 Monitored field performance of shading systems tested at LBNL

Source: Lee & Selkowitz (2009)

South-facing, large-area window, dimmable lighting controls, Berkeley, California

		Interior Shades		Exterior Shades	
		Manual	Automated	Manual	Automated
Lighting Energy Use	(kWh/ft^2-yr)	1.04 - 1.13	0.92 - 1.11	1.12 - 1.41	1.0 - 1.27
Lighting Energy Savings*	(%)	62 - 65%	62 - 69%	53 - 63%	58 - 67%
Cooling Load Savings**	(%)	Up to 15%	Up to 22%	78 - 94%	80 - 87%
Peak Cooling Load	(W/ft^2-floor)	8.0 - 9.4	8.0 - 9.8	1.6 - 3.1	2.0 - 2.5
Avg time uncomfortable***	(hours/day)	2.3 - 3.7	0 - 1.1	0.7 - 3.8	0.2 - 3.0

* Savings compared to ASHRAE 90.1-2004 (no daytime controls)
** Compared to manually-operated, conventional interior shade
*** Amount of time when brightness of window caused glare

Figure 12 Vertical cross section through automated exterior VB system with conventional slat

Image credit: Lee & Selkowitz (2009)

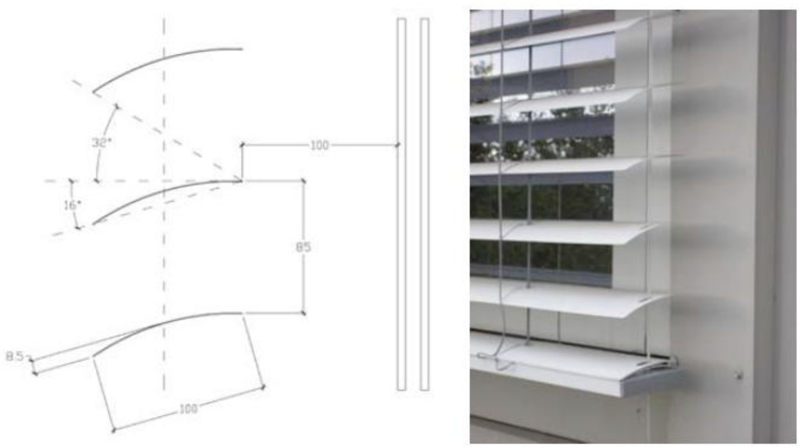
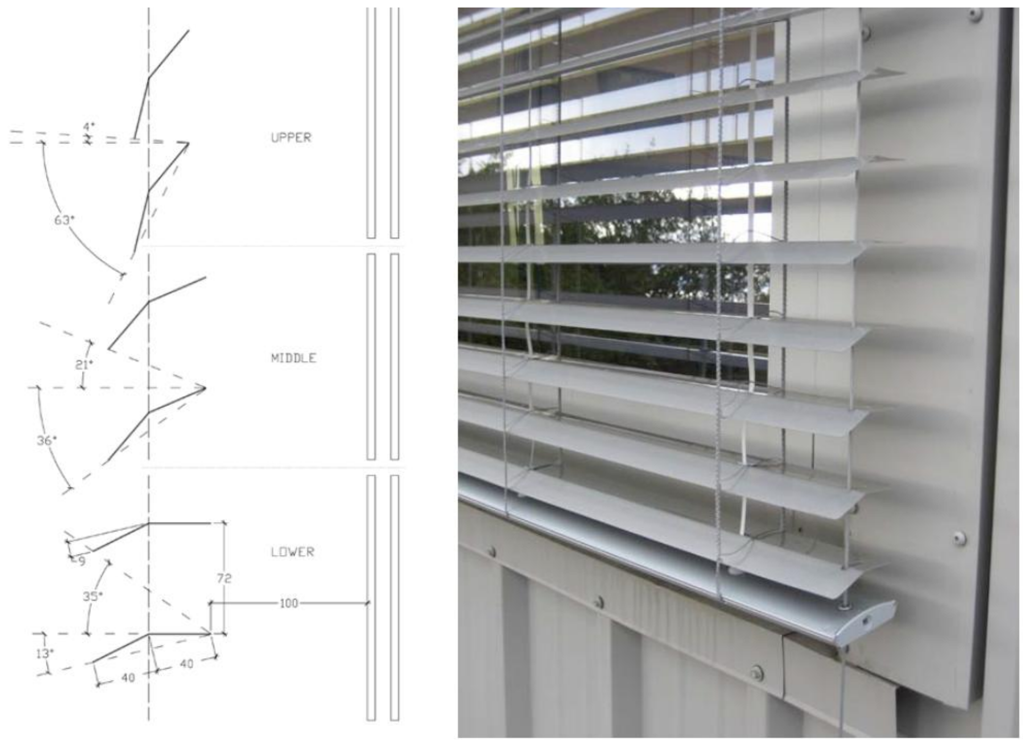


Figure 13 Vertical cross section through static exterior VB system with optical V-shaped slat

Image credit: Lee & Selkowitz (2009)



In support of LBNL's goals to develop tools supporting an integrated design process, COMFEN (short for commercial fenestration), an early facade analysis tool based on EnergyPlus, has been recently developed (LBNL, 2011a). This single-zone facade analysis tool can be used to evaluate a range of facade configurations, including automated interior and exterior shading systems with a range control options, in order to understand the impact of different design variables on facade performance. After defining a building type, location and zone properties, several additional scenarios can be quickly created and compared side-by-side. Orientation, window-to-wall ratio (WWR), glazing type, shading and lighting control can easily be varied in order to assess their impact on energy use, peak loads, daylighting and thermal and visual comfort. Optical and thermal properties of commercially-available shading systems tested by LBNL have been implemented in LBNL's WINDOW software, a public software tool used for window energy efficiency labeling and rating (LBNL, 2011b).

2.4.2. Practical considerations

Barriers to implementation. While automated exterior shading can offer significant performance benefits and overcome some of the problems associated with manual shading control and limitations of fixed exterior shading systems, these systems are more complex and more expensive in terms of both first cost and operational cost than non-automated systems (Lee et al., 2002; Lee & Selkowitz, 2006; HMG, 2008; Zelenay et al., 2011). Optimizing automated shading system performance requires commissioning at installation, regular maintenance, occupant education and ongoing re-evaluation of system performance over the building's life. At the same time it is not easy to quantify the benefits of these systems due to the challenge of defining an appropriate baseline building for comparison, as occupant shade operation can vary considerably between occupants (Inkarojrit, 2006; HMG, 2008).

Finally, the building energy code may not fully encourage the adoption of these systems. ASHRAE Standard 90.1 – an energy code for high-rise residential and commercial buildings adopted by many state and local codes, including California's Title-24, does not give credit for the system if system operation can be overridden by the occupant (ASHRAE, 2007; Lee & Selkowitz, 2009). Yet past studies have indicated the need for occupant overrides with automated shading systems because occupant preferences in terms of daylight and visual comfort vary significantly (Galasiu and Veitch, 2006; Reinhart & Voss, 2003; Veitch, 2006). Systems installed without occupant overrides could contribute to occupant dissatisfaction and generate complaints, which could lead to a poor perception of these systems. At the same time, lack of occupant overrides does not guarantee that systems will perform as designed. A better solution would be to require annual or biannual certification that systems are operating as intended. As energy code requirements in the U.S. are tightened, there is a need to address the apparent disconnect between energy and occupant comfort considerations in a systematic manner; in the case of high-performance facades this would entail specific recommendations regarding the design and operation of operable facades in the context of both energy performance and occupant comfort considerations.

Operation and maintenance (O&M). Even though automated systems have been commercially available in the U.S. for over two decades, the rate of adoption has been slow; U.S. building owners and design teams are hesitant to adopt these systems due to the higher risk and cost associated with the design and operation of a new technology (Lee & Selkowitz, 2005). Due to concerns about operation and maintenance (O&M), the client at the Marin Country Day School (MCDS) administrative building in Corte Madera, California, was initially hesitant to implement automated exterior shading, recommended by the architect in order to minimize solar gain on the west elevation and ensure that the building could operate without mechanical cooling. However the client's concerns were alleviated once they learned that the system had been installed on another local project (Zelenay et al., 2011).

By working closely with the New York Times headquarters design team and manufacturer during the design and installation phase, Lawrence Berkeley National Laboratory, hired as a third-party consultant, helped commission the automated interior shading and daylight dimming system installed on the project (Lee & Selkowitz, 2005). Thanks to the partnership and thorough testing of the systems, the design team's concerns about operation and maintenance could be addressed, while providing both the manufacturer and LBNL with valuable feedback with respect to system operation and performance. The results of the study have been published in a series of reports discussing lessons learned (LBNL, 2009).

While system operation issues at installation are generally covered by the initial warranty, extended commissioning of complex systems is typically needed to ensure proper operation throughout the life of the buildings (Zelenay et al., 2011). At MCDS, an extended warranty was negotiated with the system manufacturer, under the condition that the school conduct regular cleaning and maintenance of the shades. In the absence of a maintenance contract at the California Academy of Sciences in San Francisco, the Academy had to manage the repairs on their own – an expensive and time-consuming endeavor (Zelenay et al., 2011). While the roller shades are programmed to retract under high wind loads, there is no way to prevent occasional damage resulting from a strong initial wind gust. Roller shades were prone to additional damage due to visitors pulling on the shades, forcing the Academy to keep exterior shades in public spaces retracted during visiting hours. The cost of a maintenance contract for this particular project – a project with a very high number of exterior roller shades, was estimated between $20,000 and $30,000 per year.

Findings from the LBNL field study of a range of shading systems (see section 2.4.1 *Performance benefits*) revealed that the tubular motorized systems that only allow raising or lowering of the shading, such as those used with interior and exterior roller shades, were less complex and generally more reliable than the venetian blind systems, which need to deliver both height and slat angle control with a single motor (Lee & Selkowitz, 2009).

For owners who are not willing or able to invest the extra money and time in the design, commissioning, and operation of automated systems, fixed exterior shading may constitute a cost-appropriate alternative solar control strategy. While systems may not manage solar heat gain and daylight as well as a properly operating automated exterior shading systems, fixed systems are much easier to design and require virtually no maintenance. The innovative fixed exterior louver system with a V-shaped slat tested in the LBNL study, however, provided nearly as good performance in terms of cooling load reduction as the automated venetian blind systems tested.

2.5. DAYLIGHT PERFORMANCE INDICATORS

While attaining a well-daylit space is an important design objective, the characterization of daylight quality is challenging due to variable environmental conditions and variable occupant preferences. Variation in outdoor daylight conditions throughout the day, season and year have made it difficult to characterize the daylight levels within a space. And even though a range of visual comfort metrics have been developed for evaluating daylight uniformity within a space, the metrics cannot be reliably used to reliably predict occupant response to glare due to variation in individual preferences. Nevertheless, presently available metrics for assessing the quantity and quality of daylight can be used to good effect as design guidelines and a means to evaluate the daylight design of a space. The following section provides an overview of several of the most commonly used metrics for characterizing daylight quality, including some of their limitations.

2.5.1. Workplane illuminance

Studies have found that there is a wide variation in preferred occupant illuminance levels (Reinhart & Voss, 2003; Veitch, 2006). Despite the variation in individual preferences for daylight, individual preferences for illuminance levels in office spaces are consistent from day-to-day and generally lie between 100 and 1000 lux (Reinhart & Voss, 2003; Newsham & Veitch, 2001; Veitch, 2006). The Illuminating Engineering Society of North America (IESNA) recommends a maximum illuminance of 500 lux for computer-based tasks since lower illuminance levels are less likely to affect screen contrast due to lower luminances of reflected objects (IESNA, 1993, 535). Indeed, studies confirm that lower illuminance levels (200 – 500 lux) are acceptable and often preferred for computer computer-based tasks (Newsham & Veitch, 2001; Galasiu & Veitch, 2006). These illuminances are typically regarded as the minimum required illuminance for visual performance in offices with visual display terminals (VDTs); there is an abundance of literature suggesting that higher illuminances may be desirable for occupant health and well-being (Boubekri, 2008; Galasiu & Veitch, 2006).

Characterizing illuminance levels in a space using a single metric is difficult due to the inherent variability of daylight throughout the day and seasons. While point-in-time calculations for key times of the year can provide a reasonable indication of daylight levels in the office space, in the past decade there has been much research and effort towards developing a single metric that would summarize daylight levels over the course of the year. Key metrics for assessing daylight levels inside the space are discussed below.

Daylight factor (DF). One of the oldest metrics – the daylight factor (DF) measures the ratio of the indoor horizontal illuminance to the outdoor horizontal illuminance under an overcast CIE reference sky (Reinhart, Mardaljevic & Rogers, 2006) However, the widely-used daylight factor (DF) has major limitations since it is calculated based on the ratio of the internal illuminance at a given point to the unshaded external horizontal illuminance under a CIE overcast sky. This limitation makes the factor less relevant for climates with predominantly sunny skies. Consequently, since the metric does not account for variation in daylight throughout the day and season, which can vary significantly by climate, it cannot be user to adequately characterize daylight levels for a particular location.

Dynamic daylight metrics. Several recently developed annual metrics, also referred to as dynamic daylight metrics, are calculated based on an entire-year's -worth of climate data, making it possible to account for variation in climate and sun position (Reinhart et al., 2006; Nabil & Mardaljevic, 2005). Two such metrics include *daylight autonomy* (DA) and *useful daylight illuminance* (UDI). DA is used to determine the portion of occupied hours during which the minimum illuminance requirement at a particular point is met. UDI is similar to DA in that it also looks at workplane illuminances over a period of time, however rather than using a minimum illuminance level as the requirement, it uses an illuminance range with an upper (2000 lux) and lower (100 lux) threshold as a requirement. In other words, daylight requirements are met when it is neither too dark (<100 lux) or too bright (>2000 lux). Since high illuminance levels can result in reflections on the computer screen and affect screen contrast (IESNA, 1993), the metric can be considered as a proxy for determining whether lighting conditions are conducive to meeting the visual comfort needs of the occupant. In contrast to the DF, which assumes that movable shading systems are raised, DA and UDI account for shade operation, which can have a considerable impact on daylight levels inside the space.

The calculation of DA and UDI is more complicated than the daylight factor method, and requires the use of special software such as DAYSIM, a Radiance-based annual daylight simulation software (Reinhart, 2011). An alternative method of calculation is to use Rhinoceros 3-d modeling design software in combination with DIVA-for-Rhino – a sustainable design plug-in for Rhino which provide a front-end user interface for Radiance and DAYSIM (Jakubiec, Lagios, Niemasz, Reinhart, & Sargent, 2011).

2.5.2. Glare indices

Early measures of glare such as BRS' British Glare Index (BGI) and CIE's Unified Glare Rating (UGR) system were originally developed for assessing glare from small artificial light sources. However, these glare indices are not applicable to windows because windows are considerably larger, allowing for greater adaptation of the eye to higher luminances, and because occupants seem to be more tolerant of glare from windows (Velds, 2000). The Glare Index (GI), developed by Hopkinson (1972) based on studies of glare from large artificial light sources, was one of the first indices developed for specifically for assessing glare from windows. The index was later modified by Chauvel, Collins, Dogniaux & Longmore (1982) based on field studies in daylit spaces which revealed that subjects were more tolerant for glare from daylight. The index in its present form, known as the Daylight Glare Index (DGI), is calculated based on source (e.g. window) luminance, source size, surround background luminance, and the location of the source relative to the occupant's field of view (Chauvel et al., 1982).

While the DGI constituted an improvement over glare indices for small artificial light sources, a number of studies have shown that there is a weak correlation between DGI and occupant response to glare due to the fact that the index does not account for the effect of view on occupant response to glare, the non-uniform nature of the glare experienced through windows with venetian blind systems, and the variability in individual response to glare (Galasiu & Veitch, 2006; Wienold & Christoffersen, 2006). Some sources suggest that in the case of large glare sources such as windows the adaptation level of the occupant is largely independent of source size and distance from the occupant and primarily dependent on the vertical illuminance at the eye or the overall brightness field (Velds, 2000).

Based on the results of a study conducted in a 20-story building in Sheffield, U.K., Tuaycharoen & Tregenza (2007) explored the hypothesis that occupants with access to more interesting views, such as views of a natural landscape, and views encompassing both foreground and background elements of a landscape are more tolerant of glare. They showed that DGI is overly conservative and proposed a modification to the DGI by which windows with an interesting view be assigned a "score of interest of a scene," IV, ranging from 0 (no view) to 6 (a very interesting view) and that this value be subtracted from the calculated DGI. While the adjustment is an interesting proposition, there have been no documented studies replicating the study under different environmental conditions and a different sample of subjects.

Results of a large field study by Wienold and Christoffersen (2006) revealed that there is a poor correlation between both DGI and window luminance and subject response to glare. The study was conducted with 75 subjects in Denmark and Germany under three window-to-wall ratios, two orientations and three types of shading systems (white venetian blinds, specular venetian blinds and a vertical foil system). Based on the results of the study, Wienold and Christoffersen proposed a new glare prediction model that combines the central sum of an existing glare index (CIE glare index) and empirical data. In contrast to DGI, which determines the magnitude of the glare, DGP determines the probability that the occupant will be disturbed by glare; the glare scale is thus reduced to two categories ("disturbing" and "intolerable" glare). While this glare index is promising on account of the simplified (two-category) scale and the range of environmental conditions tested in daylit spaces, additional studies validating this index are needed to confirm its applicability to a wider range of conditions and subjects.

2.5.3. Luminance ratios

The Illuminating Engineering Society of North America (IESNA) recommends specific luminance ratios between the task and background surfaces in order to limit the effects of transient adaptation and disability glare. Three sets of luminance ratios are recommended depending on the position of the background surfaces relative to the task surface to (**Table 2**). Several other organizations, including British CIBSE (Chartered Institution of Building Services Engineers) and Swedish NUTEK (Swedish National Board for Industrial and Technical Development), recommend similar luminance ratios (Dubois, 2001). However, IESNA does not provide clear guidelines regarding how to easily define these zones when calculating luminance ratios. According to Meyer, Francioli & Kerkhoven (1996), for the purposes of assessing the impact of surface brightness on comfort, the visual field can be subdivided into two smaller fields: the "ergorama" and "panorama," which correspond to a 60° and 120° cone of vision about the line of sight, respectively (Dubois, 2001), where the 120° cone approximates the binocular field of vision.[11] This alternative method of defining direct and remote surroundings has been used by Dubois (2001) and Sutter et al. (2006).

Table 2 IESNA recommended luminance ratio limits

	Upper limit	**Lower limit**
Between paper task and adjacent VDT screen	3:1	1:3
Between task and adjacent dark surroundings	3:1	1:3
Between task and remote (nonadjacent surfaces)	10:1	1:10
Between points anywhere in the field of view	40:1	1:40

Previous studies indicate that the luminance of a visual display terminal (VDT) varies between 50 and 120 cd/m^2 depending on the screen background and the brightness setting (Dubois, 2001), however average screen luminances for negative-contrast screens (screens with black characters on a white background) for newer VDTs with liquid crystal displays (LCDs) are closer to 200 cd/m^2 (Lee & Selkowitz, 2009; Wymelenberg & Inanici, 2009). Based on this monitor luminance and a maximum luminance ratio of 1:10 for the bincoular field of vision, the maximum desirable luminance of the window would be 2000 cd/m.^{2}

[11] The human field of view consists of monocular and binocular portions. The monocular portions are the regions seen by the left or right eye, while the binocular portion is the region formed by the overlap between the two regions. The combined field of view extends 90° to either side, 60° up, and 70° down from the line of sight (IESNA, 1993, p. 76).

3. OBJECTIVES

Given that exterior shading is relatively uncommon in the U.S., the question of why it was implemented at the David Brower Center (**Figure 2**) is a compelling one. The objective of this study is to understand why the design team implemented exterior shading on this project and to identify the shading's impact on daylighting in a typical south-facing office space. The thesis is subdivided into four parts. The first part, developed around interviews with design team members, explores the reasons why the design team implemented exterior shading. The following two parts – an occupant comfort survey and field study, seek to understand occupant satisfaction with daylight in the space and pattern of interior shading and lighting operation. Given that the building is located in a dense urban area and exterior obstructions can contribute to a reduction in daylight levels, is there a need for electrical lighting inside the space? The fourth and final part compares the performance of the building with and without fixed exterior shading using a series of computer-based daylight simulations in a order to understand the implications of shading in terms of illuminance levels and lighting uniformity within the space. Each of the methods is described in more detail in the beginning of each part.

4. INTERVIEWS

The following section discusses some of the factors driving the design of the David Brower Center facade, including factors leading to the implementation of the fixed exterior aluminum louvers. Findings from interviews with key design team members highlight major design challenges and the complexity of the design process.

4.1. METHODS

Three one-hour-long interviews with design team members were conducted in July 2010 in an effort to collect information on which social, economic and environmental factors drove the implementation of exterior shading at the David Brower Center. Interviewees included the architect, Malcolm Harris from Solomon E.T.C., mechanical engineer, Tyler Bradshaw from Integral Group, and the daylighting consultant, George Loisos from Loisos + Ubbelohde, a California-based firm specializing in building energy efficiency and daylighting analysis. Two of the interviews were conducted over the phone, and one at the interviewee's firm. The interview guide is included in *Appendix B*.

4.2. FINDINGS

4.2.1. FACADE

The overall design objective for the facade was the development of a beautiful and expressive high-performance facade, where equal weight was given to its aesthetic and performance aspects.[12] The key performance objectives were controlling direct sun,

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[12] Harris, Malcolm (2010, June 30). Telephone interview with senior associate at Daniel Solomon Design Partners.

maximizing daylight and visual comfort, and limiting conductive and radiant heat losses and gains. [12,13]

In an effort to minimize energy use and peak cooling loads while providing occupants with a high-quality indoor environment, the design team pursued a narrow building footprint (**Figure 7**). Aside from proper building massing and solar orientation, a number of other passive design strategies were incorporated including a moderate window-to-wall ratio, thermal mass, natural ventilation and high-performance glazing (**Figure 7 - Figure 10**). The implementation of simple fixed exterior aluminum louvers on the south and curved southeast portions of the building early in the design process allowed the design team to decrease the peak cooling load and improve occupant visual and thermal comfort by blocking direct sun throughout much of the year (**Figure 9**). Manually-operated interior roller fabric shades, a medium gray color with a 3% openness factor and 15% visible transmittance, allow the occupants to make further adjustments to their environment. Fabric shades rather than venetian blinds were selected because, in contrast to fully closed venetian blinds, roller shades provide some daylight and view to the outside even when lowered.[14]

Due to local ordinance requirements which impose a limit on the allowable volume of the development, the height of the building was fixed, limiting the floor-to-ceiling heights. However the height of individual floors was varied based on daylight availability and programmatic requirements. For example, the top floor has the lowest height since daylight requirements are partially met through top lighting provided by a series of roof-level

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[13] Bradshaw, Tyler (2010, July 12). Telephone interview with green building design team manager at Integral Group.

[14] Loisos, George (2010, July 6). Personal interview with principal at Loisos + Ubbelohde.

skylights (**Figure 10**), while the 2nd floor has a higher floor-to-floor height in order to compensate for reduced daylight availability at the lower floors resulting from surrounding site obstructions (**Figure 14**).[14]

Facade strategies for improving light uniformity in the office spaces were proposed early in the design process. These included an exterior lightshelf with an Alanod[15] reflector – a highly reflective metal finish, on the south facade, and a Serraglaze light-redirecting film[16] (a thin film that allows diffuse light to penetrate deeper into a room) for the glazing on the

Figure 14 Axonometric view of David Brower Center (right) and adjacent condominiums

Image credit: Daniel Solomon Design Partners

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15 See Alanod-Solar website for more information: http://alanod-solar.com/opencms/opencms/Reflexion/index.html

16 See Bending Light website for more information: http://www.bendinglight.co.uk/building_home.asp

north facade. However these features, along with many of the roof skylights and the automated interior roller shades proposed for visual comfort at the curved east elevation of the building (**Figure 14**), were eliminated during subsequent design iterations and the value engineering phase. Due to its lower floor-to-ceiling height and the elimination of the light-redirecting elements, the third floor appears somewhat darker than the other floors.[14]

4.2.2. MECHANICAL SYSTEM

With relatively small internal heat gains that were in part mediated by the thermal mass of the building, and by carefully controlling external heat gains, the design team was able to implement a low-energy hydronic in-slab radiant cooling system. The system is installed in the exposed concrete ceiling slabs (at the second, third and fourth floors of the building) and also provides heating to the building. Due to their large surface area and high thermal mass, slab- integrated radiant cooling systems use relatively warm chilled water temperatures, making them well-matched with non-compressor-based cooling such as cooling towers. In addition to the improved efficiency associated with transporting thermal energy through water rather than air, the building cooling energy savings are attained through the utilization of a cooling tower, which uses about one-tenth of the energy of a chiller for one ton of chilled water cooling. [13] While a cooling tower is more efficient than a chiller, its main limitation is that it can only cool water to a certain temperature, generally a few degrees above the outside wet-bulb temperature, so its application is limited to projects with low cooling loads. Although an underfloor air distribution (UFAD) system was implemented to provide ventilation, it is the radiant slab system that handles most of the cooling load. The UFAD system has a minimal impact on cooling because the supply air is introduced into the space at a temperature close to that of the room in order to eliminate the risk of cool drafts and occupant thermal discomfort. Moreover, it is a dedicated outdoor air system (DOAS), so the flow rate is much lower (0.25-0.3 cfm/ft^2) than that of a standard system.[13]

Radiant surfaces cannot be cooled below the dewpoint temperature of the space due to risk of surface condensation. Radiant cooling systems therefore have a relatively low cooling capacity. The capacity for radiant ceilings is approximately 31.4 Btu/hr/ft^2 (99 W/m^2) (Olesen, 2008). Consequently, the David Brower Center design team aimed to reduce building loads as much as possible. Low building loads in conjunction with supplemental thermal mass allowed the mechanical engineer to assume a fixed limit for the minimum allowable surface temperature of the radiant ceiling. In other words, rather than depending on a humidity sensor to monitor indoor conditions and continually adjusting the minimum allowable surface temperature for the radiant slab, the engineer calculated the dew point temperature for the most humid day of the year and added a several degree buffer to this number to determine the minimum slab temperature setpoint – 65°F (Miazga, 2011).

While assuming a fixed minimum for the radiant slab temperature is a somewhat conservative approach in that the temperature of the slab may be well above the actual dewpoint temperature of the room throughout much of the year, the project's mechanical engineer finds that this is a simple and reliable approach to controlling the system. The alternative method – continuously tracking the room dewpoint temperature through the use of humidity sensors, brings additional risk, as sensors can be relatively inaccurate. When brand new, a quality sensor may measure RH within ±2 percent, however may drift considerably over time, up to ±5 percent RH after five years without calibration. While this more conservative control method may be appropriate for projects with low internal loads, humidity sensors may be needed in cases where high loads are anticipated. If implemented, at least two or three sensors should be installed and calibrated against each other regularly to minimize the risk of failure.[13]

4.3. Discussion

Minimizing cooling loads and ensuring occupant thermal and visual comfort were the major performance factors driving the design of the facade, which influenced the decision to implement fixed exterior shading. According the architect, the integration of the facade with the cooling system design was the reason why the shading was not eliminated during the project's extensive value engineering phase. The following sections discuss the relationship between the facade, cooling system, and cost in more detail.

4.3.1. Facade and cooling system integration

The optimization of the building massing, orientation and facade may provide an opportunity to use low-energy alternatives to compressor-based cooling such as displacement ventilation, underfloor air distribution, evaporative cooling, chilled beams, and activated slabs in many climates. Such is the case at the David Brower Center, where fixed exterior shading on the south elevation of the building contributes significantly to building cooling load reduction. This strategy, in conjunction with other fundamental design strategies, allowed the design team to minimize peak cooling loads and implement a low-energy radiant cooling system. A similar example is the Terry Thomas office building in Seattle, where the elimination of compressor-based cooling would not have been possible without fixed and automated exterior shading, which ensure that external loads do not increase the temperatures beyond the already relaxed temperature limits (Zelenay et al., 2011). The Terry Thomas design team was able to limit mechanical costs to $16/ft^2 ($172/m^2) – 10% of total project cost, by using natural ventilation in place of a traditional mechanical system with air-conditioning and a forced-air distribution system (ASHRAE's Best, 2010). In comparison, the 2007 installed cost of a mechanical system in a medium-sized office building in Seattle is estimated between $7.50 and $29 per square foot.[17] While a range of design strategies was used on the project to minimize loads, the automated exterior shading played a central role in minimizing solar gains and ensuring that the office space temperatures would not exceed specific thresholds (Zelenay et al., 2011).

While facade and mechanical system integration provides an opportunity to implement a low-energy cooling system or to eliminate the need for cooling altogether, especially in milder climates, a more aggressive space conditioning approach may require that the mechanical engineer take on additional risk in ensuring that the building meets occupant comfort needs. Unfortunately U.S. engineers tend to be very conservative in their design assumptions.[13,14] An engineer who does agree to explore a new technology will likely need more time for analysis to ensure that the system is designed correctly, possibly requiring higher design fees. Not surprisingly, engineering professionals find that clients may resist the higher fees, as they are not convinced that higher than typical fees will indeed benefit the project.[13]

Low-energy cooling approaches may also require that clients accept more flexible thermal comfort requirements. In such cases, the decision of whether or not to pursue a more aggressive approach is contingent on how open the building owner is to such an approach. In

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[17] Based on R.S. Means historical cost data for a 2- to 4-story commercial office building. A factor for project location (1.05 for Seattle) and construction year (calculated based on historical indices for Seattle of 171.4 and 194.3 for 2007 and 2011, respectively) were applied to the reported costs.

the case of the David Brower Center, the Center was indeed open to a low-energy cooling alternative and agreed to accept relaxed thermal comfort requirements and a range of passive design strategies from the project start.[14]

4.3.2. Cost

During the late design phase and early construction administration phase on the project, construction costs were increasing rapidly. Following a decade of modest construction industry inflation averaging between 1 and 3% per year, inflation rate jumped to 10% during 2004, largely driven by a 31% increase in structural steel prices (Grogan, 2005).[18] The 2005 inflation rate remained above normal at 5% due to double-digit price increases for gypsum wallboard and copper piping (Grogan 2006a; Grogan 2006b).[18] The project cost was 20 to 30% over budget, and the design team spent nearly a year trying to reduce cost. There were many times when they were not sure whether the building would even get built.[14]

Despite an extensive value engineering (VE) phase, the exterior shading remained in the project. However, the light-redirecting elements, which had been proposed to enhance occupant visual comfort by improving light uniformity head been eliminated. The question of why the shading survived the VE phase while the light-redirecting elements did not is difficult to answer. According to the mechanical engineer, the shading plays a key role in keeping the cooling loads low and had made it possible to eliminate the need for a chiller. The project architect, stated that systems at the David Brower Center that were doing more

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[18] Construction increases based on the Building Cost Index (BCI), computed based on a weighting of 64% for labor, 20% for steel, 14% for lumber and 2% for cement.

than one thing, e.g. were key to building performance, structure, and aesthetics, survived the value engineering phase, while the items that were stand-alone did not.[12] The exterior shading worked with the daylighting and the radiant ceiling cooling system and was thus not considered a viable place for value engineering. Nor was the photovoltaic array, as it performed the dual-role of sunshading and power generation while contributing to the signature look of the building parapet. The light-redirecting glass on the other hand, only improved daylighting – this was one of the reasons why it was ultimately eliminated from the project.[12]

Indeed, discussions with design professionals on other projects where exterior shading survived through the project value engineering phase reveal that in these projects shading was integrated with the project's mechanical system design (Zelenay et al, 2011). For instance, the shading system at Sidwell Friends School Washington, D.C was never thought of by the design team or client as a separate "added" cost:

> [The shading system] was conceived as an integral component of many passive and active systems dedicated to reducing the energy use and operating costs of the building. These components, with only a few exceptions, were never separated from each other and analyzed in terms of life cycle costs on a separate, case-by-case basis. They were analyzed and presented to the client holistically as a total, integrated system (As cited in Zelenay et al., 2011, p. 30).[19]

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[19] Whitney, Carin (2009, August 18). Personal correspondence with communications director, at KieranTimberlake.

The David Brower Center's daylighting consultant notes that based on the firm's experience with past projects for which shading was considered, if a discussion "revolves around a normal air-based cooling system, and one performs simple payback calculations based on annual energy savings, the payback periods are never short enough to satisfy the average developer. One needs to change the conversation to a system choice discussion, and a thermal and visual comfort discussion." [14] Many clients do not understand the benefits associated with such approaches, but are also unwilling to pay the additional design fees to carry out more detailed analyses that would illustrate these benefits.

The argument that the exterior shading remained in the project because it was a multi-functioning element required to minimize cooling loads may however be overly simplistic. According to the daylighting consultant, the decisions made during the design process do not follow a linear process, and that in the case of the David Brower Center, the delivery process governed the project more than any specific project aspect. While performance helped shape and inform the building, many other factors, such as cost, risk, and the designer's and client's priorities did as well.

4.3.3. Visual Comfort and Daylighting

While the benefit of light-redirecting elements is often difficult to quantify, these elements can play an important role in ensuring more uniform light distribution in a space, especially in spaces with low floor-to-ceiling heights where it is more difficult to bring light deep into a space. Excessive contrast ratios, i.e. greater than the 1:10 ratio between the task and remote (nonadjacent) surfaces in the field of view recommended by the Illuminating Engineering Society of North America (IESNA), can lead to decreased visual performance and the perception that lighting levels are insufficient, even if they are above the standard design target of 500 lux.[14] For this reason, the David Brower Center's daylighting consultant proposed a number of strategies to help improve daylighting uniformity in the space. The top surface of the fixed exterior shading, which itself contributes to improved daylight uniformity by blocking direct sun, was supposed to be as reflective as possible in order to redirect light into the space, while the underside of the shading was supposed to be a 30% gray to ensure visual comfort. In the end however, all shading surfaces were painted the same color for cost reasons. The two additional strategies – an Alanod reflector lightshelf on the south facade and Serraglaze light-redirecting film on the north facade were also proposed in order to improve lighting uniformity by redirecting light unto the ceiling. The geometry of the Alanod lightshelf was developed to ensure that light was reflected into the space. The Serra glazing was to be built into an awning-type metal frame assembly positioned below the exterior soffit at the 3rd floor. It was proposed that it be angled 75 degrees relative to the horizontal as opposed to installed vertically in order to increase the angle of incidence on the ceiling and allow the light to penetrate deeper into the space.

In order to ensure that at least some daylighting would enter the space in the event occupants lowered interior shading, the daylighting consultant recommended fabric roller shades for the project. In contrast to a fully closed venetian blind, roller shades transmit some light into the space even when lowered.[14] In the presence of direct sun, Loisos + Ubbelohde generally recommends a 3% openness factor, which corresponds to a visible light transmittance of approximately 15% since the fabric itself transmits light. While with proper slat adjustment, venetian blinds work well by redirecting light towards the ceiling, most occupants do not adjust blinds frequently enough to take advantage of daylighting.[14] While

An automated exterior venetian blind system could have resolved concerns associated with occupant interior shading control, however it is of course more expensive and requires considerably more maintenance than a manually-operated interior system.

In summary, daylighting uniformity is as critical as illuminance level to attaining a well-daylit space. In the typical office space it is the luminance ratios within the visual field in combination with the absolute illuminance at the worksurface that drive the occupant's perception of daylight availability. By ensuring that the luminances ratios of the different surfaces in the visual field are within a certain range we allow the iris to adjust to the lower illuminance on the worksurface and take full advantage of available daylight. [14] An environment meeting occupant's visual comfort needs can result in reduced occupant reliance on interior shading and minimize the risk of continuously deployed interior shading. This in turn can ensure better daylighting and views to the outside. It is thus preferable that potential sources of visual discomfort be largely resolved through facade design strategies other than occupant-controlled interior shading. The selection of appropriate glazing and fixed or adjustable exterior shading, light-redirecting elements, surface finishes, and office layout can be used in combination to minimize contrast ratios and ensure daylight uniformity in the space.

5. OCCUPANT COMFORT SURVEY

In an effort to understand occupant satisfaction with daylighting and visual comfort in the Center's south-facing office spaces with fixed exterior shading, the results of an occupant comfort survey, previously administered by the Center for the Built Environment (CBE) at the University of California – Berkeley, were analyzed (CBE, 2006).

The CBE occupant comfort survey, developed in 1990, serves as a valuable tool for characterizing building performance. Organized around seven key areas related to the indoor environment – thermal comfort, air quality, acoustics, lighting, cleanliness, spatial layout, and office furnishings, the survey serves as a powerful diagnostic tool for obtaining feedback from occupants regarding the design and operation of a building (CBE, 2009). The survey's automated reporting structure through a web-based interface allows for easy data collection. Additional modules with questions on specific aspects of the building design and performance can be added to the core survey, including modules encompassing more detailed questions on thermal comfort, daylighting, facade, or mechanical system performance. Since its development, the core survey has been implemented in over 475 buildings with over 51,000 individual occupant responses (as of October 2009). Survey results serve as the foundation for a comprehensive database for benchmarking buildings.

5.1. METHODS

For the purposes of this study, the responses from a CBE comfort survey administered to David Brower Center occupants in spring of 2010 are reviewed in order to establish the following: [20]

1. Do occupants use interior roller shade?
2. Why do occupants lower and/or raise the shades?
3. What is the approximate frequency with which the shades are deployed?
4. Do open-ended comments include any references to daylighting, visual comfort or shades?

Out of 150 total building occupants, 49% (73 respondents) completed the web-based survey. While building management had sent out an e-mail to all occupants with the survey website address, start date and end date, participation in the survey was voluntary and anonymous. Survey results are stored in a structured query language (SQL) database that does not contain any identifiers of the individuals who took the survey. Each survey-taker is assigned an anonymous identification number, making it possible to group results by respondent without revealing their identity.

The survey covers a number of areas, ranging from occupant workspace description and satisfaction with interior furnishings to indoor air quality and thermal comfort. Since many of the questions posed in this comprehensive survey are only remotely related to the research question, only select sections of the survey are discussed in the analysis section –

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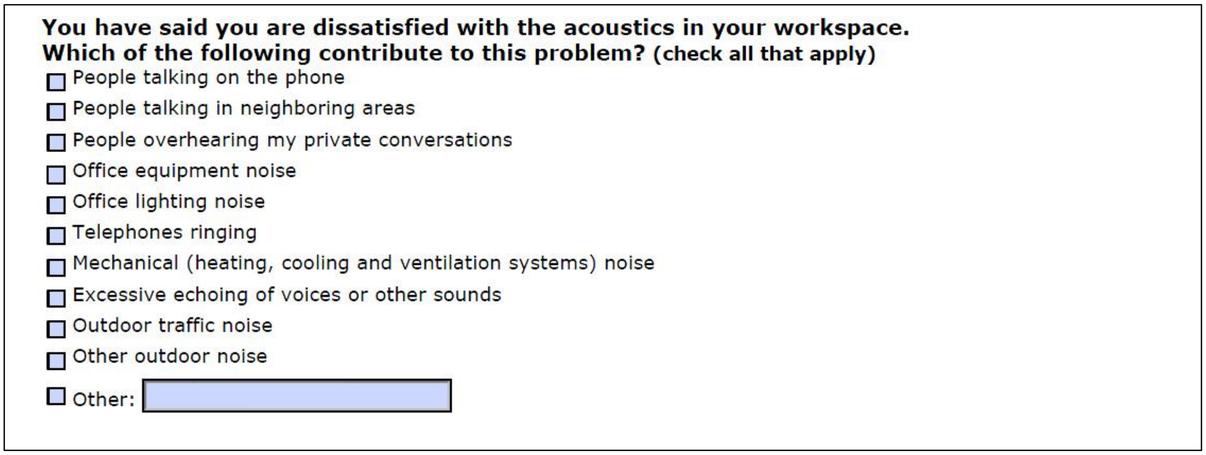
[20] The survey was administered by the Center for the Built Environment between March 22, 2010 and April 9, 2010.

sections on background, workspace description, lighting and visual comfort, and interior shading.

The survey consists of three main types of questions: questions asking how satisfied the occupant is with a specific aspect of the environment (**Figure 15**), questions asking them to select a specific answer from a list of options (**Figure 16**), and open-ended questions, where the subject can provide additional information in a comment box. A ”satisfaction” question asks the occupant to specify the degree of satisfaction based on a 7-point scale, ranging from -3 to +3, where +3 implies “very satisfied,” “+2 “satisfied,” “0” “neutral,” “-3” “very unsatisfied,” etc. (**Figure 15**). Respondents who indicate dissatisfaction (“-3,” “-2,” or “-1” on the scale) with a particular aspect of their environment are branched to a follow-up “branching” question asking them about the causes of their dissatisfaction (**Figure 16**). Satisfaction ratings are tabulated for each point on the scale (**Figure 17**).[21]

Figure 15 Satisfaction question from occupant comfort survey

[21] For more information on CBE's web-based Occupant Indoor Environmental Quality (IEQ) see http://www.cbe.berkeley.edu/research/survey.htm.


You have said you are dissatisfied with the acoustics in your workspace.
Which of the following contribute to this problem? (check all that apply)

- ☐ People talking on the phone
- ☐ People talking in neighboring areas
- ☐ People overhearing my private conversations
- ☐ Office equipment noise
- ☐ Office lighting noise
- ☐ Telephones ringing
- ☐ Mechanical (heating, cooling and ventilation systems) noise
- ☐ Excessive echoing of voices or other sounds
- ☐ Outdoor traffic noise
- ☐ Other outdoor noise
- ☐ Other:

Figure 16 Branching question from occupant comfort survey

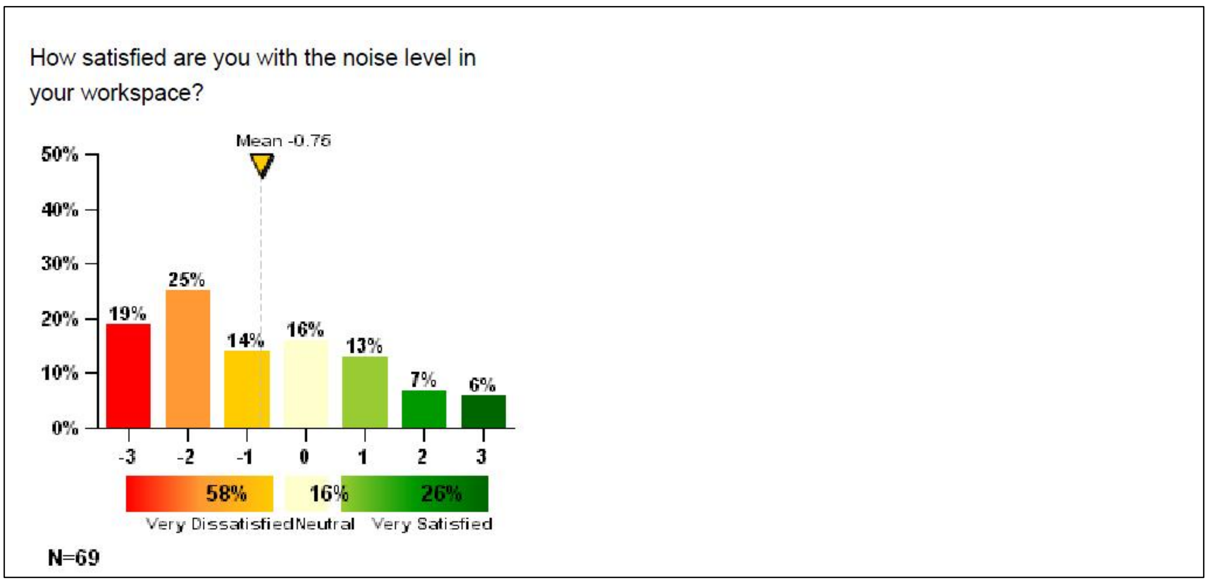


Figure 17 Tabulated survey results

5.2. FINDINGS

Occupant comfort survey results are included in *Appendix C*. Since the questions posed by this thesis are pertinent only for occupants in spaces with fixed exterior shading, survey results have been sorted to only include responses from subjects in south-facing office spaces on the 2^{nd} and 3^{rd} floors. Out of the 73 total respondents, 22% (N=16) are located in the south-facing office spaces on the 2nd or 3rd floor –only responses from these respondents are discussed in the following sections.

5.2.1. Background

Survey results show that 81% of the respondents located in south-facing office spaces with fixed exterior louvers on the 2nd and 3rd floor had occupied the building between 7 and 12 months (at the time the survey was administered) and that 75% of the respondents spent more than 30 hours per week in their workspaces.

5.2.2. Workspace description

Two-thirds of respondents (N=11) sit on the 3rd floor, with the remaining 1/3 (N= 5) sitting on the 2nd floor. 75% of respondents (N=12) sit within 5 ft of a window, two sit between 5 and 15 ft of a window, and another two more than 15 ft from a window. The majority of respondents sit in shared offices (**Figure 18**).

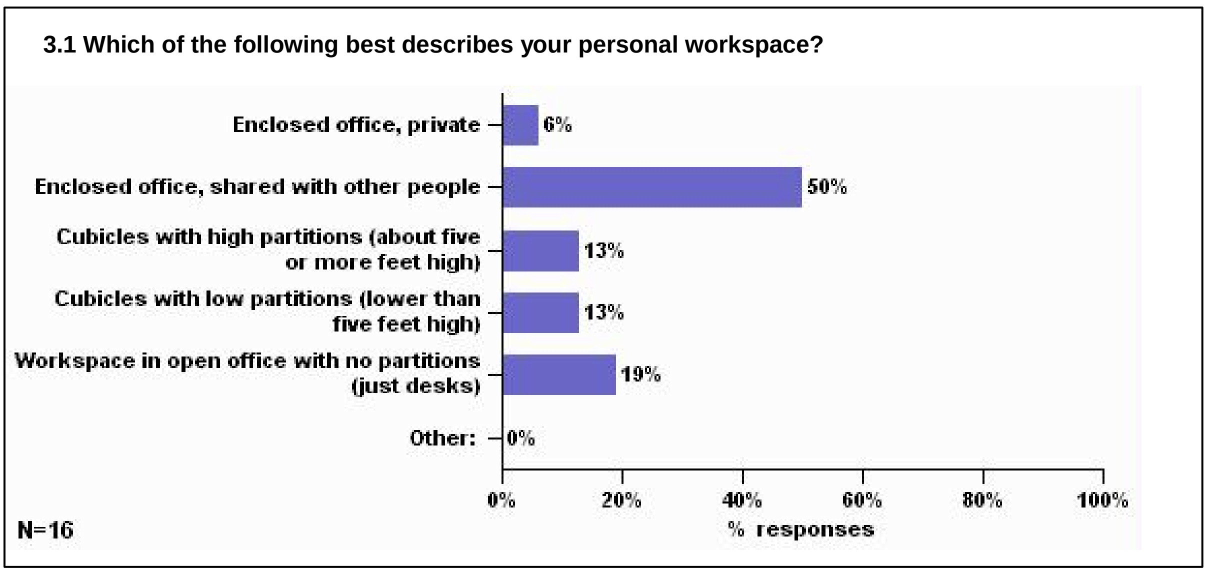


Figure 18 Workspace type (offices with louvers)

5.2.3. LIGHTING AND VISUAL COMFORT

Daylight levels. The survey results indicate that 63% (N=10) of the occupants in the 2nd and 3rd floor south-facing office spaces are either satisfied or very satisfied with the amount of daylight in the space (**Figure 20**). Three occupants stated however that they are either moderately or very dissatisfied with the amount of daylight. One of the subjects cited their workspace location (too far from the window) as the source of their dissatisfaction, while the other two cited insufficient amount of daylight, and more specifically a lack of direct sunlight, as the primary reason for dissatisfaction. One of them stated in the open comment box that there is "not enough DIRECT sunlight. horizontal exterior installations block it," while the other person stated that there is "very little direct sunlight; don't see sun during day except early morning." Interestingly, both of the occupants who had expressed dissatisfaction with the lack of direct sunlight sit within 5 ft of the window. In the context of the whole building, this question scored somewhat low, since the mean satisfaction score for the whole building is 1.89 (**Figure 19**) compared with 1.13 (**Figure 20**) for the respondents in offices with shades.

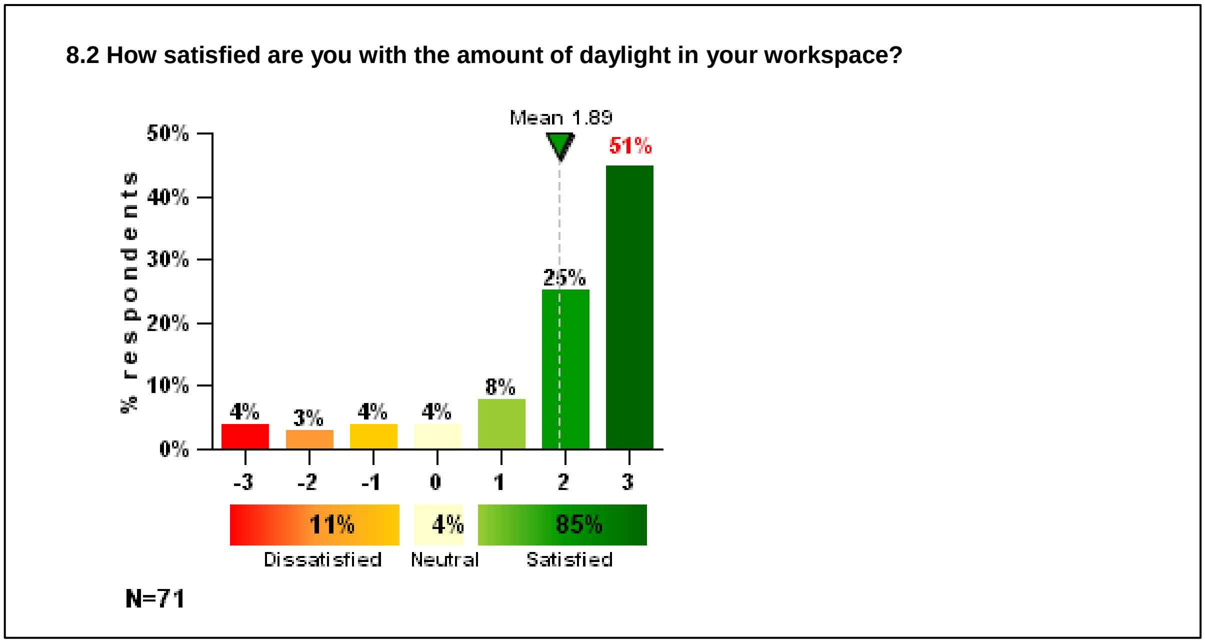


Figure 19 Daylight levels (whole building)

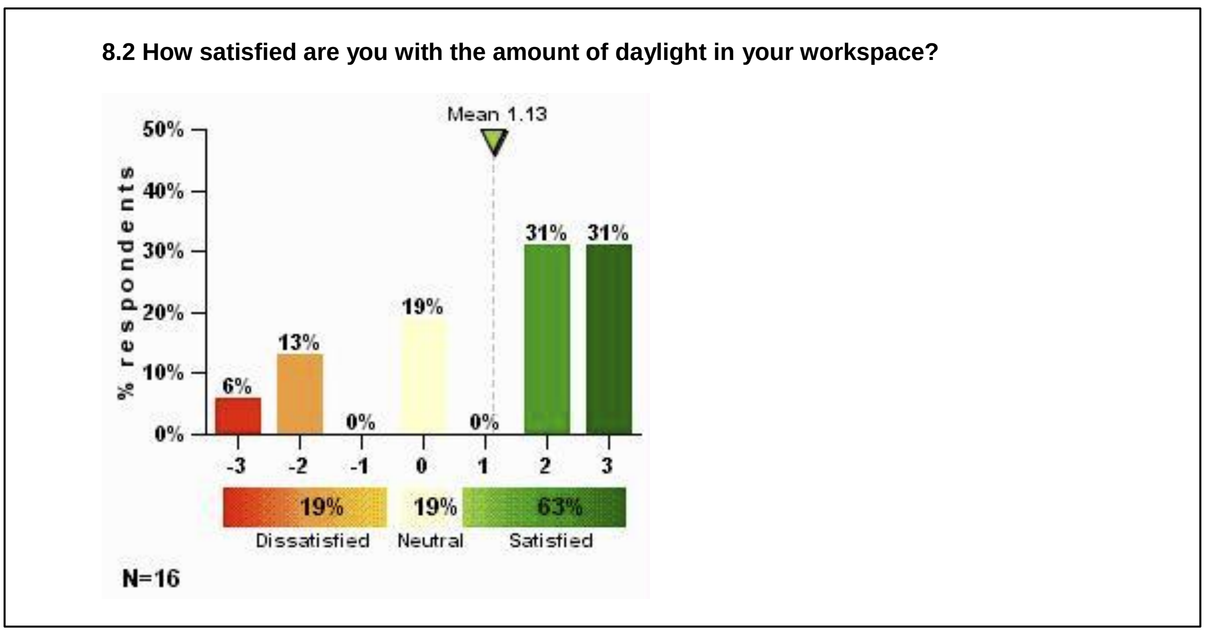


Figure 20 Daylight levels (offices with louvers)

Electrical lighting levels. Results indicate that occupants are satisfied with the amount of electrical lighting, with only one of the occupants – an occupant sitting more than 15 ft away from the window, expressing dissatisfaction. The respondent stated that while they do not like the overhead lighting and that the task lighting is too hot.

8.3 How satisfied are you with the amount of electric light in your workspace?

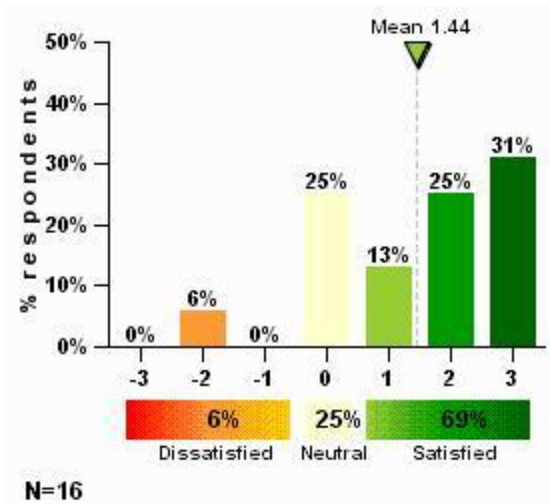


Figure 21 Electrical lighting levels (offices with louvers)

Visual comfort. A third of respondents (N=5) stated that they are slightly or somewhat dissatisfied with the visual comfort of the lighting in their workspace (**Figure 22**). Three out of the five respondents listed daylight, while the remaining two respondents stated electrical lighting as the source of their discomfort (**Table 3**).

8.4 How satisfied are you with the visual comfort of the lighting (e.g., glare, reflections, contrast)?

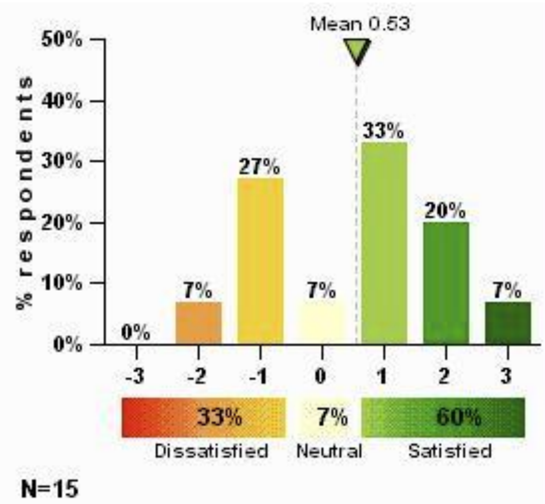


Figure 22 Visual comfort (offices with louvers)

Table 3 Sources of visual discomfort

Respondent	**Source**
1	Daylight reflecting on computer screen, glare from bright surfaces (walls, partitions, etc.)
2	Daylight reflecting on computer screen, other*
3	Daylight reflecting on computer screen, glare from windows
4	Flicker due to electrical lighting
5	Other*

* The reasons for discomfort given for the “other” responses (respondents 2 and 5) included automatic lighting controls and discomfort headache due to fluorescent lighting.

5.2.4. INTERIOR SHADING OPERATION

All 16 respondents sit in offices equipped with manually-operated interior roller shades (**Figure 23** and **Figure 24**). The majority of responses indicated that shades are generally closed less than 50% of the time (**Figure 25**). In fact, 40% of the respondents (N=6) indicated that shades are rarely closed – less than 25% of the time. Approximately half of the respondents (N=7) stated that they adjust interior shading one or more times per day. Occupants close interior shading primarily to control reflections on computer screens (**Figure 26**) and open interior shading to let in more daylight and see the view to the outside (**Figure 27**).

Figure 23 Interior roller shades in a southeast-facing 2nd floor suite

Figure 24 Interior roller shades in a south-facing 3rd floor suite

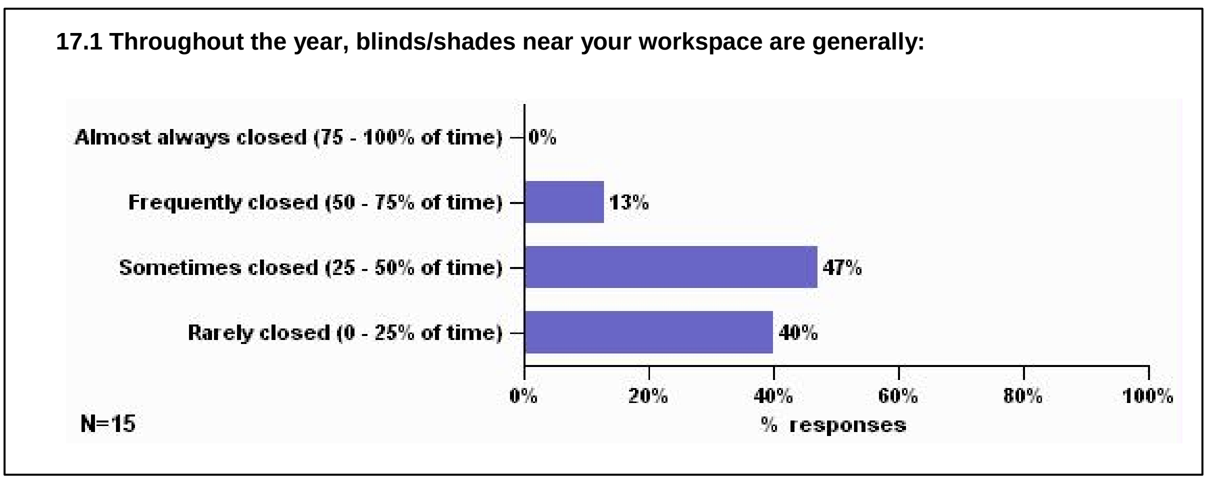


Figure 25 Interior shading deployment (offices with louvers)

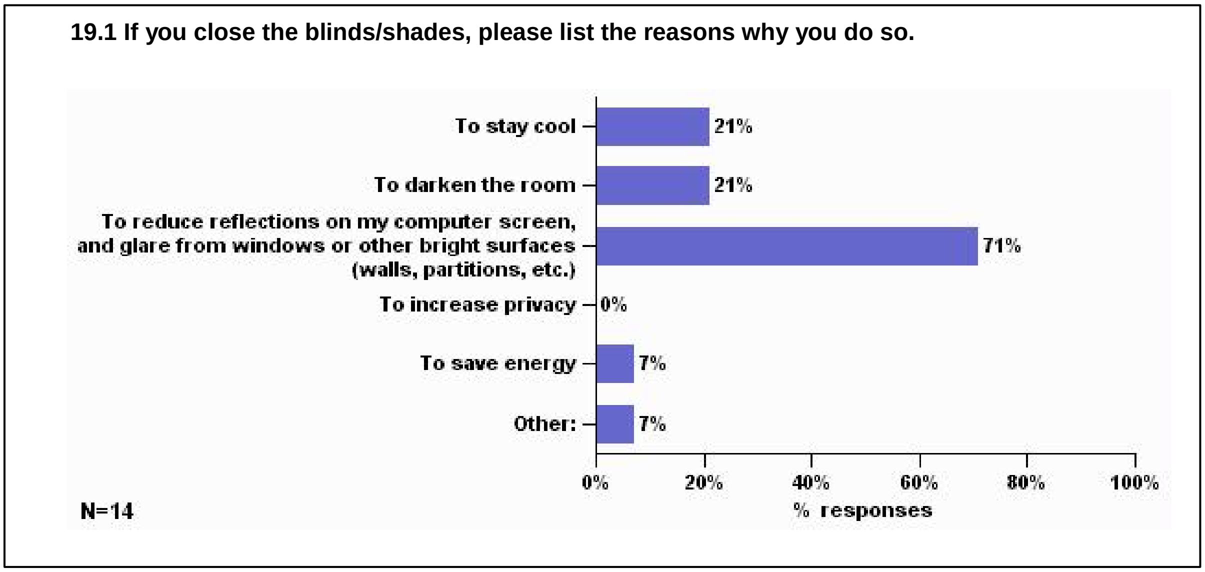


Figure 26 Reasons for closing interior shading (offices with louvers)

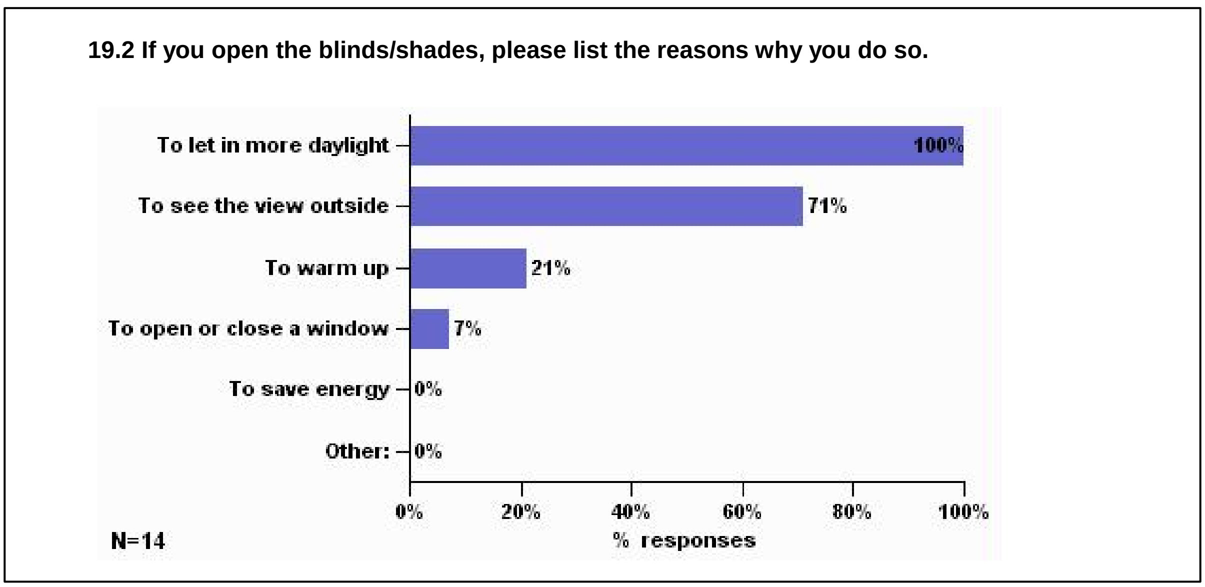


Figure 27 Reasons for opening interior shading (offices with louvers)

5.3. DISCUSSION

The primary focus of this survey was an assessment of occupant satisfaction with daylight levels, visual comfort, and occupant operation of interior shading (reasons for use and frequency of use). Since the focus of this thesis is the impact of the exterior aluminum louvers on performance, only survey responses from subjects in south-facing office spaces on the 2nd and 3rd floors are analyzed. While only 16 occupants residing in south-facing offices with exterior shading took the survey (not a statistically significant sample), the survey responses are revealing nonetheless and worthy of a brief discussion.

Approximately two-thirds (N=10) of occupants residing in offices with exterior louvers (N=16) are satisfied with daylighting in their workspace. Half of the dissatisfied occupants cited visual discomfort (N=3), while the other half cited insufficient daylight (N=3) as the source of their dissatisfaction. Daylight ratings from dissatisfied occupants along with their location with respect to the window and sources of dissatisfaction are summarized in **Table 4**. Out of those dissatisfied with daylight levels, one respondent (a respondent sitting more than 15 ft away from the window) stated that there is too little daylight. The other two respondents, both sitting within 5 ft of the windows, felt that the fixed exterior shading blocks too much daylight and that they would like to have some direct sunlight in their workspace. While this suggests that direct sunlight is desired by some occupants, at least at certain times, it could not be determined from the survey when and why it is desired. It should be noted that the time of year when the survey was administered (late March) follows a winter period characterized by mostly cloudy skies and frequent rain.

Interior shading is used by 50% of the occupants on a daily basis. Survey results suggest that while there are times when interior shading needs to be deployed for visual comfort reasons, much of the time interior shading is not required. Shading remains open between 50 to 75% of the time according to half of the respondents, and more than 75% of the time according to the other half of respondents. Occupants close interior shading primarily to control reflections on computer screens and/or glare from bright surfaces. This suggests that on-site monitoring of shade operation within the space is likely to be a good indicator of when occupant visual comfort needs are not met.

While occupant reliance on interior shading is relatively low (see section 5.2.4 *Interior shading operation)*, suggesting that visual comfort needs are met most of the time, three respondents (19%) did express dissatisfaction with visual discomfort. Sources of discomfort included daylight reflecting on the computer screen and glare from bright surfaces (walls, partitions, etc.). While this suggests that the exterior shading alone is not a sufficient strategy for ensuring visual comfort, it is unclear whether the occupants experience discomfort even when interior shading is deployed.

In summary, the survey reveals the following about occupants in south-facing office with exterior louvers:

- 38% (N=6) of respondents (N=16) are dissatisfied with either visual comfort due to daylight or the amount of daylight.
- Two respondents are dissatisfied with the amount of daylight and would have liked more direct sunlight at their workspace.
- While roller shades are raised much of the time, there are times when occupants lower the shades to meet visual comfort needs.
- The primary source of dissatisfaction with visual comfort are computer screen reflections due to daylight.
- Occupants lower shades primarily to control reflections on computer screens and/or glare from bright surfaces.

- Occupants raise shades in order to let in more daylight, most also open shades to see the view outside.

Table 4 Sources of dissatisfaction with daylight

Resp. #	Amount daylight rating	Visual comfort rating	Location	Reason for dissatisfaction
1	2	**-2**	Less than 5 feet	Daylight reflecting on my computer screen, glare from bright surfaces (walls, partitions, etc.)
2	2	**-1**	Less than 5 feet	Daylight reflecting on my computer screen, visual discomfort due to electrical lighting
3	2	-**1**	Less than 5 feet	Daylight reflecting on my computer screen, glare from bright surfaces (walls, partitions, etc.)
4	**-2**	-1	Less than 5 feet	Not enough daylight (no direct sunlight), visual discomfort due to electrical lighting
5	**-3**	2	Less than 5 feet	Not enough daylight (no direct sunlight)
6	**-2**	0	More than 15 feet from window	Not enough daylight (too far from window)

6. FIELD STUDY

A three-week field study of a representative south-facing office space was conducted from the end of November to mid-December in order to understand how occupants operate interior shading and lighting, and to provide reference measurements for the development of the computer model. A series of sensors, data loggers, and a camera programmed to take time-lapse photographs were temporarily installed in the space to monitor occupancy, lighting and shading control. Measured data from the office were compared with results from the computer simulation runs in order to determine how close the computer predictions were to the field-measured values. The following sections discuss the space selection criteria and experimental setup in more detail.

6.1. METHODS

6.1.1. SPACE SELECTION CRITERIA

A single south-facing office space was selected for a more detailed analysis entailing a combination of site measurements and computer simulation of daylight in the space. Since only the second and third floor office spaces have fixed exterior louvers, only offices on these floors were visited. A total of three offices meeting these criteria were visited in October 2010:

1. A small two-occupant office on the 2^{nd} floor
2. An 8-workstation open plan suite on the 2^{nd} floor
3. A large suite with partially enclosed two- to three-occupant spaces on the 3^{rd} floor

Since one of the objectives of the site measurement phase was to survey occupant control of shading and lighting, the two larger offices were proposed as candidate spaces for the study since these larger offices had more occupants and hence a bigger possible sample of subjects. Between the two larger suites, the 2nd floor suite was selected, because this suite provided a more open layout (**Figure 28** and **Figure 29**). Moreover, the offices on the west end of the 3rd floor suite looked out directly onto a highly reflective roof of an adjacent building, an untypical exterior condition for the David Brower Center.

Figure 28 View out window

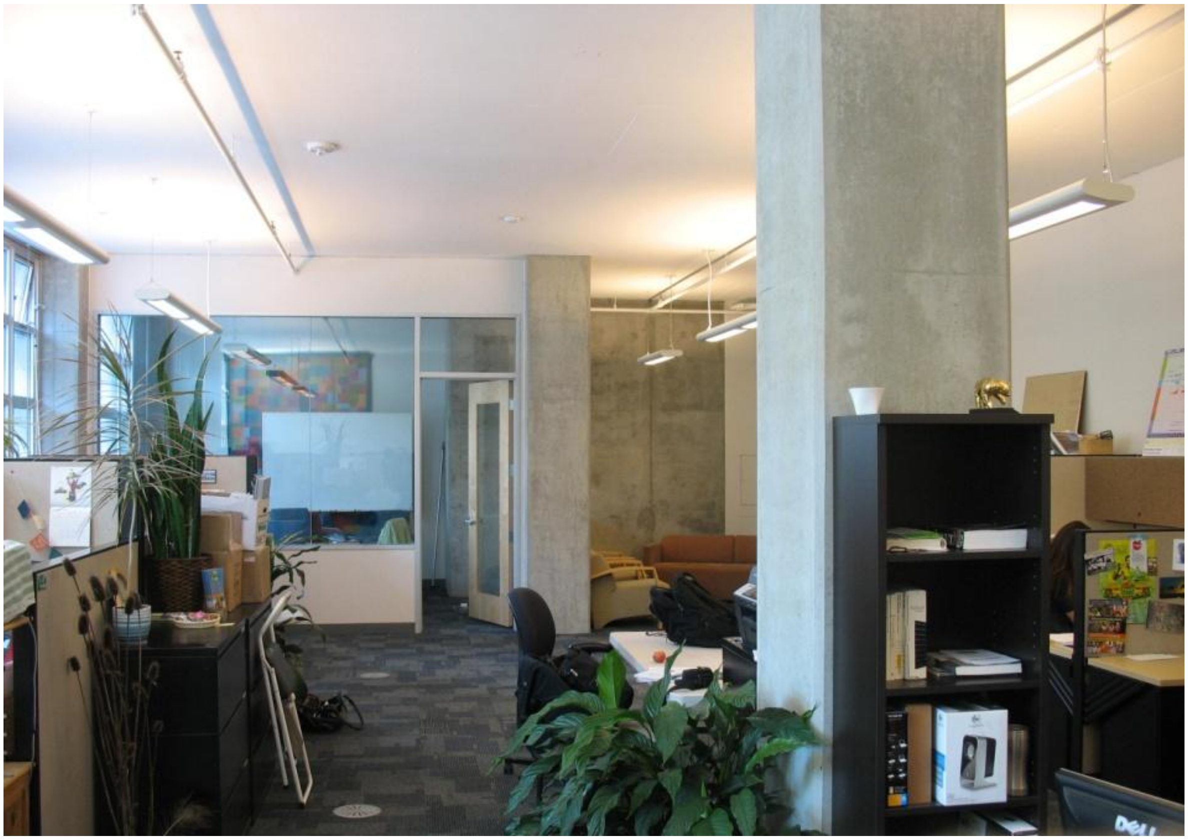
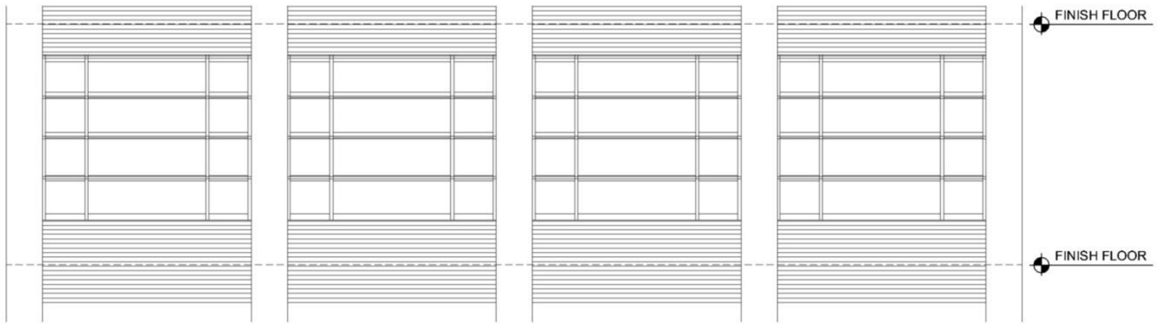
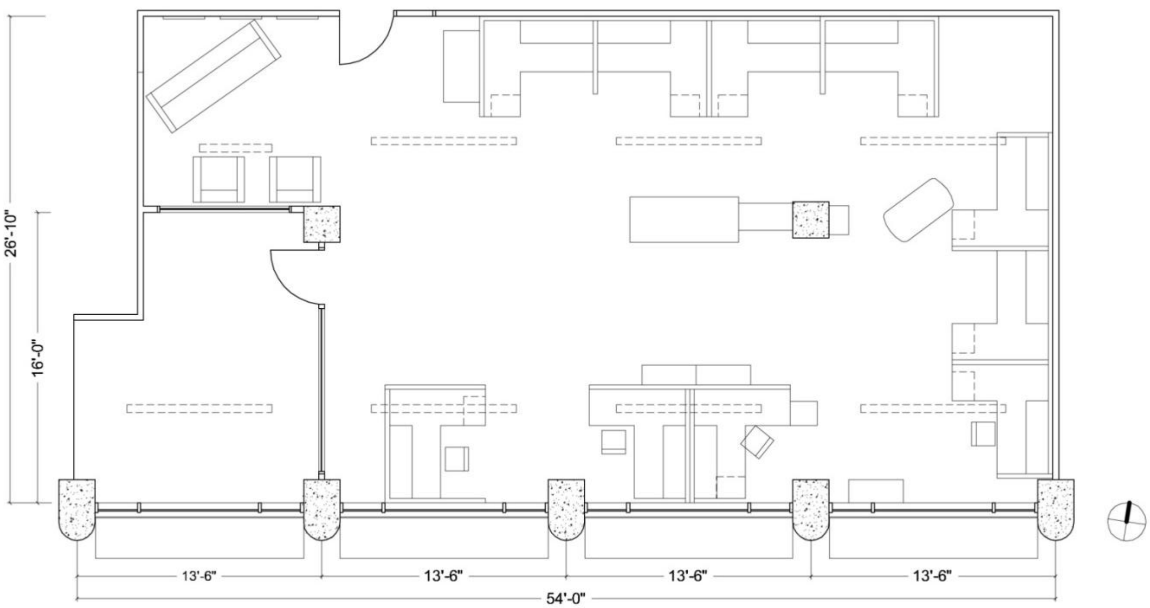


Figure 29 View towards conference room

6.1.2. SPACE DESCRIPTION

The office space selected for the study is a 40 ft by 27 ft open-plan suite on the second floor with an adjacent 14 ft by 16 ft conference room (**Figure 28**). Four of the ten workstations are located at the perimeter of the space, two are located along the wall at the west end of the space, and the remaining four workstations are located at the rear of the space, 25 ft inboard of the facade. An exterior elevation of the office, a plan with the workstation layout, and a section through the exterior wall are included in **Figure 30**, **Figure 31**, **Figure 32**, respectively.





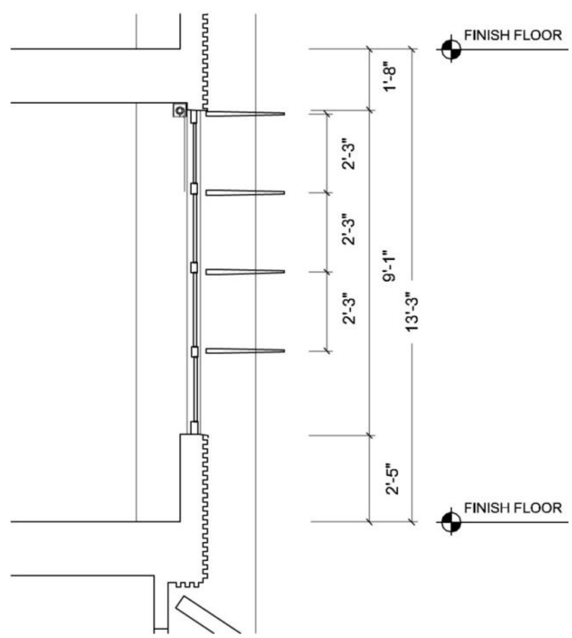


Figure 30 Exterior elevation (top)

Figure 31 Office plan (middle)

Figure 32 Section through the exterior wall (right)

6.1.3. Occupancy, lighting, and shading control monitoring

The test period was scheduled for the three weeks preceding the winter solstice (Nov. 24th through Dec. 16th). This period was selected because a direct sunlight analysis conducted prior to the measurement phase revealed that in contrast to summer months, some direct sunlight hits the facade in the morning and afternoon (see **Figure 49** in section 6.2.1 *Exterior illuminance and sky conditions* under field study findings). Illuminance levels, occupancy, overhead electrical lighting use and shading control were all monitored during the three-week test period using several different types of sensors, data loggers, and a camera programmed to take time-lapse photographs. Four perimeter workstations – workstations at which occupants were most likely to be affected by direct sunlight (e.g. direct sunlight falling on the occupant, glare from windows, reflections on computer screens, etc.), were selected for closer monitoring (see equipment setup diagram in **Figure 33**).

Occupancy. InteliTimer Pro (IT-200-PC model) Watt Stopper loggers were mounted below each of the four workstations to monitor occupancy. The sensors were mounted so that they would only "see" the occupant at the particular workstation (**Figure 34**) and were set to "timeout" after 15 minutes of no movement, meaning that if the sensor detected no movement over the course of a 15-minute period, it would log the time along with the condition ("unoccupied") to the logger memory. However, as soon as the sensor detected any movement, the time along with the state ("occupied") would be immediately logged to logger memory. Thus, while the "unoccupied" period could be as short as 1 minute, there could never be an occupancy period of less than 15 minutes, even if the occupant was present at their desk for less than 1 minute. While setting the occupancy timeout period to 5 minutes could have provided data at a greater resolution, this type of resolution was not necessary for the purposes of this study. Moreover, setting the logger to “timeout” after 15 minutes rather than 1 or 5 minutes resulted in the logging of fewer data points and thus ensured that logger memory (with a capacity of 4096 log points) would not become full before the end of the logging period. Off-site testing of occupancy loggers prior to field test indicated that the sensors reliably logged occupancy with a “timeout” period of 15 minutes.

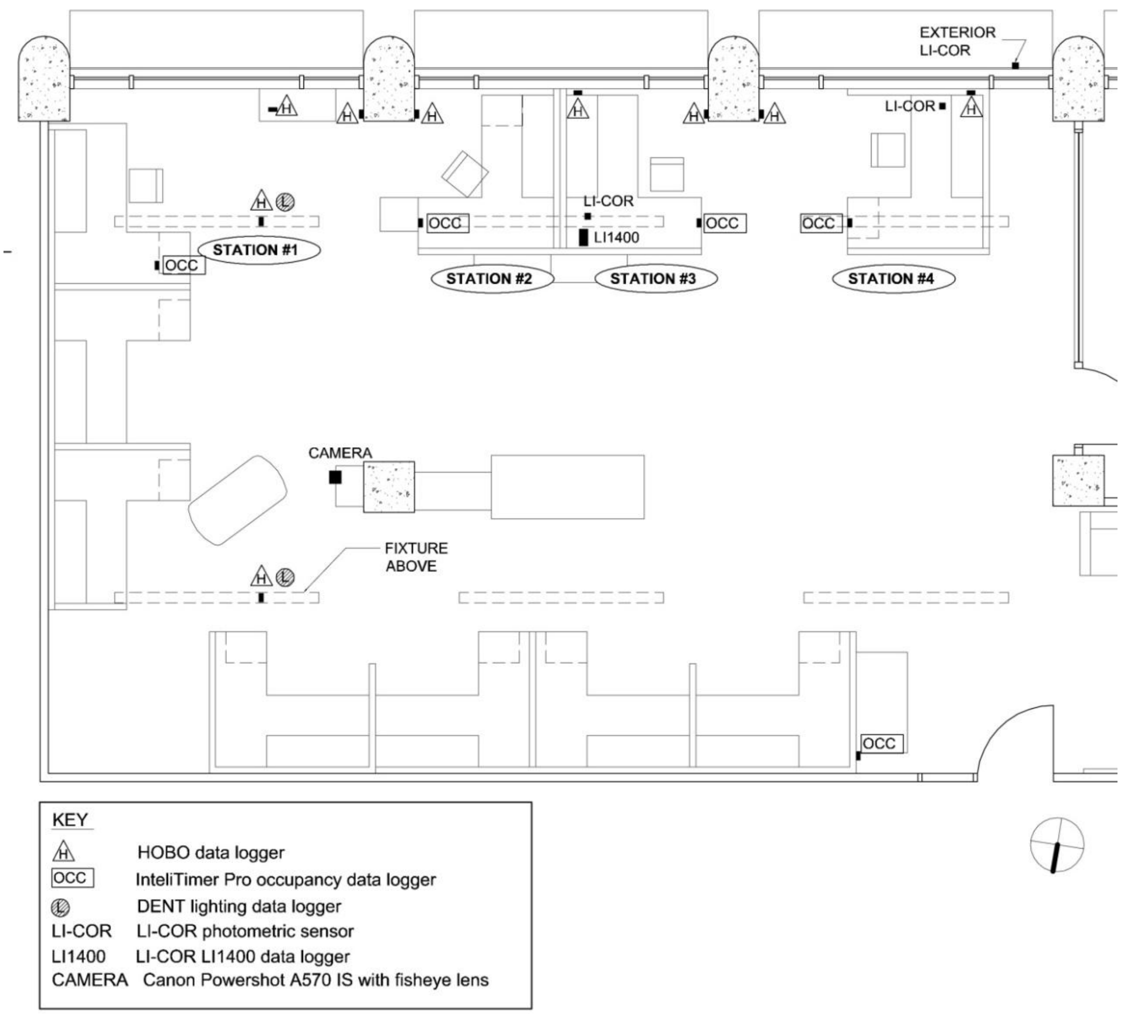


Figure 33 Equipment setup diagram

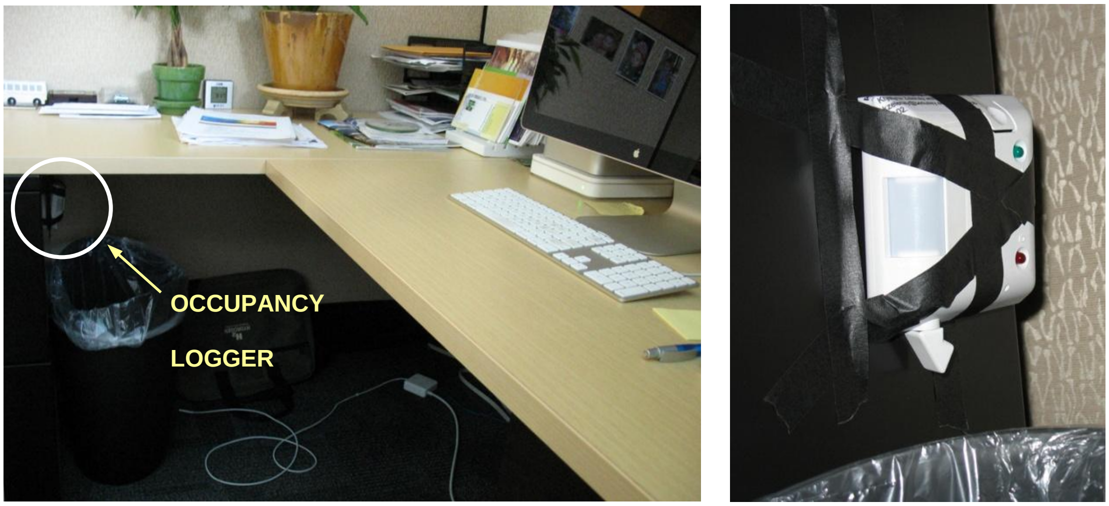


Figure 34 InteliTimer Pro Watt Stopper logger mounted below workstation

Lighting control. Overhead lighting in the monitored office consists of two rows of 96"-long light fixtures (each with two 32W T8 fluorescent bulbs) running in parallel with the facade (**Figure 33)**, manually controlled by users by a triple wall switch adjacent to the office entry door. Bi-level switching at each light fixture (a minimum code requirement for commercial buildings in California) as well as a separate switch leg along perimeter zone fixtures provide users with three possible overhead lighting settings: (1) one bulb in rear row of fixtures on, (2) one bulb in each row of fixtures on, and (3) all bulbs on (**Figure 35**).

Two Dent Instruments TOU-L lighting loggers (**Figure 36**) were mounted below each row of fixtures, one in the perimeter zone and one in the rear zone (see plan in **Figure 33** for location). In addition to the Dent lighting loggers, which measure the "on/off" status of lighting, two Onset HOBO U12 RH/Temp/Light data loggers were mounted below each row of fixtures in order to monitor light levels, which were in turn used to determine the active lighting setting out of the three possible settings. Since the HOBO U12 Temp/RH/Light loggers are designed to measure relative rather than absolute light levels indoors, the data collected by the logger is useful primarily for observing relatively large instantaneous changes in light levels, such as those associated with the on/off switching of electrical lighting.

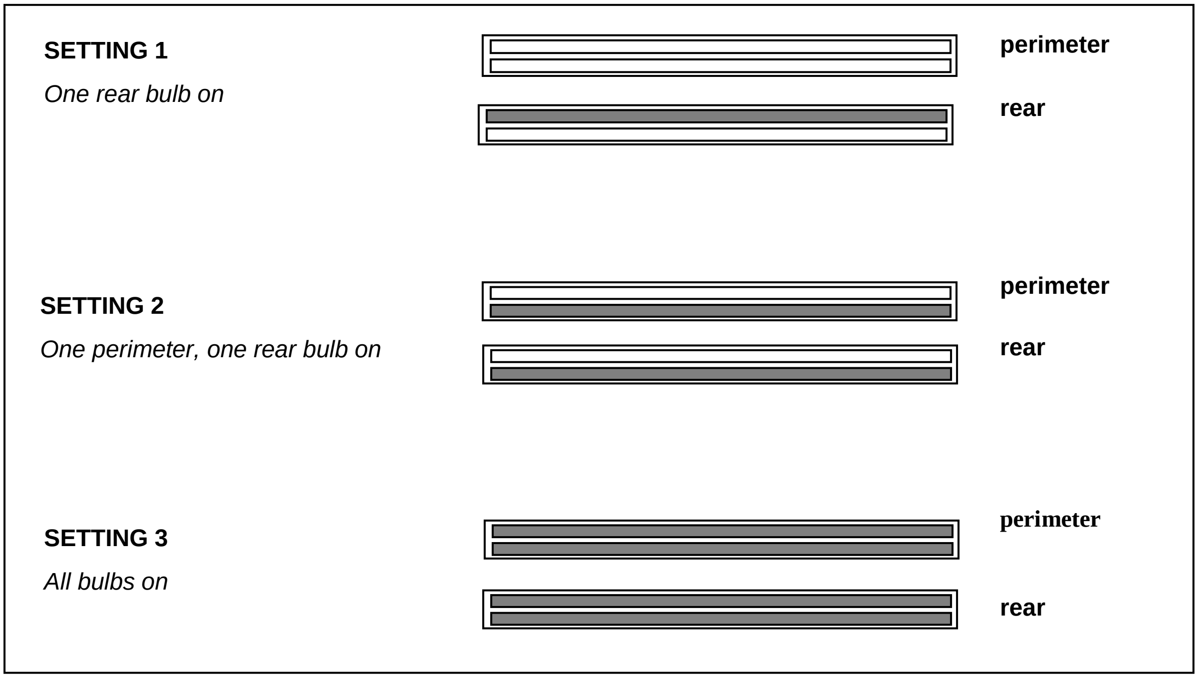


Figure 35 Overhead lighting settings

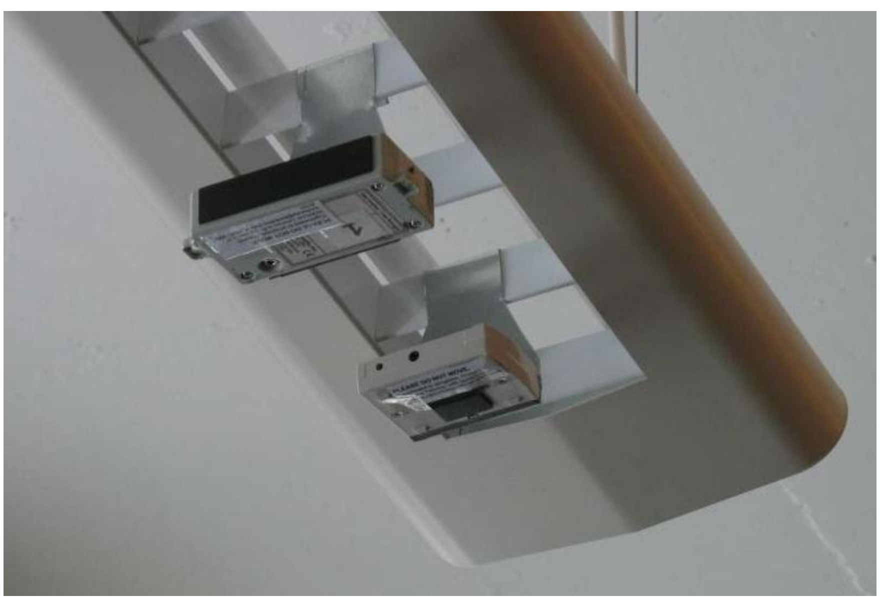


Figure 36 Dent lighting logger (left) and HOBO RH/Temp/Light data logger (right)

Interior shading operation. Roller shade operation was monitored using a Canon PowerShot A570 IS camera with a fisheye lens, programmed to take time-lapse photographs of the facade (**Figure 37**). In order to ensure occupant privacy, the camera was mounted securely on top of a bookshelf near the center of the room and oriented so that it would only "see" the upper portion of the windows (**Figure 38**). The camera was programmed to take a photograph of the facade and ceiling every 5 minutes through a script saved to a reformatted SD memory card.[22] The time-lapse photographs of the facade and ceiling also served as a supplemental source of information on lighting use and were used to confirm when lighting was on and whether one or both fixtures was on during the test period.

Since the time lapse photographs only reveal the upper portion of the shading, seven Onset HOBO U12 RH/Temp/Light data loggers were mounted 3 ft above the window sill, several inches inboard of each roller shade, to monitor the lower portion of the window (**Figure 39**). Tests conducted prior to equipment installation, indicated that a change in the logged vertical illuminance could be used to determine whether roller shades had been deployed past the HOBO data logger.

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[22] To learn more about automating a camera through the SD memory card and software required for formatting the SD card for scripting, visit http://chdk.wikia.com/wiki/CHDK for information on the Canon Hack Development Kit, or the StereoData Maker site at http://stereo.jpn.org/eng/sdm/index.htm.

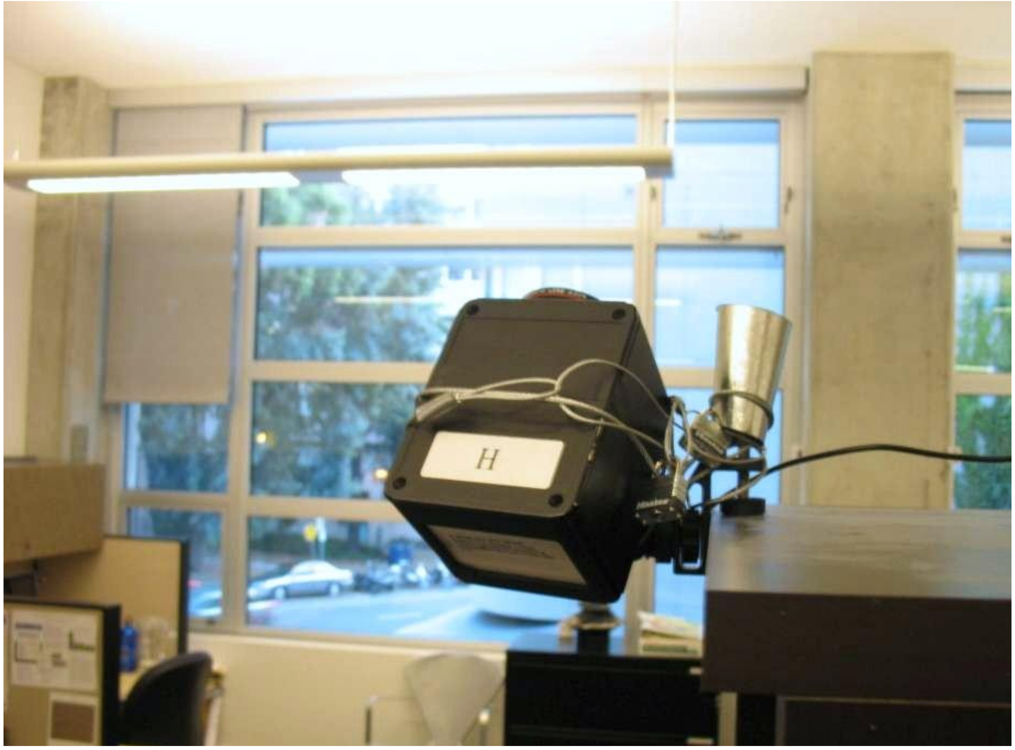

Figure 37 Fisheye lens camera used for monitoring shade and lighting control

Figure 38 Fisheye lens photo of upper portion of facade and ceiling

Figure 39 HOBO RH/Temp/Light data loggers used for monitoring shade deployment

6.1.4. ILLUMINANCE MEASUREMENTS

Indoor illuminance levels. Two LI-COR LI210SA photometric sensors (accuracy of ± 5%) were used to measure instantaneous global horizontal illuminance levels at two workstations. Illuminance levels were measured at the level of the worksurface at 5-minute intervals and logged to a LI-1400 data logger. Reusable adhesive putty was applied to the base of the LI-COR sensor mount to prevent the sensor from slipping on the work surface. The sensor further from the facade (workstation #3) was subject to more shading from surrounding objects (**Figure 40**).

Figure 40 LI-COR LI210SA photometric sensors mounted at workstation #3 (left) and workstation #4 (right)

Outdoor illuminance levels. Exterior illuminance measurements were collected in order to monitor outdoor sky conditions throughout the test period and to provide reference illuminance levels for assessing the accuracy of the computer daylight model. Prior to taking measurements, the accuracy of illuminance sensor readings was assessed under uniform lighting conditions in the overcast sky simulator at the Center for the Built Environment at the University of California – Berkeley (**Figure 41**). Sensor readings were compared to a reading taken with a Konica Minolta T-10 illuminance meter. All four of the sensor readings were within 1% of the actual illuminance level – 8400 lux (780 fc), three of which had readings within 0.5% of the actual illuminance level.

Simultaneous instantaneous measurements of horizontal global illuminance on the roof and vertical global illuminance on the facade were collected and logged at 5-minute intervals using LI-COR LI-210SA sensors and a LI-COR LI-1400 data logger (**Figure 42**). The facade sensor served as an intermediate checkpoint for assessing whether the surrounding site, especially the adjacent Oxford Plaza apartment building, which has a significant impact on the amount of daylight reaching the south facade of the David Brower

Center, had been modeled with sufficient detail. See section 7.1.2 *Model calibration* for a more detailed description of computer model calibration.

Figure 41 LI-COR photometric sensors in overcast sky simulator

Figure 42 LI-COR LI-1400 data logger

The roof sensor was mounted on top of an 11-ft-tall mechanical fence to ensure that the sensor had an unobstructed view of the sky and no shading from adjacent buildings and roof equipment (**Figure 43** and **Figure 44**). The facade sensor was mounted on the exterior wall of the office space, 28 in. from the centerline of the nearest column and 18 in. below the window sill (**Figure 45**).


Figure 43 (left) Sensor used to measure global horizontal illuminance

Figure 44 (right) LI 1400 data logger at base of mechanical fence

Figure 45 Sensor used to measure vertical illuminance on the facade

Upon the completion of the data collection phase, the global horizontal illuminance data collected at the roof was analyzed using daylight and sunlight availability data for specific months and times of the day for San Francisco in order to determine the test period sky conditions – overcast, sunny, or intermediate. The vertical facade illuminance measurements taken on site were used to calibrate the computer model (discussed in section 7.1.2 *Model calibration*).

Sky conditions determined based on measured global horizontal illuminances were confirmed by reviewing 2-minute time lapse films of the San Francisco Bay Area acquired through University of California's Lawrence Hall of Science (LHS) website (University of California, n.d.). The time-lapse films, created daily as part of an ongoing project to help children understand the weather by correlating the view from LHS with weather data and satellite imagery, consist of a series of photographs of the bay area taken over a 24-hour period (**Figure 46**).

Figure 46 View of the San Francisco Bay Area from the Lawrence Hall of Science

6.2. Findings

The data collected during the three-week measurement period has been included in appendices D through H. The following sections discuss the results of occupancy, lighting and shading control monitoring, as well as exterior and interior illuminance data in detail. A dimensioned plan of the space is included in section 6.1.2 *Space description* while the measured material reflectances used for the computer model are included in *Appendix I*.

6.2.1. Exterior Illuminance and Sky Conditions

Global horizontal roof illuminance and vertical facade illuminance data collected at the David Brower Center are included in *Appendix D*. A sample graph for the week of Nov. 29th is included in **Figure 47**. The corresponding measured global vertical facade illuminance data is shown in **Figure 48**. In addition to the global horizontal illuminance collected on the roof, the graph shows reference illuminance data for clear and overcast days for Oakland and San Francisco, the two closest weather station locations. The Oakland illuminance data represents average hourly values obtained from a TMY3 file – data typically used in annual building energy and daylight simulations. The San Francisco data represents instantaneous illuminance data obtained from daylight availability tables; these hourly illuminances (included in *Appendix E)* are calculated based on the Robbins-Hunter daylight prediction model (Robbins, 1986). Instantaneous illuminance data for Berkeley or Oakland was not available. The two sources of illuminance data are discussed in more detail below.

Typical Meteorological Year (TMY) weather data. The TMY weather data set consists of hourly data for twelve typical meteorological months (January through December) taken from different years and concatenated to form a single year. The data sets are generated based on measured meteorological data and modeled solar values but can also contain interpolated values if original observations are missing (Wilcox & Marion, 2008). The TMY3 data set, covering years from 1991 to 2005, contains more recent and more accurate data than the TMY2 data set, which covers years from 1961 to 1990.[23] The illuminance data is calculated using luminous efficacy models developed by Perez, Ineichen, Seals, Michalsky, & Stewart (1990) and model inputs include direct normal radiation, diffuse horizontal radiation, solar zenith angle, and dew point temperature (Wilcox & Marion, 2008). The uncertainties associated with modeled average hourly illuminances for a clear sky are relatively low (1- 2%), however can be much higher for partly cloudy skies due to the variability of sky conditions over the course of one hour (Wilcox & Marion, 2008).[24] It should be noted that the irradiance and illuminance values are hourly averages calculated for the 60-minute period ending at the timestamp, thus 30 minutes was subtracted from each hour when graphing the TMY3 illuminance values against measured data (**Figure 47**). Thus, it is not surprising that the TMY3 values are slightly different from the instantaneous illuminance data measured on site. The discrepancy could however also be explained by differences in illuminances between Oakland and Berkeley.

Robbins-Hunter daylight model. The Robbins-Hunter daylight prediction model is a method for generating hourly and monthly illuminance data in a tabular format developed at the Solar Energy Institute (SERI) for the Department of Energy. The calculated illuminances are a function of location, cloud cover, sky clearness, turbidity, altitude above sea level, and

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[23] TMY data can be downloaded from the National Solar Radiation Database on National Renewable Energy Laboratory's website: http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

[24] The model uncertainty value does not take into consideration the uncertainty associated with the occurrence of the precise meteorological conditions used to model daylight availability (Wilcox and Marion, 2008).

a series of extraterrestrial illuminance monthly constants. Since the Robbins-Hunter model daylight availability tables only contained hourly illuminance values, missing values were linearly interpolated at 5-minute intervals for the purposes of graphing against measured illuminance data (**Figure 47**).

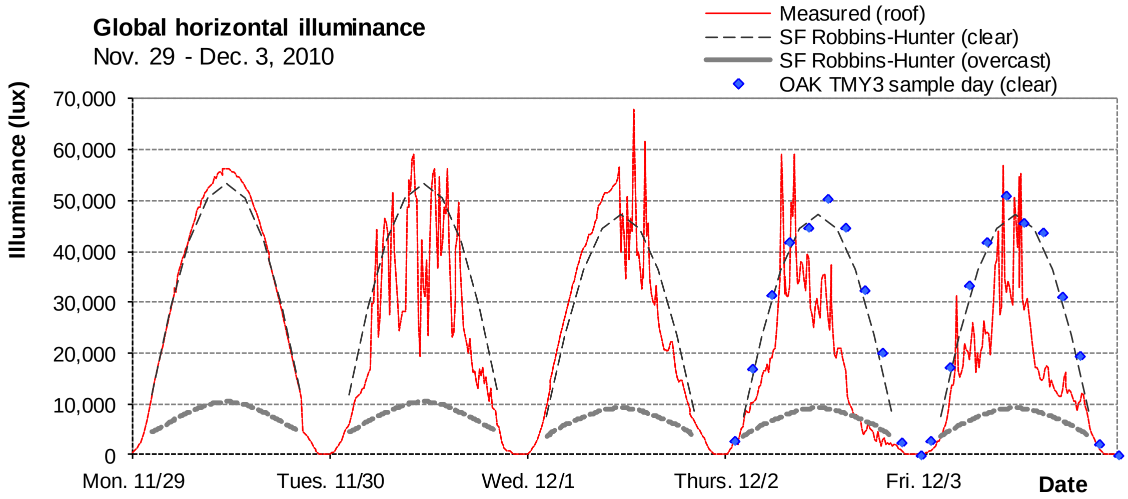

Figure 47 Global horizontal illuminance measured on roof (sample work week)

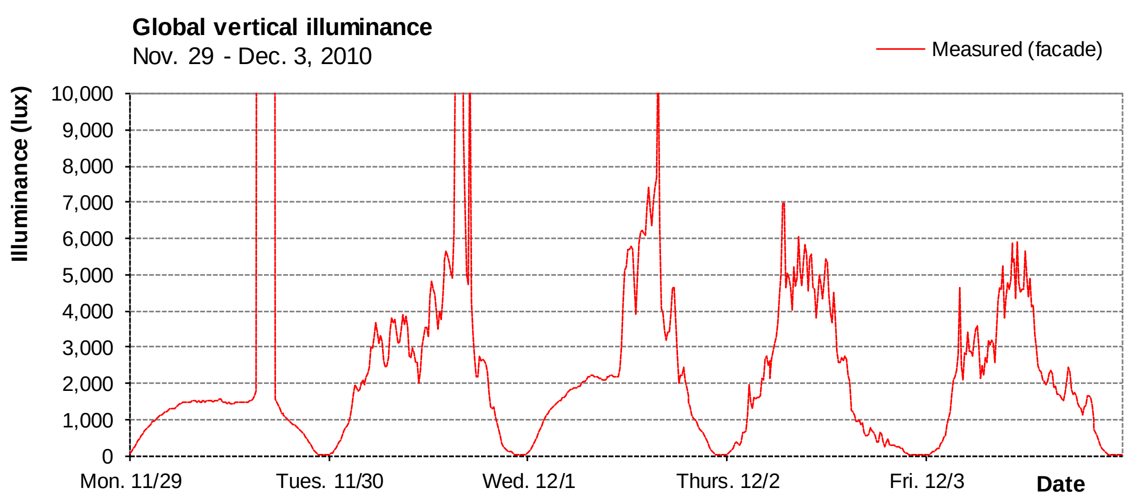

Figure 48 Global vertical illuminance measured on the facade (sample work week)

Measured global horizontal illuminance data. Overall, the global horizontal illuminance graphs show fairly good agreement between the data collected on the roof and the clear day illuminance data from the San Francisco daylight availability tables, however it should be noted that the daylight availability data serve as a rough reference only since the data is for San Francisco, not Berkeley. The midday discrepancy between measured and predicted illuminance values under a clear sky cannot be explained without a more detailed analysis, but could be caused by a number of factors, including differences in sky conditions between San Francisco and Berkeley and/or the limitations of the Robbins-Hunter daylight prediction model. Presumably, if differing amounts of air pollution and humidity were factors, the difference would be smallest near noon – when sunlight has the least amount of atmosphere to travel through, and highest in the morning and afternoon. This however, is not the case.

The global horizontal illuminance measurements collected over the test period (consisting of 14 weekdays and 8 weekend and holiday days) reveal that there were two entirely clear weekdays (Nov. 24th and 29th) and one holiday day (Nov. 25th). Moreover, on Dec. 1st and Dec. 7th the sky was clear for the entire first half of the day but became partially cloudy in the afternoon. For the majority of the time however, the sky was partially or mostly cloudy. There were two working days (Dec. 8th and 12th) where the sky was nearly uniformly overcast.

Measured vertical facade illuminance data. While the global horizontal illuminance levels provide information on outdoor sky conditions, the global vertical facade illuminance provides information on the amount of daylight reaching the outside of the office window sill. The vertical facade illuminance is largely affected by the adjacent condominium apartment building which blocks much of the view of the sky. In standard daylight analysis it is typically assumed that the obstruction has a brightness equal to approximately 1/10 of the part of the sky which is obstructed, thus the daylight contribution from the obstructed part of the sky is reduced by 90% (Baker & Steemers, 2002, p. 37). The shading mask in **Figure 49** shows that the part of the sky blocked by Oxford Plaza apartments results in shading between 10:00 and 14:00 from October to March. As a result of the surrounding site obstructions, the daylight reaching this part of the facade at this time of the year is mostly diffuse, with the exception of a brief period when direct sunlight falls on the facade in the afternoon, between 13:45 and 14:30 on clear days (see Nov. 29th graph in **Figure 48**). Illuminance levels for a sample overcast day (Dec. 8th) and a sample clear day (Nov. 29th), average 1,045 and 1,322 lux, respectively.[25] Interestingly, the average facade illuminance for a sample intermediate day (Nov. 30th) – 2,947 lux, is considerably higher than for the clear day.

The sky luminance of an overcast sky is highest in the zenith area – immediately overhead, and darkest along the horizon. In contrast, under a clear sky the sky is brightest in the zone around the sun and along the horizon (Baker & Steemers, 2002, p. 33). Since the exterior obstructions to the south of the David Brower Center block the lower part of the sky and the horizon at this time of the year, this explains why the average facade illuminance under a clear sky is only slightly higher than that under an overcast sky even though there is a considerable difference in global horizontal illuminance for these two types of skies (Figure **50** and Figure **51**).

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[25] These averages exclude the illuminances during the period when direct sunlight hits the facade (13:45 and 14:30) in order to ensure that this extreme does not affect the averages for the clear sky and intermediate skies.

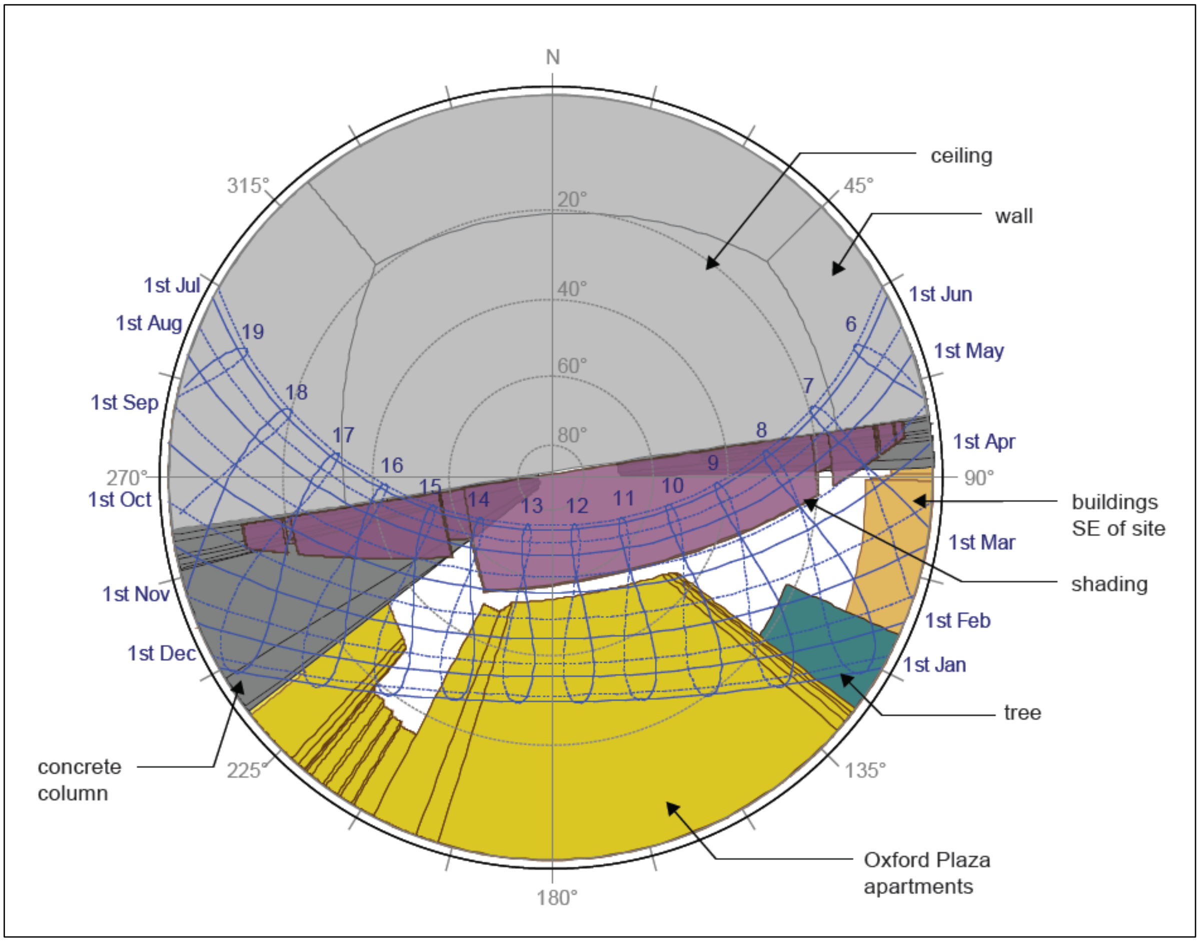


Figure 49 Shading mask showing sky obstructions (facade sensor point)

The high facade illuminance on the intermediate day on the other hand is due to the diffusing effect of the clouds. In addition to the direct sunlight component, an increase in the diffuse skylight component results in higher vertical illuminance levels than under a clear sky alone. The different sky conditions as seen from the hills east of Berkeley are shown in **Figure 52.**

Figure 50 Global horizontal illuminance on roof under different sky conditions

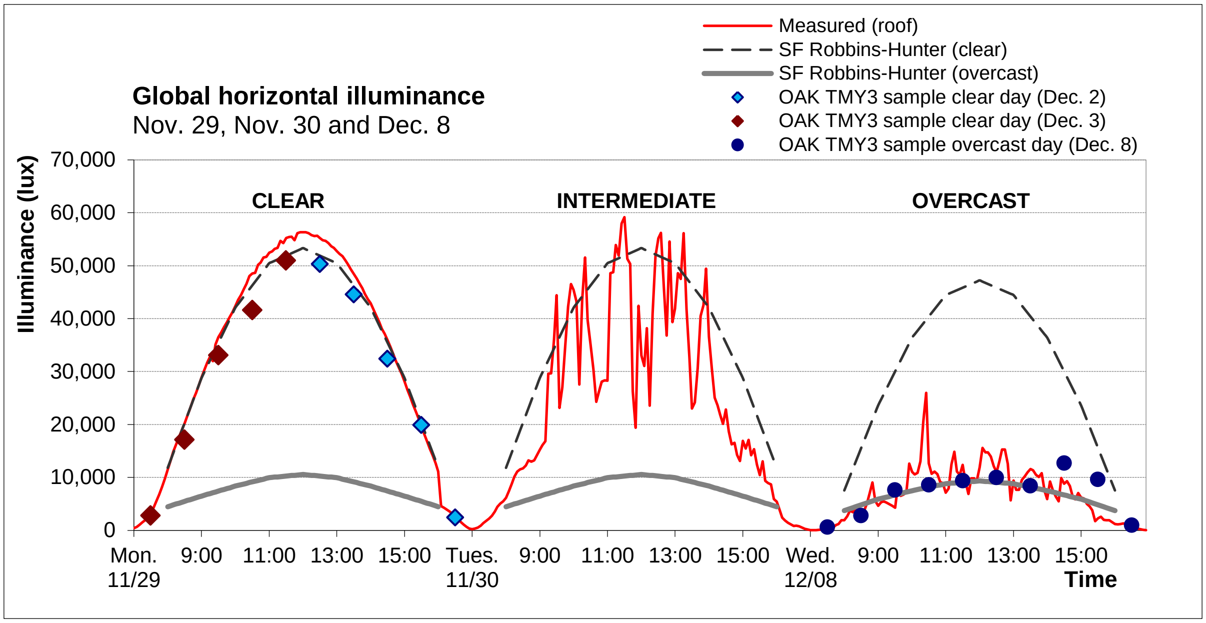


Figure 51 Global vertical illuminance on facade under different sky conditions

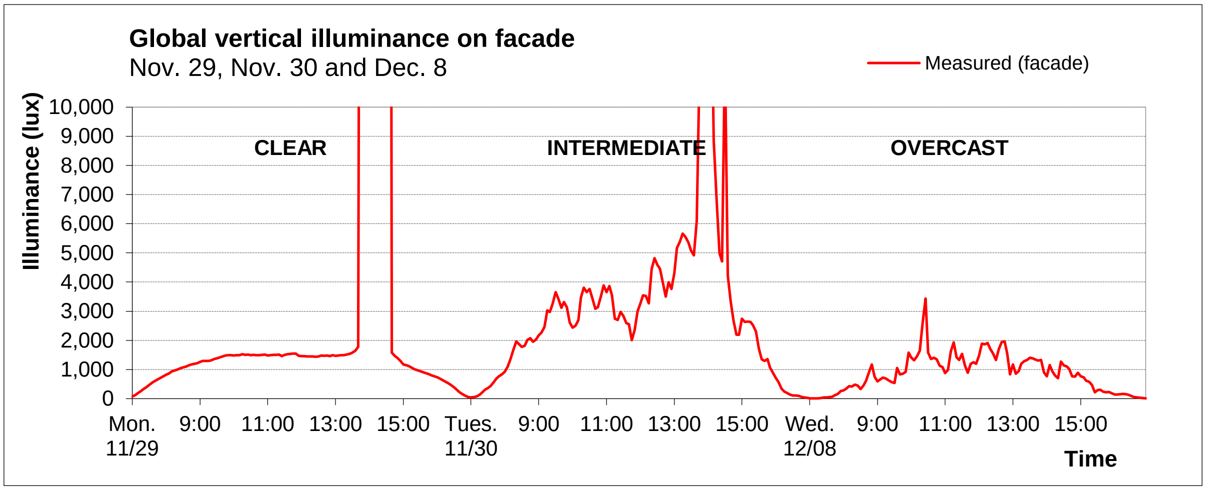


Figure 52 View of Berkeley under clear, intermediate and overcast skies

Clear, Nov. 29, 9:00 **Intermediate, Nov. 30, 9:00** **Overcast, Dec. 8, 9:00**

Clear, Nov. 29, 12:00 **Intermediate, Nov. 30, 12:00** **Overcast, Dec. 8, 12:00**

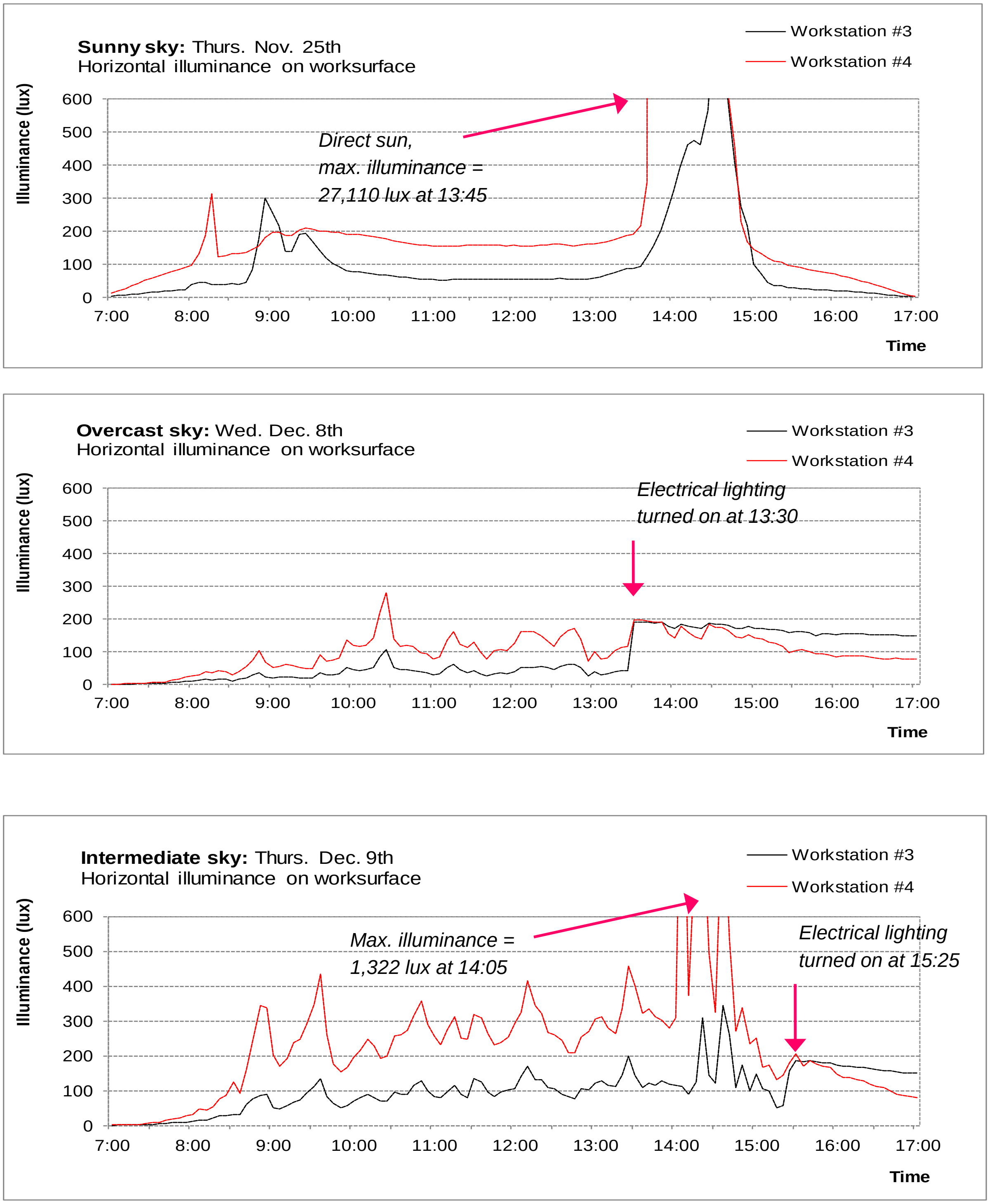
Clear, Nov. 29, 15:00 **Intermediate, Nov. 30, 15:00** **Overcast, Dec. 8, 15:00**

The measured illuminance data reveals that the majority of the monitored days were in fact characterized by an intermediate sky, which yielded highest average illuminances on the facade. Nine out of a total of the fourteen monitored workdays had an average facade illuminance (calculated as an average of the instantaneous measurements taken at 5-minute intervals) considerably higher than the clear days (Nov. 24th and 29th). Only two days had lower average illuminances (Dec. 8th and 14th) while average illuminances on Dec. 9th were only slightly higher (6%) than on the clear days. The averages for the intermediate days typically ranged from 2,700 to 3,100 lux – considerably higher than the averages for the two clear days: 1,382 and 1,383 lux. This suggests that average incident illuminance on the facade is highest on intermediate not clear days.

6.2.2. Interior illuminance

Illuminance data collected at the two workstations – included in *Appendix H*, reveals that for clear and overcast sky conditions daylight levels in the perimeter of the office space are considerably lower than the IESNA recommended levels, and slightly lower under intermediate skies. Representative illuminance levels at workstations #3 and #4 for the three sky conditions are shown in **Figure 53.** It should be noted that measured lighting levels at workstation #3 may be underestimated due to the position of the LI-COR sensor, which was positioned underneath a desk storage closet and close to several desk items, which may have contributed to a slight shading of the sensor (**Figure 40**). On the other hand, lighting levels collected by the sensor at workstation #4, are relatively high due to a more "advantageous" positioning of the sensor – close to the window with virtually no obstructions. In fact, sensor #4 provides a better reference point for typical daylight levels at the perimeter workstations. (see **Figure 33** for a plan with sensor positions).

Figure 53 Interior illuminance on a representative sunny, overcast and intermediate day



Sunny day. The data for a representative sunny day (Thurs., Nov. 25th) was collected on Thanksgiving day – the office was unoccupied and the electrical lighting was turned off. The graph in **Figure 53** illustrates that diffuse light is the main source of daylight throughout the day, with the exception of a brief (45-minute) period mid-afternoon when some direct sun falls on the worksurface of station #4. For the representative sunny day, illuminance levels at workstations #3 and #4 were quite uniform throughout the day, ranging between 50 and 100 lux, and 150 and 200 lux, respectively (with the exception of a brief period in the morning and an hour-long period in the afternoon).

Overcast day. Horizontal daylight illuminance levels for the perimeter workstations #3 and 4 for the first half of a representative overcast day ranged between 30 to 60 lux, and 80 to 170 lux, respectively (**Figure 53**). Interestingly, while the office was occupied on this day, electrical lighting was not turned on until 1:30 pm (see hourly graphs in *Appendix H*).

Intermediate day. Average worksurface illuminance levels on a representative intermediate day (Dec. 9th) are considerably higher (but also more variable), than on the clear or overcast days. Illuminance levels on the intermediate day ranged between 50 and 200 lux for workstation #3 and 200 and 400 lux for workstation #4 (**Figure 53**).

6.2.3. Occupancy

Perimeter workstation occupancy is highly variable, as illustrated by the occupancy profile graphs in **Figure 54**. Hourly occupancy data for the four perimeter workstations is included in *Appendix F*. Three out of the four workstations are rarely occupied in the mornings; the occupants generally occupy these workstations in the afternoon. Occupants also frequently stay after 17:00 and sometimes as late as 20:00 or 21:00. Below is a summary of occupancy patterns at each workstation:

Workstation #1 Occupied once per week on average, afternoon, 1 to 2 hours at a time

Workstation #2 Occupied 3 times per week on average, afternoon, 2 to 3 hours at a time

Workstation #3 Occupied every day, most of the working day, occupant is away from desk 25 to 50% of the time

Workstation #4 Occupied 3 to 4 days per week on average, afternoon, several hours at a time

It should be noted that occupancy at the beginning of the three-week test period (Nov. 24th through Dec. 15th) was affected by Thanksgiving holiday weekend (Thurs., Nov. 25th through Sun., Nov. 28th).

Figure 55 shows sample data collected by one of the occupancy sensors. The data shows that the occupant arrived at their workstation shortly before 9:00. As discussed earlier, the occupancy logger was set to "timeout" after 15 minutes, meaning that if the sensor detected no movement over the course of a 15-minute period, it would log the time along with the condition ("unoccupied") to the logger memory. However, as soon as the sensor detected any movement, the time along with the state ("occupied") would immediately be logged to logger memory. Thus, while the "unoccupied" period could be as short as 1 minute, there could never be an occupancy period of less than 15 minutes, even if the occupant was present at their desk for less than one minute.

Figure 54 Weekday occupancy profile graphs by workstation

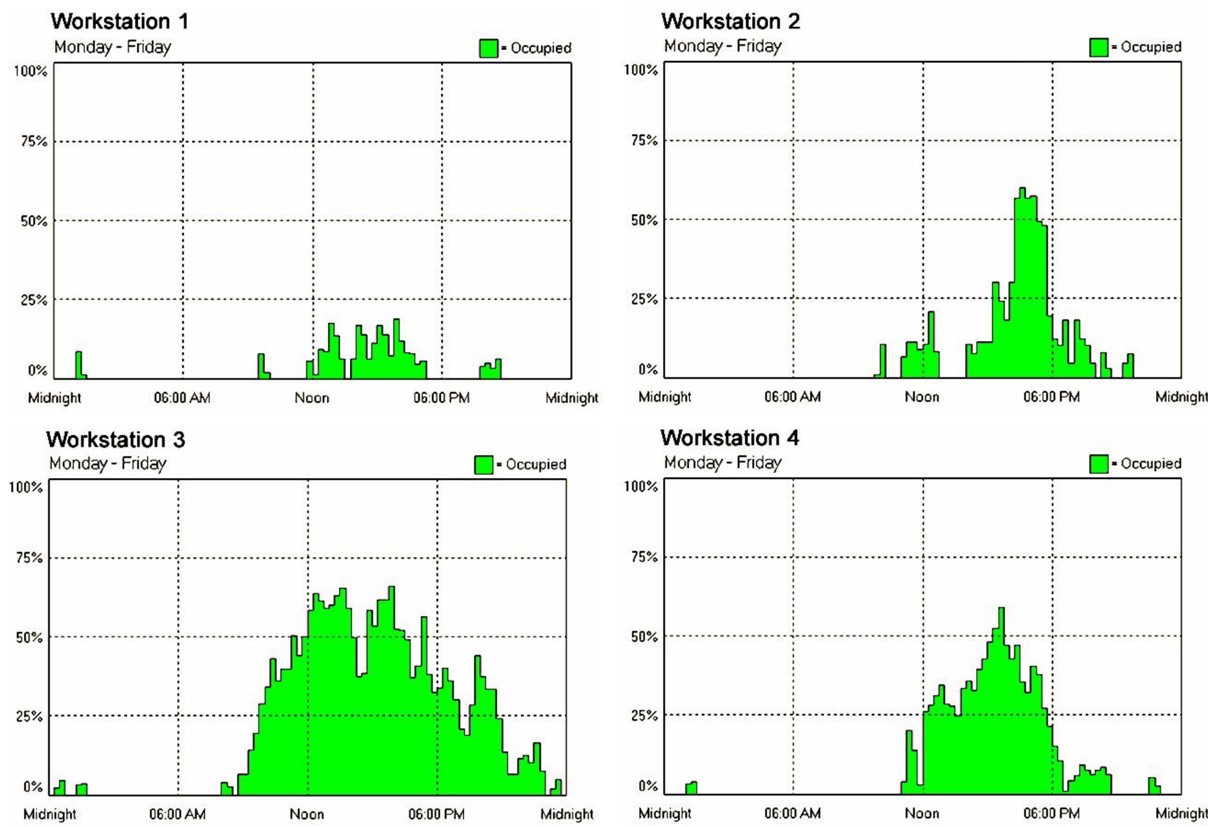
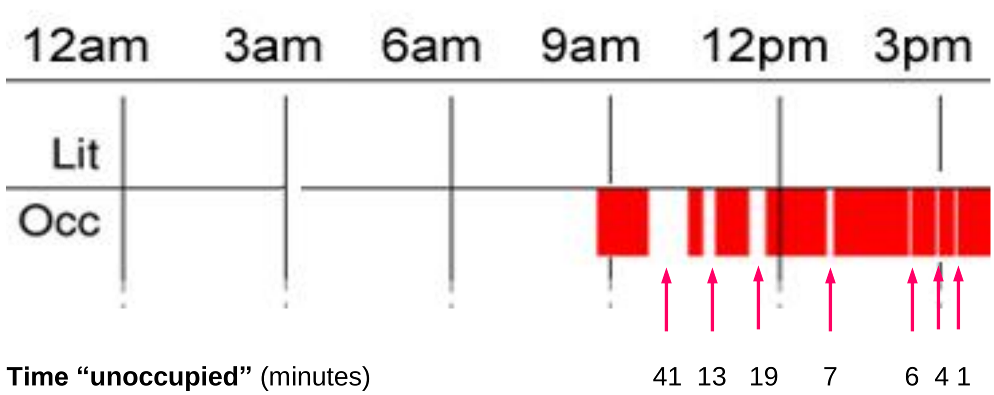


Figure 55 Sample data collected by occupancy logger



NOTE: *In this case, time "unoccupied" refers to the time during which no motion at the workstation was detected*

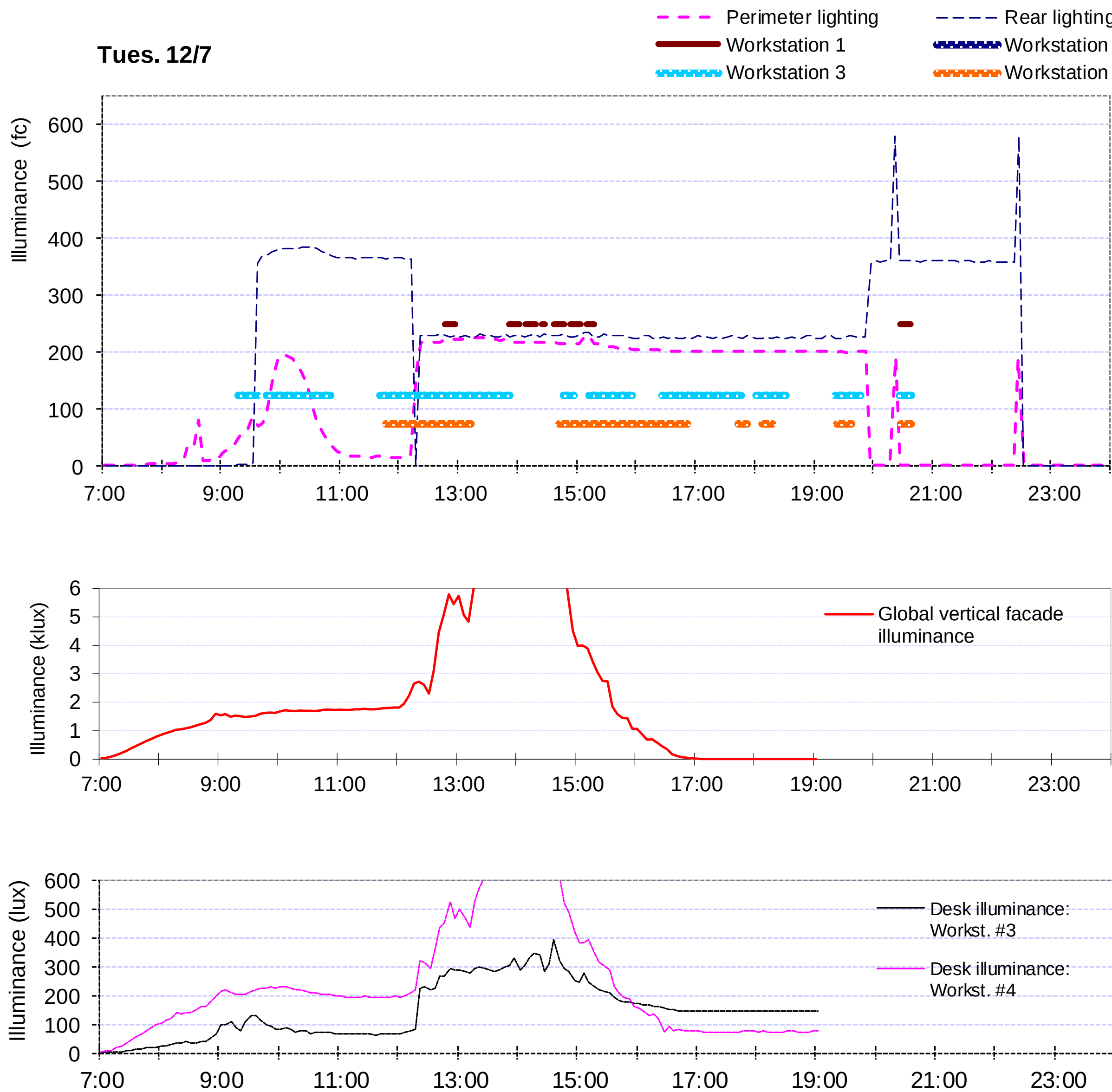
6.2.4. LIGHTING CONTROL

Lighting control data was collected using DENT lighting loggers throughout the test period (Nov. 24th through Dec. 15th) and additional data was collected using HOBO data loggers for part of the test period (Dec. 3rd through Dec. 15th). While the DENT lighting logger data only reveals whether lights were on or off, the data collected using HOBO data loggers provides approximate illuminance levels (measured several inches below the fixture) and can thus be used to determine the exact lighting settings. The following sections look at the relationship between illuminance levels and lighting control and discuss occupant use of the three different lighting settings.

Illuminance levels. The relationship between exterior sky conditions, interior lighting levels and lighting control, is shown in the hourly graphs included in *Appendix H*, which also include information on occupancy in the perimeter workstations. A sample graph is shown in **Figure 56.**

The lighting control data (see *Appendix G*) reveals that while lighting is often turned on in the morning, this is not always the case. On 50% of the monitored workdays (14 days total) the lighting was first turned on (either partially or fully) before 11:00, 29% between 11:00 and 14:00, and 21% after 14:00. For the days on which the lighting was turned on before 11:00, the sky was clear on three of the days, overcast on two, and intermediate on the remaining two days.

Figure 56 Lighting control, occupancy and illuminance graphs for Dec. 7th

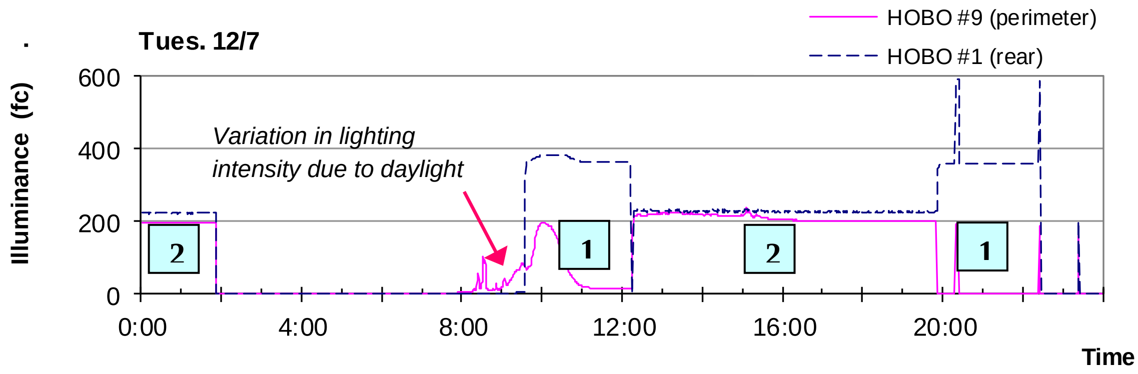


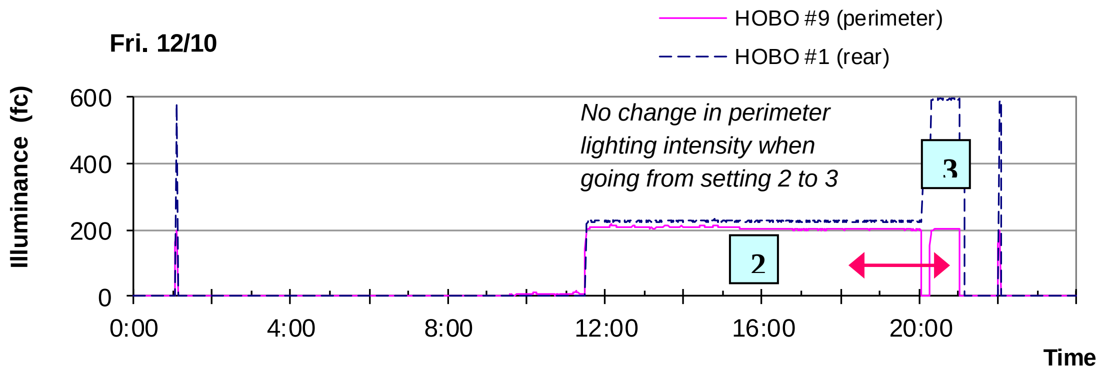
When lighting is turned on, it typically remains on for the remainder of the day. Finally, when the lighting is on, both the outer (perimeter) and the inner rows of fixtures are typically on, however there are times when only the rear row of fixtures is on (e.g. morning and late afternoon on Tues., Dec. 7,th all day on Mon. Dec. 13th and Tues. Dec. 14,th and early afternoon on Wed. Dec. 15th). The hourly graphs in *Appendix H* reveal that perimeter occupants do not always feel the need to turn on lighting in the morning, thus lighting levels are adequate for some of these occupants for at least some of the time.

Lighting settings. While the absolute lighting measurements taken by the HOBO U12 Temp/RH/Light loggers are characterized by a relatively large error, the data collected by the HOBO loggers is useful for observing large instantaneous changes in light levels, such as those associated with a change in the lighting settings. Since the HOBO loggers were mounted below the overhead light fixtures, facing the ceiling, variations in daylight levels detected by the sensors are relatively small in comparison with the variations in electrical lighting levels. While the graphs do reveal some variation in lighting intensity on account of a small amount of daylight reaching the logger, particularly in the readings taken by the perimeter HOBO data logger on sunny mornings (**Figure 57**), the change is more gradual than the change in light levels resulting from an adjustment to the overhead lighting settings.

The HOBO lighting control graphs in *Appendix G* reveal that during times when the lights are on, light levels consistently alternate between the same three levels (**Figure 57**), and based on the consistency of these levels throughout the test period, it is possible to associate each level with one of the three possible lighting settings: (1) one bulb in rear fixture on, (2) one bulb in each row of fixtures on, and (3) all bulbs on (**Figure 58**).

Figure 57 HOBO lighting control data for two sample days





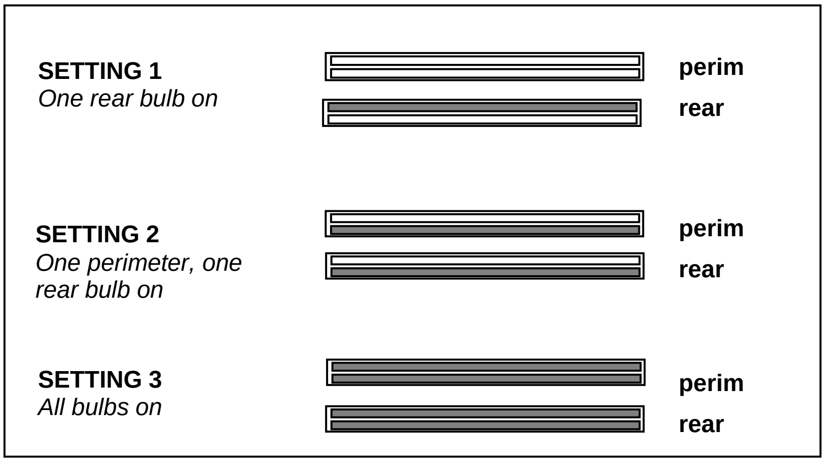


Figure 58 Overhead lighting settings

The lighting data reveals that one of the bulbs in the perimeter fixture was out. Unlike the rear fixture, where we notice a large change in lighting intensity when going from setting 2 (one bulb on) to 3 (both bulbs on), the lighting intensity measured at the perimeter fixture is the same for both settings (see graph for Fri., Dec. 10th in **Figure 57**). The lighting settings along with the corresponding lighting levels (for electrical lighting only) have been listed in **Table 5**. As expected, the sum of the illuminance measured at the rear fixture for settings 1 and 2 – 360 and 230 fc, respectively, equals to 590 fc – very close to what was measured at setting 3. Moreover, the HOBO lighting control diagrams indicate that intermediate light settings (settings 1 and 2) are used predominantly during the daytime, with setting 3 typically only used after dark.

Table 5 Light settings and corresponding electrical lighting intensities measured at fixtures

	Electrical lighting illuminance (fc)	
Setting	**Perimeter fixture**	**Rear fixture**
1	0	~360
2	~200	~230
3	~200	~600

6.2.5. Shading control

The interior roller shades were all retracted at the start of the three-week test period, with the exception of one small shade at the west end of the room, which was deployed half-way (**Figure 59**). The time-lapse photographs revealed that the occupants did not deploy or retract the shading during the test period, even on sunny days. Since none of the shades had been deployed, the data collected by the HOBO data loggers mounted several inches inboard of the facade was not reviewed.

Figure 59 Fisheye lens photo of upper portion of facade and ceiling

6.3. Discussion

As a result of surrounding site obstructions, especially the Oxford Plaza apartment buildings south of the David Brower Center, the daylight reaching the facade of the office space at this time of the year (late November and early December) is mostly diffuse, with the exception of a brief period when direct sunlight falls on the facade in the afternoon. The measured illuminance data reveals that the majority of the monitored days during the test period were characterized by an intermediate sky, which yielded highest average illuminances on the facade. The average vertical facade illuminances for the intermediate days typically ranged from 2,700 to 3,100 lux – considerably higher than the averages for the two clear days: 1,382 and 1,383 lux.

Illuminance data collected at the two workstations, included in *Appendix H*, reveals that workplane illuminances at the perimeter of the office space are low for clear and overcast sky conditions but somewhat higher under intermediate skies. At workstation #4, the illuminances monitored for a sample clear, overcast and intermediate days were 50 to 200 lux, 80 to 170 lux, and 200 to 400 lux, respectively. While workplane illuminances near the window under an intermediate sky are only slightly below the IESNA recommended range of 300 to 500 lux for computer-based tasks, illuminances on clear and overcast days are much lower. This implies that daylight is insufficient for all but the perimeter workstations in the space, and even for the perimeter workstations, daylight levels on clear and overcast days may be too low.

Lighting in the office space is turned on often, presumably to compensate for low daylight levels in the space. Unfortunately, due to the limited duration of the study as well as a limited number of illuminance, lighting and occupancy sensor points (none of which were positioned at the rear of the space), it is not possible to analyze the relationship between workplane illuminance and lighting switch-on events in detail. However **Table 6** below shows light switch-on events during daylit hours (9:00 to 16:00) as a function of global vertical facade illuminance.

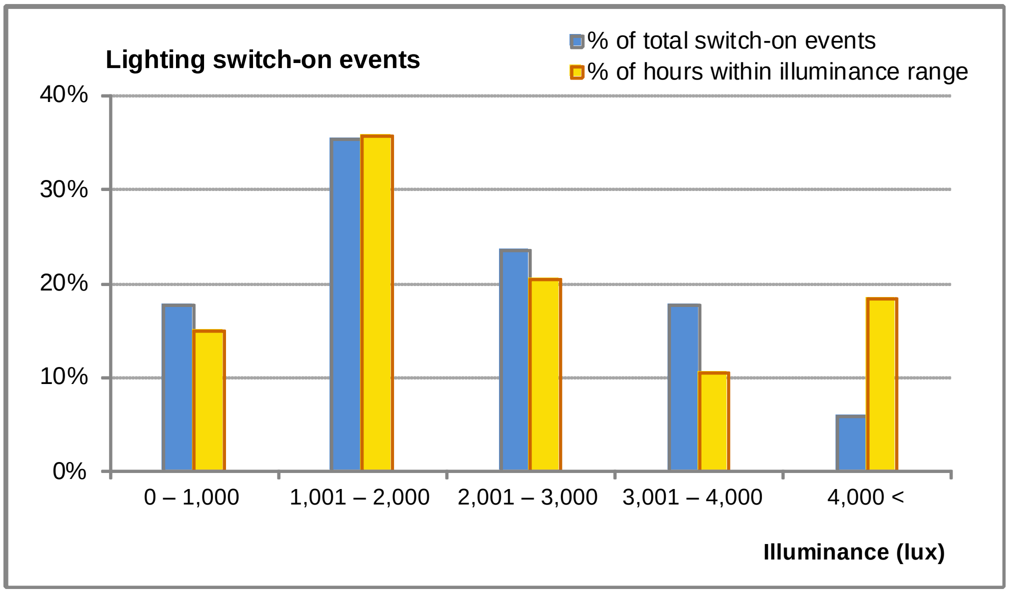
The total number of switch-on events, 17, is not sufficient for understanding whether there is an association or the nature of the association between facade illuminance and switch-on events. However, if the samples were doubled and the distribution remained the same, the data would indicate that occupants were less likely to turn on lighting when facade illuminance was higher than 4,000 lux (**Figure 60**). At lower illuminances no correlation is evident, presumably because light switch-on events at are strongly correlated with time of arrival (Galasiu & Veitch, 2006), while the % of hours within illuminance range listed in the table include all occupied hours, not just the hours at which occupants arrived in the office. (This type of analysis was not possible because the arrival of rear workstations occupants was not monitored).

Table 6 Light switch-on events as a function of facade illuminance[1]

Global vertical facade illuminance (lux)	No. of switch-on events [1]	% of total switch-on events	% of hours within illuminance range
0 – 1,000	3	18%	15%
1,001 – 2,000	6	35%	36%
2,001 – 3,000	4	24%	20%
3,001 – 4,000	3	18%	11%
4,000 <	1	6%	18%
Total	**17**		

[1] Calculated for daylit hours (9:00 to 16:00) only

Figure 60 Lighting switch-on events as a function of illuminance



When lighting is turned on, it typically remains on for the remainder of the day. Intermediate light settings – setting 1 (one rear bulb on) or setting 2 (one rear and one perimeter bulb on) are used predominantly during the daytime, with setting 3 (all four bulbs on) typically only used after dark. This suggests that at least some occupants may consciously choose a particular setting (e.g. to attain a target increase in illuminance levels in the space, minimize electrical energy use through the selection of an intermediate light setting, etc.), even if they do not do so consistently. Moreover, the predominant use of the intermediate lighting settings (settings 1 and 2) during daylit hours suggests that these intermediate settings may be preferred by some occupants during daytime hours.

Since the lighting is operated at partial capacity for close to 2/3 of the time, the bi-level fixtures with a separate switch leg for the perimeter row of fixtures may provide substantial electrical lighting energy use savings relative to the single switch – that is, if we presume that occupants would have operated the lighting in the same way if a single switch had been installed. If we only look at times when the office was occupied (typically 9:00 to 18:00) and only daylit hours in November/December (8:00 to 16:00), over the 9-workday monitoring period, approximately 63% savings in electrical lighting energy use were attained by using a combination of the intermediate rather than the full-power lighting settings (**Table 7**).

Finally, shading was raised throughout the duration of the test period. This suggests that the occupants did not feel the need to lower the roller shades for visual or thermal comfort reasons which in turn implies that the facade adequately controls direct sunlight. It should be noted however, that the occupancy in this space is quite variable (occupants are frequently away from their workstations) and that this could to some extent affect the pattern of lighting and shading operation.

Table 7 Estimated electrical lighting energy use savings

Occupied (daylit) hours only, 9:00 to 16:00				
Total daylit hours = 9 days x 7 hrs/day = 63 hours				
	Hours	**% of daylit time**	**Power**	**Energy used**
Lights off	27.25	43%	0%	
Setting 1	19.25	31%	25%	4.8
Setting 2	16.5	26%	50%	8.3
Setting 3			100%	
Total time lights on	**35.75**		**Total (actual)**	**13.1**
			Total (100%)	**35.8**
			Savings	**63%**

7. SIMULATIONS

The office space monitored during the field study was selected for a more detailed daylight analysis in order to compare the performance of a case with and without shading in terms of daylight levels and light uniformity at different times of the year. The inputs for the computer model, the process of calibrating the computer mode, and the performance metrics used to assess daylight levels and uniformity are discussed in the next few sections.

7.1. METHODS

In order to understand the impact of shading on visual comfort and daylight availability in the office space, two cases – one with and one without the exterior aluminum louvers were simulated using Radiance-based daylight simulation software. Moreover, since occupant-controlled interior shading can have a significant impact on daylighting, a third case – one without exterior louvers but with manually-controlled interior roller shades, was simulated. It was assumed that shades would be lowered in the presence of direct sun and raised in the beginning of the following day, upon the occupant's return to the office.

The office space geometry was modeled using Rhinoceros 3-d modeling software (Rhinoceros for Windows, v. 4) and the daylight simulations were then conducted directly from Rhino using the DIVA-for-Rhino plug-in (Jakubiec et al., 2011). DIVA-for-Rhino provides a user-friendly front-end interface to Radiance – a state-of-the-art lighting analysis software (Ward & Shakespeare, 1998), by allowing the user to define parameters (model geometry, weather file, material parameters, analysis grid, sky conditions and other settings) and run Radiance simulations directly from Rhino. In addition to creating realistic renderings and luminance distributions within the space, the plug-in allows the user to run climate-based annual daylight simulations using DAYSIM as the background simulation engine (Reinhart, 2006; Reinhart, 2011).[26] Some of the dynamic daylight metrics calculated by DAYSIM include Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI). For a more detailed description of these metrics see section 2.5 *Daylight performance indicators.*

7.1.1. Model geometry and materials

The 40-ft by 27-ft office space and the surrounding site was modeled in Rhino in considerable detail. While most of the model geometry (space dimensions, window layout, surrounding buildings and landscape) was determined using the April 20th, 2007 construction drawing set for the David Brower Center, workspace location and furniture dimensions and layout were determined on site. See **Figure 31** in section 6.1.2 *Space description* for a detailed office plan and layout of the furniture in the space.

Since the David Brower Center is located in a dense urban area, the surrounding buildings highly influence the daylighting in the office space. The computer model thus included the Oxford Plaza apartments immediately south of the David Brower Center, the Marsh Berkeley Art Center to the west of the David Brower Center, and two campus buildings (Cal Athletic Ticket Office and Edwards Stadium) across Fulton Street to the east (**Figure 61**). A combination of on-site measurements and aerial maps obtained using Google Earth were used to determine the dimensions and position of the surrounding buildings.

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[26] DAYSIM is a dynamic daylight metrics simulation tool developed by National Research Council Canada and at the Solar Building Design Group of the Fraunhofer Institute for Solar Energy Systems (Reinhart, 2006). DAYSIM uses the Perez sky model (Perez et al., 1990) and daylight coefficient method to calculate location-specific illuminances and lighting energy use over the course of a year (Bourgeois, Reinhart & Ward, 2008).

Unlike the Oxford Plaza apartments, the buildings to the east and west of the site do not contribute to the diffuse interreflections, however they do block direct sunlight in the early morning and late afternoon. Thus, while Oxford Plaza apartments were modeled in greater detail, buildings to the east and west of the site were modeled as simple cubes. The David Brower Center and surrounding buildings were rotated 9° east of South to match the urban fabric (the y-axis in the computer model corresponds to North). The extents of the computer model are illustrated in **Figure 62**.

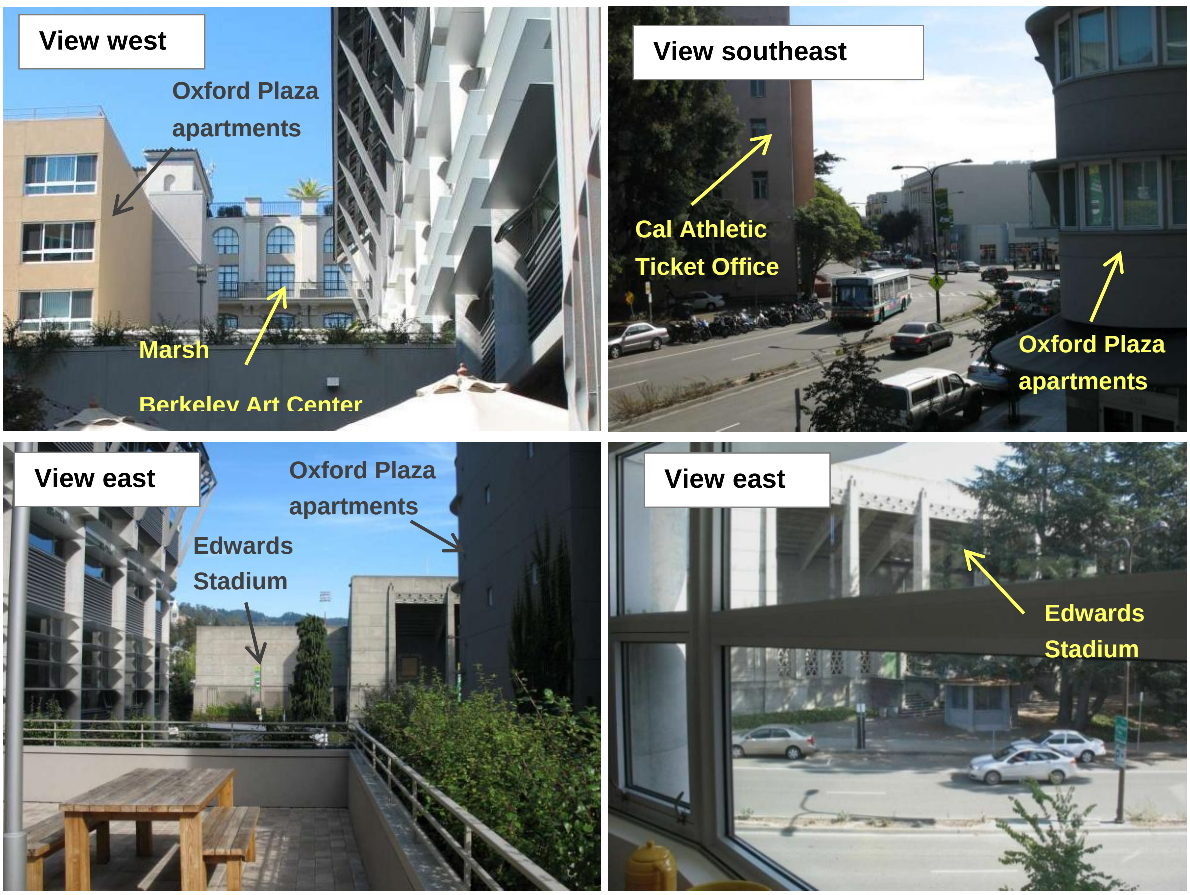

Figure 61 Site conditions to the east, southeast and west of the David Brower Center

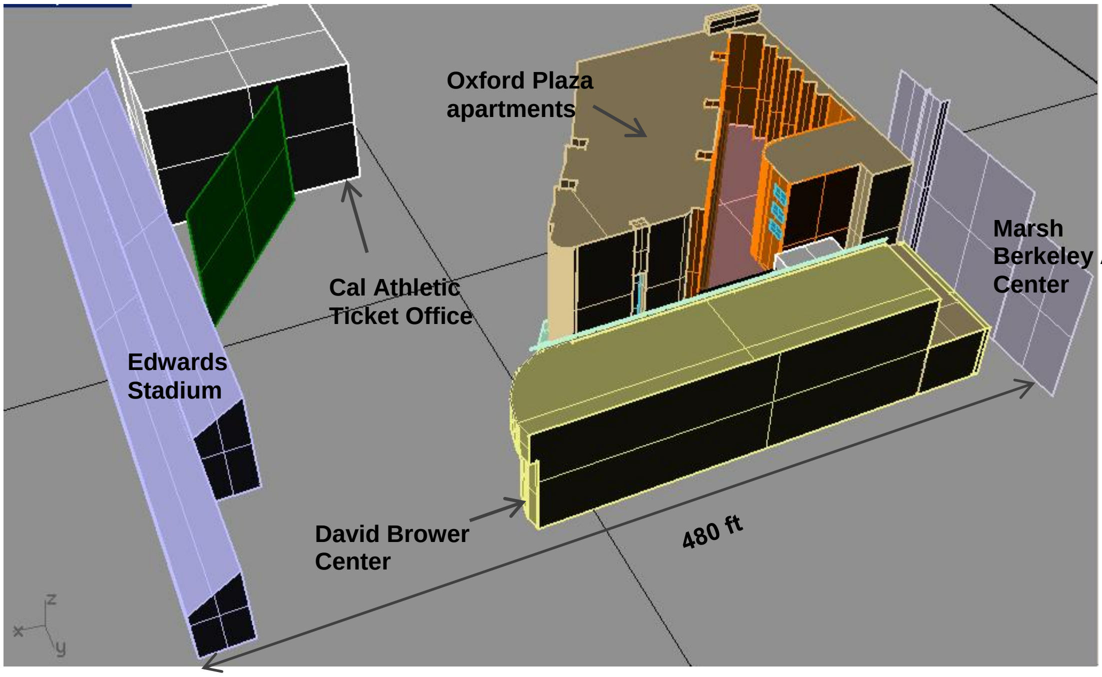

Figure 62 Rhino computer model of the David Brower Center and surrounding buildings

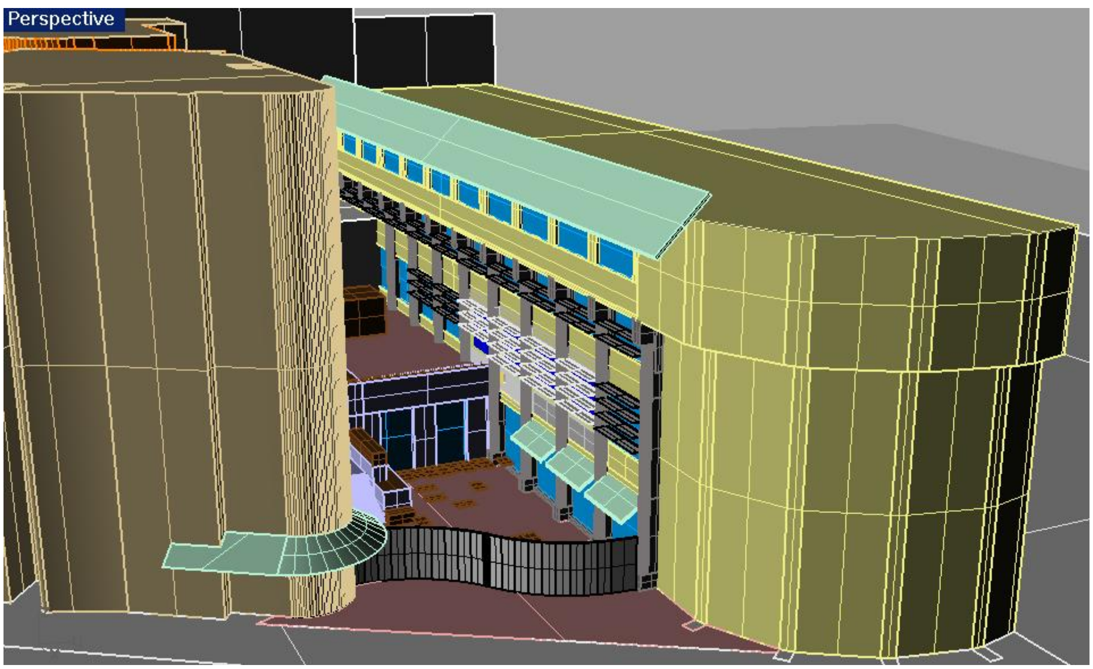

Figure 63 Rhino computer model: view of courtyard and south elevation

Reflectances of interior finishes, furniture and outside surfaces (paving, surrounding buildings, etc.) were measured using a Philips surface reflectance chart (**Figure 64**). Reflectances of specular surfaces and surfaces which are not uniformly diffuse such as carpet were estimated based on reflectance values cited in existing literature (IESNA, 1993; Robbins, 1986; Baker & Steemers, 2002). Glazing transmittance was obtained from the April 20th, 2007 construction drawing set for the David Brower Center. Since only the reflectance of each surface was important for the purposes of obtaining accurate illuminance and luminance values, material properties did not include color information – all materials were modeled neutral grey. The properties for the materials used in the Radiance simulation are listed in *Appendix I*.

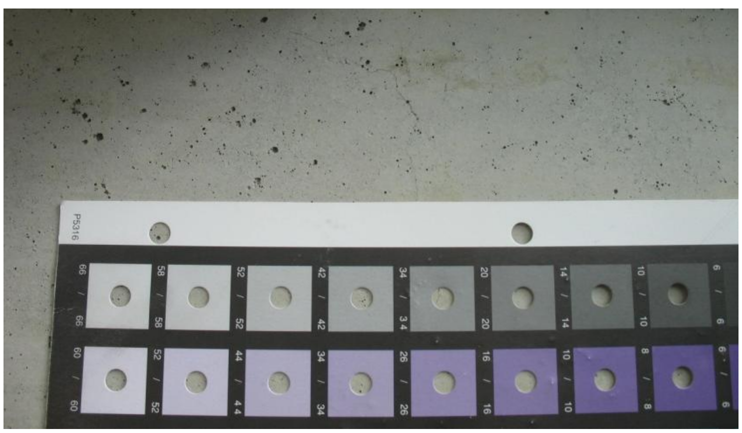

Figure 64 Philips surface reflectance chart

7.1.2. MODEL CALIBRATION

As discussed in section 6.1.4 *Illuminance measurements*, exterior illuminance measurements collected throughout the three-week test period provided information on sky conditions and reference measurements for checking the accuracy of the computer model.

The calibration process consisted of the following steps:

1. ***Sky selection.*** Two sky models were defined using the Radiance *gensky* command for the purposes of calibrating the model: the CIE clear sky model and the Robbins-Hunter daylight prediction model described in section 6.2.1 *Exterior illuminance and sky conditions*.

2. ***Comparison of vertical facade illuminances.*** Hourly global vertical facade illuminance values obtained on site were compared to simulated illuminances for a sunny day using the two sky models from step 1 in order to determine whether site conditions and surrounding buildings were accurately modeled.

3. ***Comparison of global horizontal illuminances at workstation #4.*** Hourly global horizontal illuminances collected at workstation #4 were compared to the simulated values for a CIE clear sky in order to determine whether the office space geometry and material properties had been accurately modeled. Measured values were compared to simulated values with and without an adjustment factor accounting for the difference in simulated and measured vertical facade illuminance values from step 2.

The above steps are described in more detail below.

Step I: Sky selection. The sky for calibrating the computer model was defined using the *gensky* Radiance command. Since illuminance levels are highly variable under overcast sky conditions, only clear sky models in conjunction with data measured on a sunny day were used for the illuminance comparisons. Two different methods were used to define the skies for the simulations.

The first sky was defined using *gensky* in combination with the +s option, which produces a CIE standard clear sky distribution for a given month, day and time for a particular latitude and longitude. Required inputs include the date, local time, and location coordinates. The CIE clear sky model does not account for local variation in illuminances resulting from moisture content and air pollution.

The second sky model was defined using additional parameter options available in *gensky*, which allow the user to control zenith irradiance and solar radiance. If measured direct and diffuse illuminance data for the site is available, instead of a standard CIE sky, the user can use *gensky* to specify a custom sky using the –B and –R options, which control zenith irradiance and solar radiance. This approach will result in a more accurate sky description than the one based on the standard CIE sky model. Zenith irradiance and solar radiance are calculated based on the horizontal diffuse and horizontal direct irradiance, respectively.[27] While global horizontal illuminance had been collected during the three-week monitoring period from end of November to mid-December, no direct or diffuse data had been collected. Thus, in order to calculate the required inputs for –B and –R, the diffuse component was approximated using daylight availability tables for San Francisco containing illuminance values calculated based on the Robbins-Hunter daylight prediction model (Robbins, 1986).[28] The diffuse illuminance was then divided by the global horizontal

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[27] The horizontal diffuse and horizontal direct irradiances inputs for the *gensky* command are calculated by converting illuminances to irradiances using a constant luminous efficacy factor K_R = 179 lm/W. While in reality luminous efficacy varies based on the type of sky, in this case of the *gensky* command Radiance requires an input calculated based on this constant luminous efficacy value.

[28] See section 6.2.1 *Exterior illuminance and sky conditions* in chapter 6 *Field study* for a brief discussion of the Robbins-Hunter daylight prediction model.

illuminance for a given month and hour in November,[29] and the measured global horizontal illuminance was multiplied by this factor to determine the site diffuse component. Direct illuminance was calculated by subtracting the calculated diffuse component from global illuminance. While this approach for generating a sky can only serve as an approximation at best since the illuminance values from the daylight availability tables are averages for the month of November and are also for a nearby location rather than the actual site, together with the CIE standard sky model, the two models provide a reasonable reference for comparing simulated and measured facade illuminance. The calculated factors along with the corresponding diffuse and direct illuminance levels used as input for *gensky* (following conversion into irradiances) are listed in **Table 8**.

Table 8 Illuminances used for clear sky definition using the *gensky* –B and –R options

Date	Time	DBC roof (global) [lux]	Robbins global (Nov.) [lux]	Robbins diffuse (Nov.) [lux]	Diffuse component (Robbins)	Estimated DBC diffuse component, [lux]	Estimated DBC direct component [lux]
11/25	8:00	13,094	11,810	4,150	26%	3,405	9,689
11/25	9:00	30,538	28,790	6,270	18%	5,461	25,077
11/25	10:00	45,320	42,090	7,100	14%	6,541	38,779
11/25	11:00	54,963	50,470	7,460	13%	7,078	47,885
11/25	12:00	57,938	53,330	7,560	12%	7,193	50,745
11/25	13:00	54,106	50,470	7,460	13%	6,968	47,138
11/25	14:00	44,063	42,090	7,100	14%	6,360	37,703
11/25	15:00	28,905	28,790	6,270	18%	5,169	23,736
11/25	16:00	11,281	11,810	4,150	26%	2,933	8,348

The input for the *gensky* command for the two different methods was as follows:

Method 1: *gensky mm dd hh* +s *-a* 37.87 *-o* 122.27 *-m* 120

Method 2: *gensky mm dd hh +s -B* 40.19 *-R* 283.49 *-a* 37.87 *-o* 122.27 *-m* 120

where the inputs are defined as:

[29] Since the calibration of the model was performed for a single clear sky day (November 25th), only November diffuse sky components were calculated.

mm – two digit month

dd – two digit day

hh – two digit hour

+*s* – sunny sky with sun

-*B* – zenith irradiance, computed from the horizontal diffuse irradiance (in W/m^2)[27]

-*R* – solar radiance, computed from the horizontal direct irradiance (in W/m^2)[27]

-*a* – The site latitude used for the calculation of the sun angle. Positive denotes degrees north.

-*o* – The site longitude positive used in the calculation of solar time and sun angle (denotes degrees west).

-*m* – The site standard meridian (positive denotes degrees west of Greenwich) used in the calculation of solar time.

The following example illustrates the input for noon on November 25th:

gensky 11 25 12 +*s* -*B* 40.19 -*R* 283.49 -*a* 37.87 -*o* 122.27 -*m* 120

The command generates a sunny sky for Nov. 25th at 12 pm pacific standard time at latitude 37.87° N and longitude 122.27° W.

Step II: Comparison of vertical facade illuminances. Since illuminance levels are highly variable under overcast sky conditions, hourly comparisons between the computer model illuminance outputs and field measurements were made for a sunny day only. Three sunny days (Nov. 24th, Nov. 25th and Nov. 29th) had been identified based on the global horizontal illuminance data collected on the roof (see section 6.2.1 *Exterior illuminance and sky conditions* for illuminance data). Since lighting use data collected during the monitoring phase revealed that on Nov. 24th and Nov. 29th lighting inside the space had been on, simulation output was compared to the measured values on the facade for Nov. 25th (Thanksgiving holiday), since no lighting had been on this day. This same day was then used for calibrating the inside of the interior of the space (see next section). The vertical facade illuminances were simulated using the parameters listed in **Table 9**.

Table 9 Ambient parameters used to calibrate exterior of model

Parameter	Value
Ambient bounces, *ab*	5
Ambient divisions, *ad*	1000
Ambient super-samples, *as*	500
Ambient resolution, *ar*	1500
Ambient accuracy, aa	0.1

The relatively high value for the ambient bounces was selected in order to account for the externally reflected daylight from surrounding buildings. A high ambient resolution (*ar*) value and low ambient accuracy (*aa*) were selected due to the relatively large site extents; the maximum dimension between surrounding site obstructions was 480 ft (this does not include the size of the ground plane, which had a dimension equal to 1.5 of the maximum dimension between site obstructions); see **Figure 62**.

Following initial simulations, minor adjustments to site obstructions to the east and southeast of the site were made. A tree and buildings to the east and southeast of the site had not initially been modeled but were later added since they block direct sunlight in the morning (**Figure 62**).

Measured and simulated vertical facade illuminances are presented in **Figure 65**. The graphs show that the simulated hourly vertical facade illuminances are in fairly good agreement for the model calculated using the CIE clear sky model without the additional –B and –R parameter inputs (within 17%), with the exception of the simulated values under direct sun at 2 pm (-35%) – see (Table 10). Slightly larger discrepancies occur with the sky model generated using the diffuse and direct components calculated based on the Hunter-Robbins daylight model, where there are five hours where illuminance are under- or overpredicted by 20 to 40%.

The discrepancies for the two models are likely due to differences in the modeled and actual skies – for the cases where the simulated values are lower than the ones measured, the diffuse sky component for the actual sky may be underpredicted in the computer sky models. However, since diffuse illuminance data was not collected, it is difficult to identify the exact source of the discrepancy. Since there is better agreement between the measured values and values simulated using the CIE sunny sky model without the additional –R and –B parameter inputs, it is this model that will be used to calculate daylight performance metrics for specific times of the year. Annual simulations will be conducted using TMY3 weather data for Oakland, which includes hourly direct and diffuse solar radiation for a typical meteorological year.

Figure 65 Global vertical illuminance on the facade

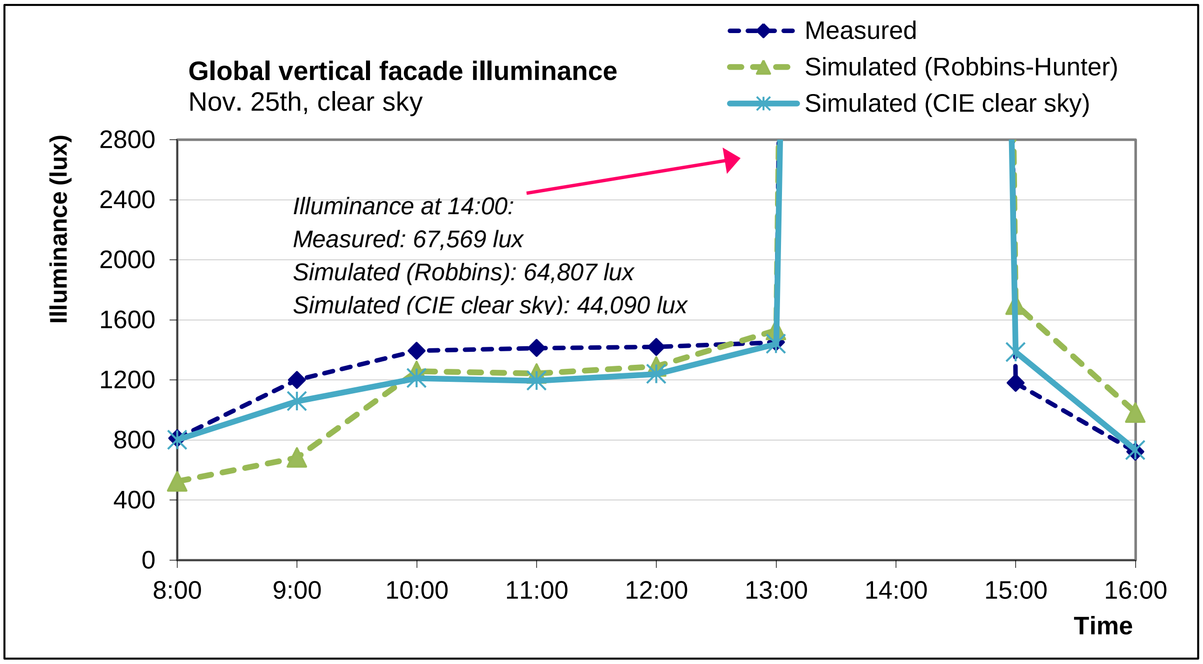

Table 10 Actual and simulated facade illuminances

Time	Illuminance (lux)			Error	
	Measured	Simulated (Robbins-Hunter)	Simulated (CIE clear sky)	Simulated (Robbins-Hunter)	Simulated (CIE clear sky)
8:00	812	524	801	-35%	-1%
9:00	1,199	683	1,058	-43%	-12%
10:00	1,394	1,258	1,212	-10%	-13%
11:00	1,412	1,243	1,195	-12%	-15%
12:00	1,419	1,289	1,239	-9%	-13%
13:00	1,451	1,532	1,440	6%	-1%
14:00	67,569	64,807	44,090	-4%	-35%
15:00	1,180	1,701	1,385	44%	17%
16:00	721	982	733	36%	2%

Step III: Comparison of workplane illuminances.

The interior of the model was calibrated by calculating horizontal workplane illuminances and comparing them to the hourly measured illuminances at the LI-COR sensor at workstation #4 (see **Figure 33** and **Figure 40** in section 6.1.3 *Occupancy, lighting, and* *shading control monitoring* for sensor position) using the CIE clear sky model. Since the simulated vertical facade illuminances were lower than those measured (step 2), simulated values at the workstation were compared to values as measured as well as measured values with an adjustment factor accounting for the lower facade illuminance.

The ambient parameters used for these simulations matched the ones used for calibrating the exterior of the model, with the exception of ambient bounces, which was increased from the 5 bounces used in the tests comparing exterior vertical facade illuminances to 7 in order to account for the higher interreflected component of daylight inside the space (**Table 11**).

Table 11 Ambient parameters used to calibrate interior of model

Parameter	**Value**
Ambient bounces, *ab*	7
Ambient divisions, *ad*	1000
Ambient super-samples, *as*	500
Ambient resolution, *ar*	1500
Ambient accuracy, aa	0.1

Measured and simulated illuminances at the facade and the reference point on worksurface #4 are presented in **Figure 66**. The graphs show that the measured workplane illuminances are within ±37% of the measured values (**Table 12**). However, after applying the adjustment factor accounting for the lower simulated vertical facade illuminances, simulated values at the sensor point were all within ±28% of the measured values. The discrepancy between the measured and simulated values at 9 am and 10 am (-28% and -19%, respectively) may be due to the inaccurate modeling of the interreflected daylight component from the ceiling. A closer inspection of the time-lapse photographs revealed that in the morning the ceiling is illuminated by sunlight reflected from the exterior shading (**Figure 67**). This effect may not be as pronounced in the computer model due to the fact that the tree southeast of the site had been modeled as an entirely opaque plane, so the plane does not allow any direct sunlight to pass through (**Figure 61**). However, it was not possible to more accurately model the complex daylighting effect of the tree.

Figure 66 Horizontal workplane illuminance at workstation #4

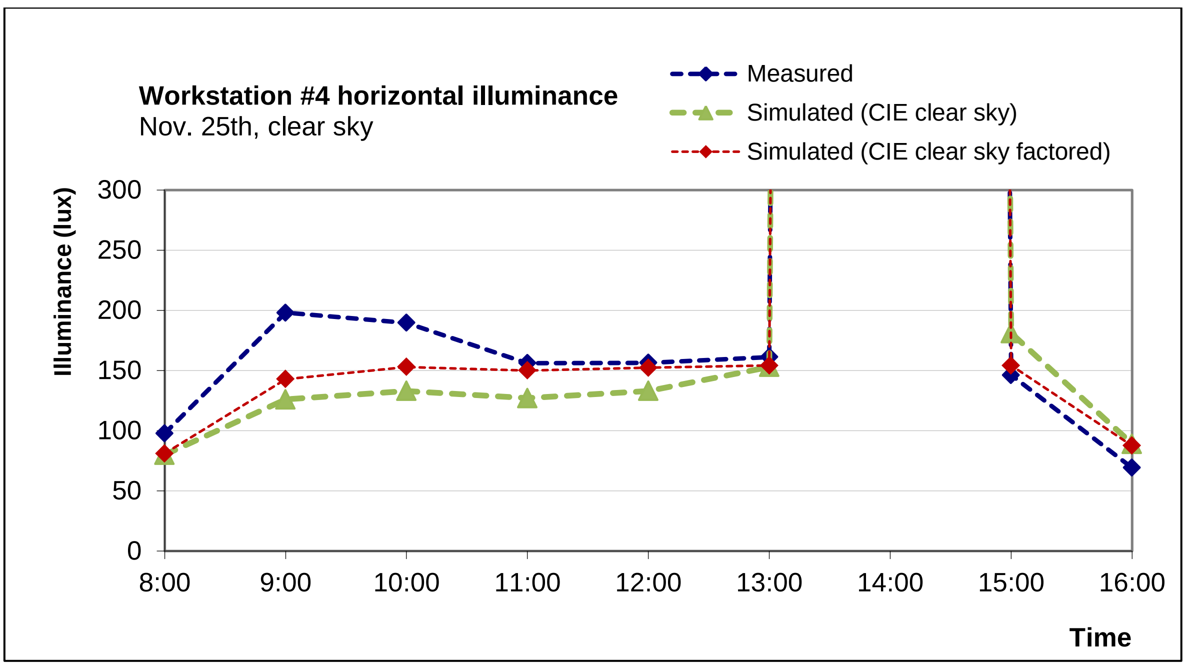

Table 12 Actual and simulated workplane illuminances at workstation #4

Date	Time	Illuminance (lux)			Error		
		Measured	Simulated (CIE clear sky)	Simulated (CIE clear sky factored)	Factor[1]	Simulated (CIE clear sky)	Simulated (CIE clear sky factored)[2]
11/25	8:00	98	80	81	1.01	-18%	-17%
11/25	9:00	198	126	143	1.13	-36%	-28%
11/25	10:00	190	133	153	1.15	-30%	-19%
11/25	11:00	156	127	150	1.18	-19%	-4%
11/25	12:00	156	133	152	1.15	-15%	-3%
11/25	13:00	161	153	154	1.01	-5%	-4%
11/25	14:00	25020	15,805	24222	1.53	-37%	-3%
11/25	15:00	146	181	154	0.85	24%	5%
11/25	16:00	69	89	88	0.98	29%	26%

[1] Factor is equal to measured vertical facade illuminance divided by simulated vertical facade illuminance.
[2] CIE clear sky factored values calculated by multpliying simulated values by the factor listed.

Figure 67 View of facade at 10:00 on Nov. 25th

7.1.3. SIMULATION PROCEDURE AND ASSUMPTIONS

In order to assess daylight quality within the space, two types of simulations for two perimeter workstations (#2 and 4) were conducted: point-in-time and annual simulations. The point-in-time simulations were used to determine the luminance ratios within the occupant's field of view, while the annual simulations were conducted to calculate daylight levels in the space. In contrast to the point-in-time simulations which assess daylight at specific times of the year, the dynamic daylight simulations are used to assess daylight variation in the space over a period of time. Since the point-in-time simulations are based on CIE clear and overcast skies, they represent two extreme sky conditions – a perfectly clear and perfectly overcast sky; the annual simulations account for location-specific annual variations in sky conditions and include the range of intermediate sky conditions characteristic of the East Bay climate. The specific metrics used to evaluate daylight quality are discussed in detail in the next section.

Cases modeled. The baseline model geometry used for the simulations was discussed in section 7.1.1 *Model geometry.* Three cases were modeled:

1. Case with fixed exterior louvers (baseline)
2. Case without fixed exterior louvers (none of the aluminum louvers on the south facade are included in the model)
3. Case without fixed exterior louvers and with manually-operated interior roller shades (annual simulations only)

Workstations. Calculations were performed for two workstations – workstations #2 and #4 **(Figure 70)**. For both workstations, annual illuminance levels were calculated for fixed sensor points at the level of the workplane (29" above the floor). Luminance ratios were calculated for the occupant's field of view. See the next section for a more detailed description of how the illuminance sensor points and the field of view were defined.

Dates and times (point-in-time simulations). The point-in-time simulations were conducted for representative times of the year and two different skies:

a. CIE clear sky[30] – 9 am, noon and 3 pm on June 21,st Sept. 21,st and Dec. 21st

b. CIE uniformly overcast sky – noon on June 21st

Weather data (annual simulations). For the annual simulations, a TMY3 weather file for Oakland in Energy Plus (.epw) file format was used.[31] DAYSIM, the simulation engine used for annual daylight calculations, uses hourly solar radiation data from this file in conjunction with the Perez sky model to calculate the luminance distribution of the sky for a range of sky conditions throughout the year (Reinhart, 2006).

Occupancy (annual simulations). A weekday occupancy schedule from 8:00 to 18:00 (Monday through Friday) was defined for the annual calculations. The schedule includes a one-hour lunch break from 12:00 to 13:00 and accounts for major U.S. holidays and daylight savings time (second Sunday in March to the first Sunday in November).

Shading operation (annual simulations). Since the field study revealed that office occupants did not lower shading during the study duration (see 6.2.5), presumably due to a lack of need for shading, the baseline case (case with louvers) was modeled with interior shades raised. For the case with manually-controlled interior roller shades, an in-built DAYSIM occupant shading control model – Lightswitch, was used to account for the effect of interior shade operation on annual illuminance levels. The model was developed based on

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[30] The calibration procedure revealed that the CIE clear sky model is a reasonable approximation for the site modeled (see section 7.1.2 *Model calibration* for more information).

[31] See chapter *6 Field study,* subsection *6.2.1 Exterior illuminance and sky conditions* for a more detailed discussion of TMY data.

field studies of occupant electrical lighting and interior shading control in one- and two-person offices (Reinhart & Voss, 2003; Reinhart, 2004, Reinhart, 2006). The model differentiates between active users (those who adjust lighting and shading in response to daylight conditions) and passive users (those who keep electric lighting on throughout the working day and blinds closed throughout the year). For the active user case, when the threshold of 50 W/m^2 radiation at the workplane sensor is exceeded, interior shading in DAYSIM is lowered.[32] Interior shading is raised the following morning or upon the user's return to the office after a period of absence. Since the field data does not provide any information on the user types within the space, a combination of passive and active users was specified for the purposes of the simulation.

Six sensor points were defined at the level of the worksurface at all four perimeter workstations. An additional sensor was defined at the center of each monitor (**Figure 68**). It was assumed that only the large middle roller shade would be lowered when direct sunlight at any of the sensor points exceeded the threshold value of 50 W/m^2 (**Figure 69**).[33] Effective fenestration occlusion with lowered shades is 60%.

Ambient parameters. The ambient parameter settings used for both the point-in-time and the annual daylight calculations are listed in **Table 13**.

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32 The 50 W/m^2 threshold is used as an indication of the presence of direct sunlight. While DAYSIM also provides an option to control shading based on DGP (daylight glare probability), visual comfort analysis revealed that throughout much of the year, vertical eye illuminance, E_v, and DGP for a number of the shaded and unshaded cases are outside of the validity range of DGP (DGP > 0.2 and E_v > 380 lux). This control option was consequently not used.

33 While the conservative assumption for the simulation would have been to assume that all interior roller shades are lowered in the presence of direct sunlight, this may not have been a realistic assumption since each window has three roller shades (one large one and two smaller ones) and an occupant may not close all three roller shades at the same time.

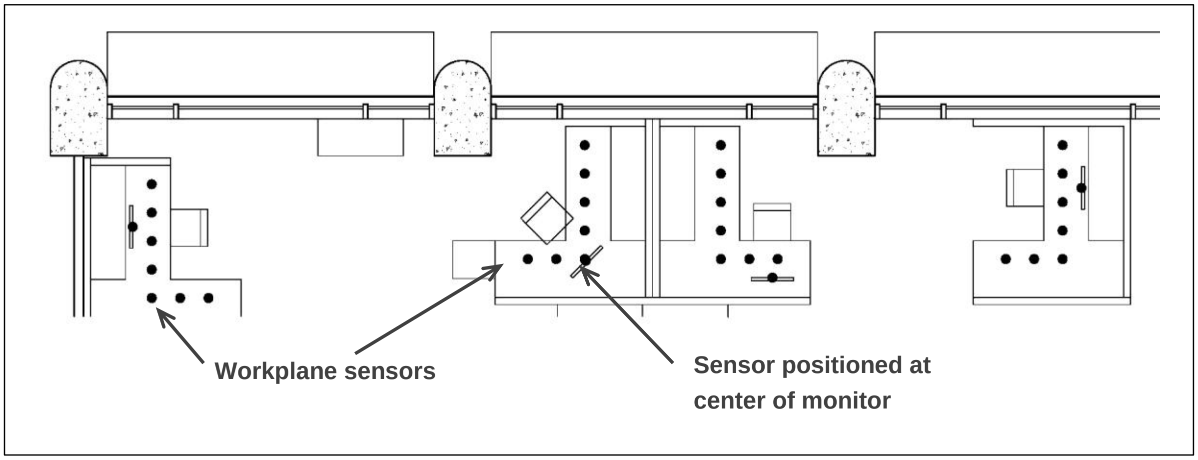

Figure 68 Control sensors for interior shades

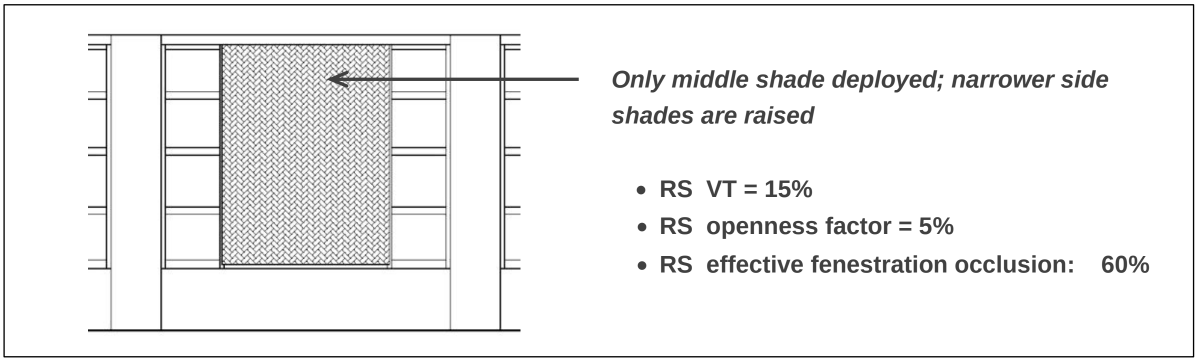

Figure 69 Interior elevation of typical bay showing case with lowered interior shading

Table 13 Ambient parameters used in simulation

Parameter	**Value**
Ambient bounces, *ab*	7
Ambient divisions, *ad*	1400
Ambient super-samples, *as*	700
Ambient resolution, *ar*	1000
Ambient accuracy, aa	0.15

7.1.4. Data analysis

All of the cases modeled (workstations, times, and sky conditions) and the performance metrics used for the daylight analysis are summarized in **Table 15**. The performance indicators used to assess daylight quality – presence of direct sunlight, daylight autonomy (DA), luminance ratios and DGP, are described in detail on the next few pages. Luminance ratios and DGP are used as the primary metrics for evaluating visual comfort. Presence of direct sunlight and the daylight illuminance (UDI) were also used as indicators of visual discomfort, however, as discussed in the background section, the metrics are indirectly related to visual comfort.

Presence of direct sunlight. In order to determine times when direct sun reaches the workplane at workstations #2 and 4, a shading mask for both workstations was created using Ecotect Analysis sustainable building design software (Autodesk, 2011).[34] Model geometry was exported from Rhino and imported into Ecotect in order to calculate periods during which a reference point at the center of the worksurface is shaded (e.g. by surrounding site obstructions, facade elements, office furniture and partitions). The shaded and unshaded periods are displayed as an overlay on a stereographic sun diagram – a polar sun-path diagram in which the solar azimuth is plotted as an angle from North (0-360°) and solar altitude is given as the distance from the center of the diagram (0-90°). Elements of the Ecotect 3-d model were assigned to different-colored layers in order to differentiate between individual shading objects within the stereographic diagram (**Figure 73**).

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[34] Ecotect Analysis software is a comprehensive whole-building design analysis tool that can be used to assess building performance in the context of its site, including thermal performance, solar radiation and overshadowing and reflections.

Workplane illuminance. Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) were used to assess daylight levels throughout the year. A threshold of 300 lux was defined for DA. In addition, an illuminance frequency distribution was calculated based on hourly illuminances to understand variation in daylight levels throughout the year. Four to five sensor points were defined for each workstation at the level of the workplane, 29" above the floor (**Figure 70**). The average workplane illuminance was calculated for each workstation based on these points, all located in close proximity to the occupant (within a 2 ft radius). Since the majority of the work performed in this office is computer-oriented a target workplane illuminance range of 300 to 500 lux was selected (see discussion under section 2.5 *Daylight performance indicators*).

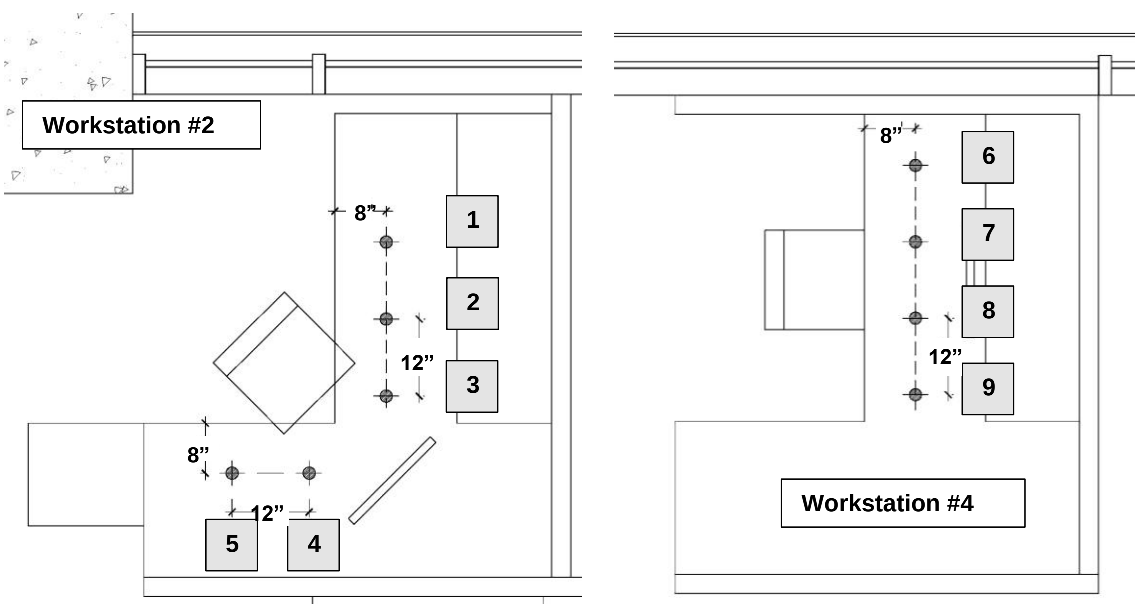


Figure 70 Workplane illuminance sensor points

Luminance ratios. Luminance ratios were calculated for workstations #2 and 4. Simulations were conducted for the dates discussed in section 7.1.3 *Simulation procedure*. It was assumed that the occupant is sitting at their workstation and looking towards the VDT (visual display terminal). An eye level of 47” from the floor (in line with the top of edge of the computer monitor) was assumed. The monitor was rotated 10 degrees from vertical and positioned 24” from the occupant, measured along the line of view (**Figure 71**).

The field of view was simulated assuming a 180° cone of vision, which approximates the actual human field of view (90° to either side, 60° up, and 70° down from the line of sight). Luminance ratio limits between the task area and the immediate surroundings, and the task area and remote surroundings are summarized in **Table 14**. It was assumed that the VDT constituted the primary task area and that the screen has a luminance of 200 cd/m^2, which corresponds to the average luminance of a negative-contrast LCD screen (screen with black characters on a white background). A sheet of white paper with 80% reflectance was modeled on the worksurface for reference.

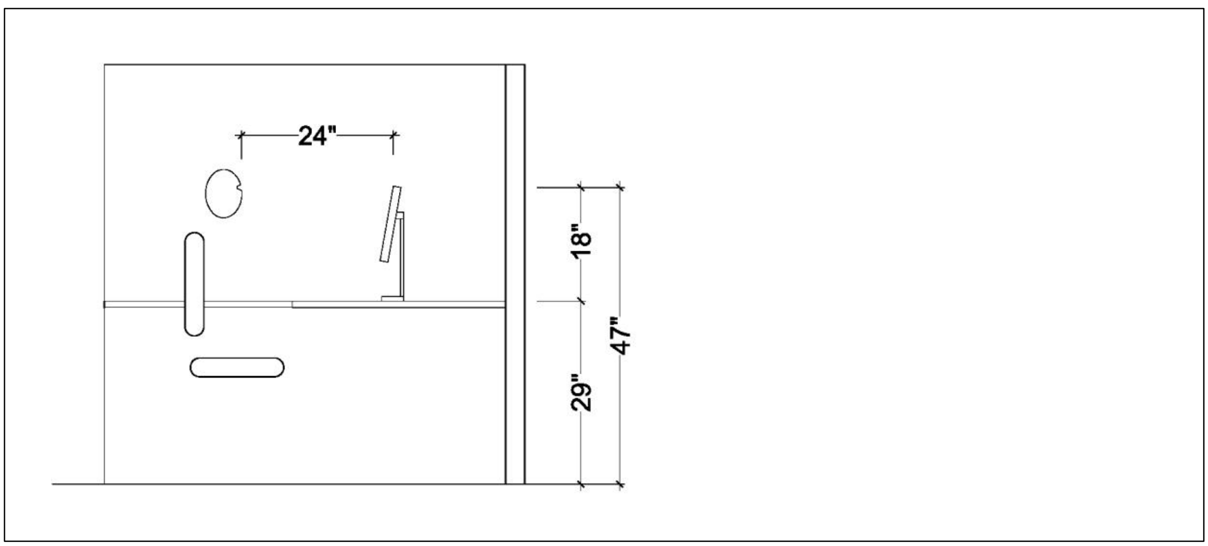


Figure 71 Occupant position with respect to the VDT and work surface

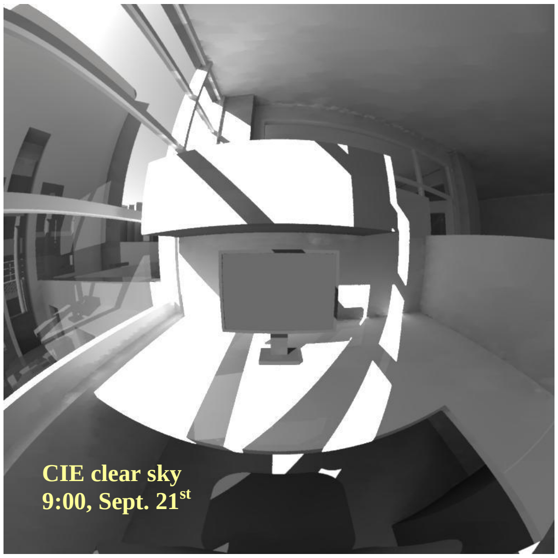
Radiance fish-eye view renderings were post-processed and evaluated using two Radiance programs, *wxfalsecolor* and *evalglare* (**Figure 72**). *Wxfalsecolor* is a program which can be used to display Radiance RGBE (*.hdr and *.pic) images, display luminance/illuminance values of any point within the field of view and search for minimum and maximum luminance values. A falsecolor overlay can be applied to the image to delineate areas within specific luminance ranges. *Evalglare* is a program that detects glare sources within the occupant's field of view (defined based on a 180° cone of vision) using one of the three methods for calculating thresholds:

A. User-defined fixed luminance value

B. A multiplier of the average luminance

C. A multiplier of the average task area luminance

For the luminance ratio analysis, method A was used; a fixed luminance value was defined based on the IESNA limits between a) the task and adjacent surroundings and b) task and remote (nonadjacent surfaces) (**Table 14**). The focus of the analysis was on the upper limit – rendered images of the occupant's field of view were evaluated to see whether any area exceeded either the 1:3 or 1:10 limits. Since the VDT screen (200 cd/m^2 average luminance) was assumed as the primary task area, the values corresponding to the luminance ratio limits for the ergorama and panorama were 600 and 2000 $cd/m,^2$ respectively. These values were specified as the input for *evalglare*, and the program was used to create an overlay indicating areas exceeding the specified luminace threshold (**Figure 72**).



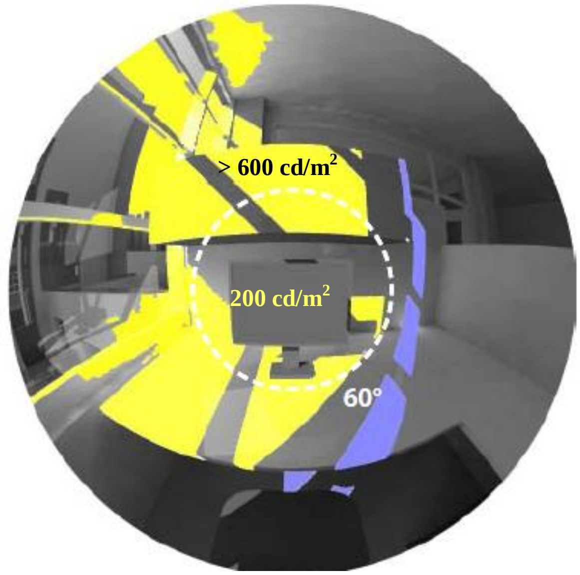


Figure 72 Sample 180° fisheye view of workstation #4 (left); image post-processed in *evalglare* showing areas exceeding luminance threshold (right)

A circular area corresponding to the field of view was defined in each of the renderings to help identify glare sources. An example of the input to *evalglare* is presented below:

evalglare -b 600 *-c* Workstation_4_062109_eval600.pic *–d*

The –b option in the equation above represents the threshold luminance value (pixels exceeding this value are masked). The –d option enables detailed *evalglare* output, where in addition to the standard output (DGP, DGI, average luminance of the image, vertical eye illuminance, and several other glare indices, and average luminance of all glare sources) the program also calculates the position and average luminance of each glare source.

Table 14 IESNA luminance ratio limits

IESNA classification	Zone definition (Meyer et al. 1996)	Corresponding cone of vision[1]	Upper limit	Lower limit
Between paper task and adjacent VDT screen	N/A	N/A	3:1	1:3
Between task and adjacent dark surroundings	“Ergorama”	60°	3:1	1:3
Between task and remote (nonadjacent surfaces)	“Panorama”	120°	10:1	1:10

[1] The 60° and 120° cones of vision for the adjacent and remote surroundings prescribed by IESNA are defined based on the Meyer et al. (1996) definition of the ergorama and panorama.

Glare. Daylight-glare probability (DGP) was used for evaluating the likelihood of glare, however the validity range for DGP – DGP > 0.2 and vertical eye illuminance, $E_{v,}$ > 380 lux (Wienold, 2009), limited its applicability to only a few of the cases modeled. The vertical eye illuminance was considerably lower than 380 lux this for most of the cases with fixed exterior louvers and for several of the cases without shading due to reduced space daylight levels on account of site obstructions. The DGP glare rating scale is subdivided into the following ranges:

DGP ≤ 0.35 A; best class office: glare weaker than “imperceptible”

DGP ≤ 0.40 B; good class office: glare weaker than “perceptible”

DGP ≤ 0.45 C; reasonable class office: glare weaker than “disturbing”

Since DGP could not be used to assess glare in most of the cases with louvers, the daylight glare index is provided. However, as discussed in the background section, past research has indicated that this metric has a poor correlation with occupant response to glare, so the metric is only provided for comparison purposes.

Table 15 Metrics used to assess daylight quality for cases with and without exterior shading

		Workstation #2 and #4 analysis			
		Clear			Overcast
Metric	Annual	June 21	Sept. 21	Dec. 21	June 21
Direct sun: shading mask	x	-	-	-	-
Direct sun: shading mask - w/out louvers	x	-	-	-	-
DA	x	-	-	-	-
DA - w/out louvers	x	-	-	-	-
DA - w/out louvers w/ int. RS	x	-	-	-	-
Lum. contrast ratios	-	9, 12, 15	9, 12, 15	9, 12, 15	12
Lum. contrast ratios - w/out louvers	-	9, 12, 15	9, 12, 15	9, 12, 15	12
DGP[1]	x	9, 12, 15	9, 12, 15	9, 12, 15	12
DGP - w/out louvers[1]	x	9, 12, 15	9, 12, 15	9, 12, 15	12

[1] Calculated for workstation #4 only.

7.2. FINDINGS

7.2.1. PRESENCE OF DIRECT SUNLIGHT

Figure 73 and **Figure 75** show periods of the year when direct sunlight reaches the worksurface reference point at workstations #2 and 4. These two diagrams, which exclude the effect of shading from the fixed exterior aluminum louvers and interior furnishings, reveal that approximately 75 and 60% of direct sun is blocked during occupied hours (8:00 to 18:00) at workstations #2 and #4, respectively, due to shading from structural concrete columns and surrounding site obstructions alone. Oxford Plaza apartments have a significant impact on midday shading during fall and winter months (October to mid-March) and additional shading is provided in the mornings by buildings and landscape southeast of the site. The stereographic sun diagrams shown in **Figure 74** and **Figure 76** show that fixed exterior shading effectively blocks direct sunlight during remaining times of the year.

Due to significant shading from Oxford Plaza and concrete structural columns, the impact of the exterior louvers is relatively small.[35] This is especially clear in the case of the lower two louvers. While the uppermost two louvers effectively block midday (10:30 to 14:30) sun from April to October, most of the lower part of the window is shaded by the Oxford Plaza apartment building which blocks midday sun from October through March.

Interestingly, late afternoon sun is blocked not only by concrete structural columns but also by the 5-1/2-ft-high workspace partitions, oriented perpendicular to the facade. This suggests that in the case of a less shaded facade, these partitions could have a positive effect on occupant visual and thermal comfort by blocking low-angle afternoon sun.

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[35] Oxford Plaza apartments block direct sun from reaching the center of the workplane from late morning to late afternoon from the fall equinox to the spring equinox, while the concrete columns block direct sun for at least a couple of hours in the morning and afternoon throughout majority of the year.

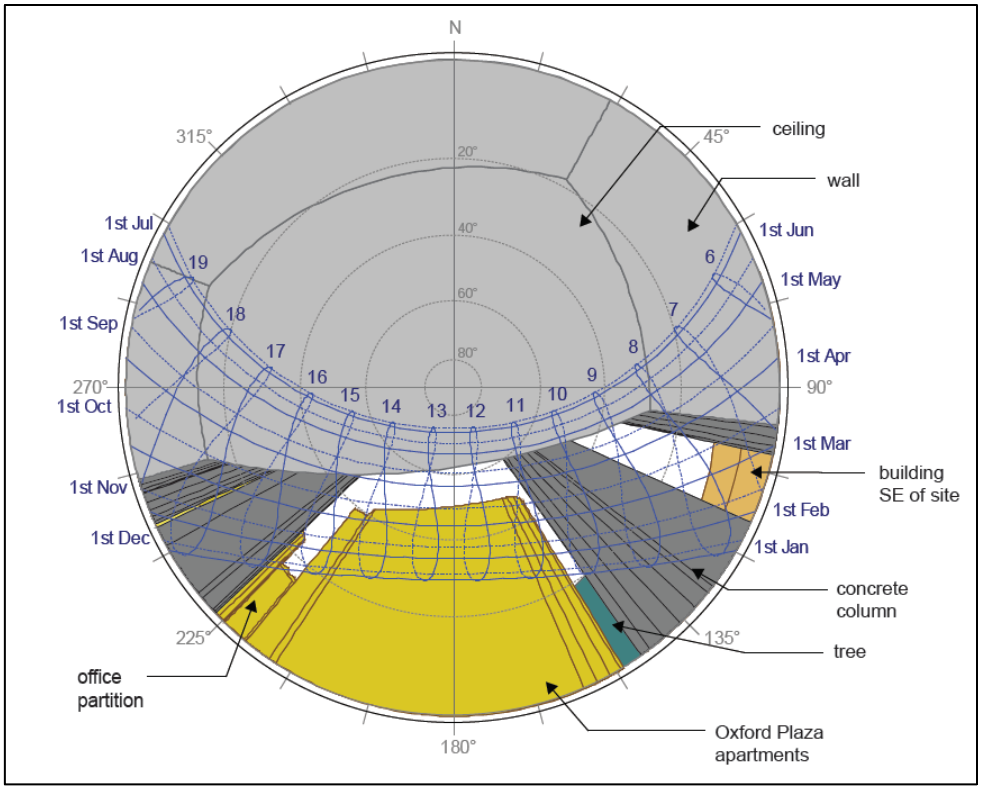

Figure 73 Workstation #2 shading mask (without louvers)

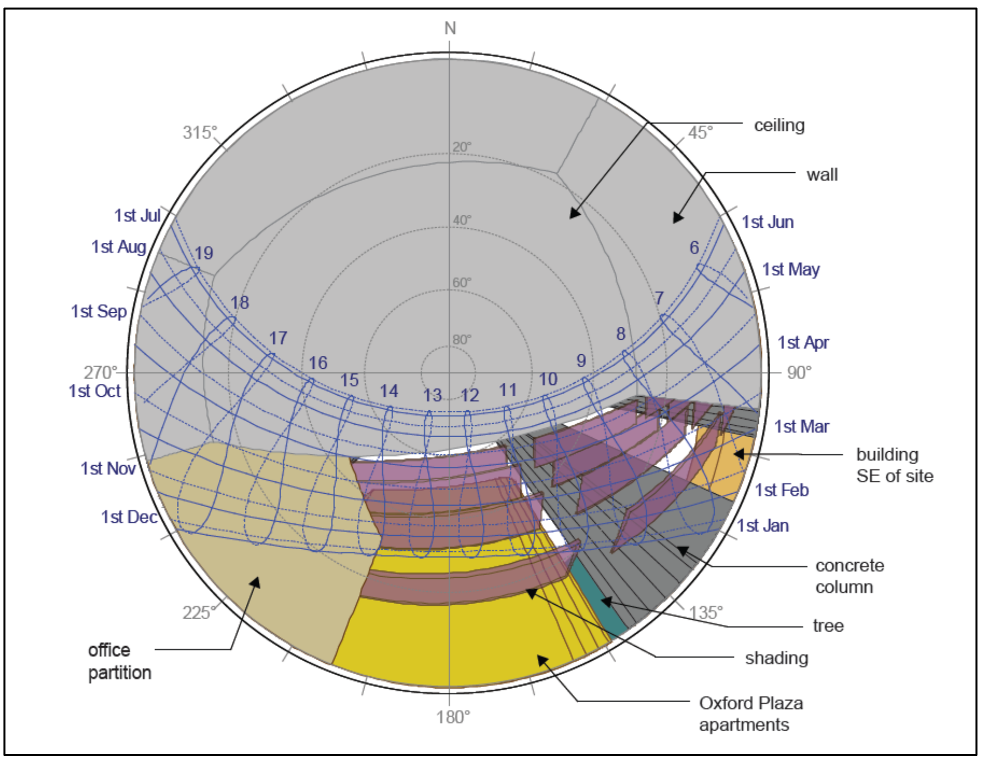

Figure 74 Workstation #2 shading mask (with louvers and cubicle partitions)

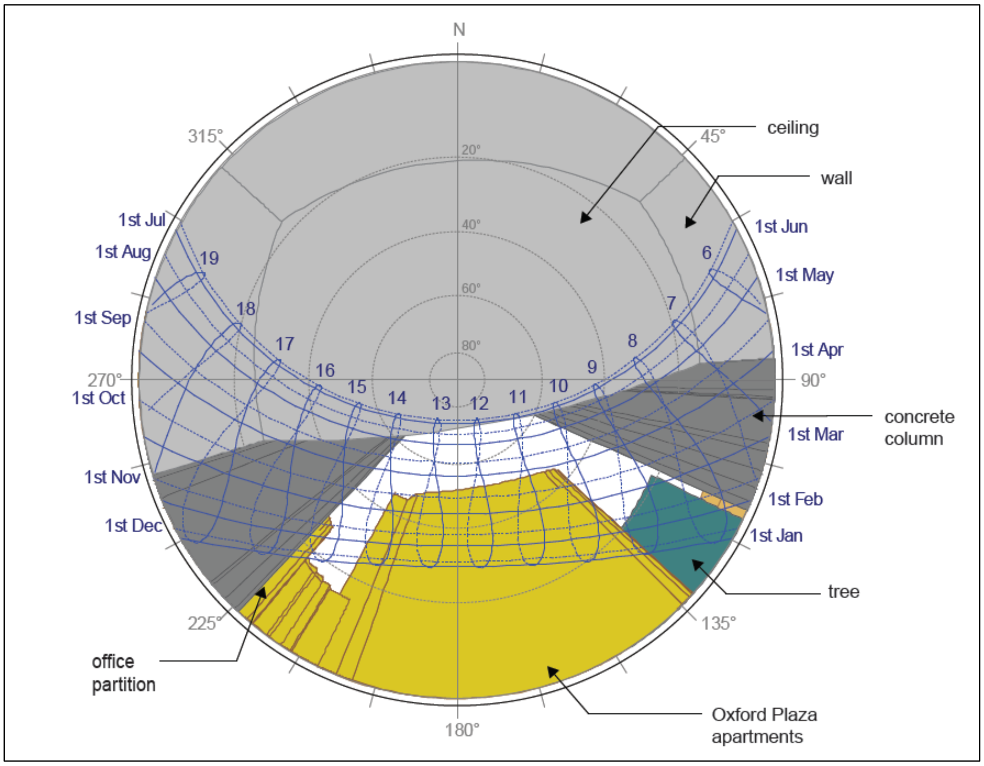

Figure 75 Workstation #4 shading mask (without louvers)

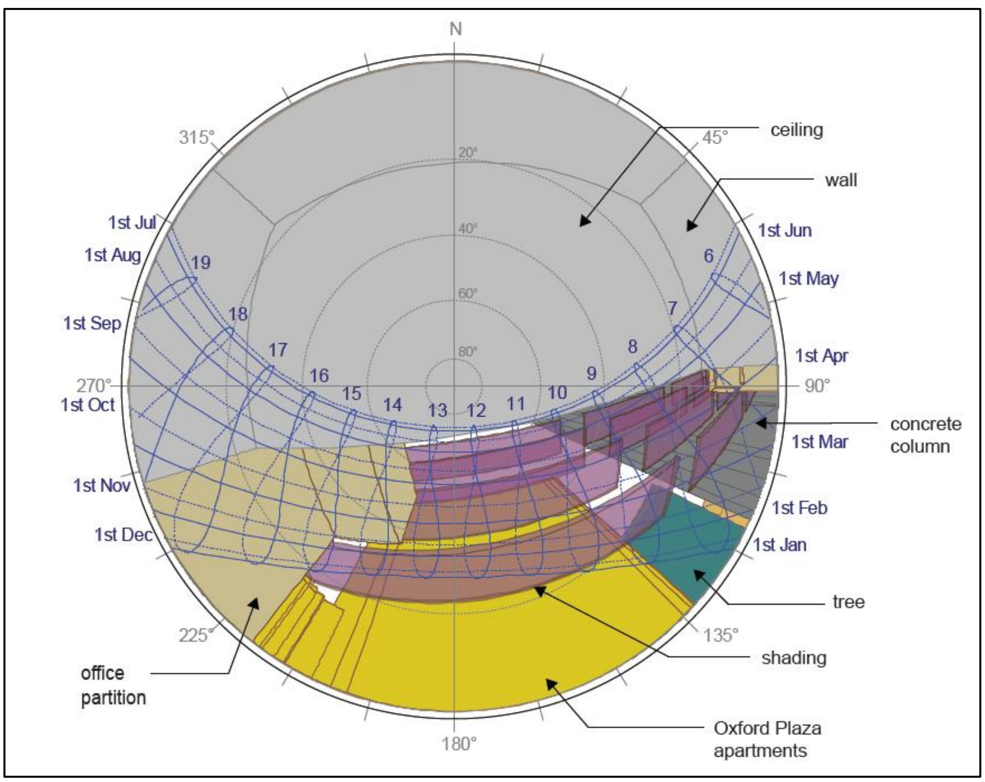

Figure 76 Workstation #4 shading mask (with louvers and cubicle partitions)

7.2.2. WORKPLANE ILLUMINANCE

The results of annual daylight calculations are presented in **Table 16**. Since results for the two workstations analyzed (#2 and #4) were relatively close, the results for all of the sampled points (**Figure 70**) at both workstations were averaged.[36] The results indicate that illuminance levels at the two workstations are above 300 lux 57% of occupied hours[37] for the case with fixed exterior shading, and 91% for the case without shading (**Table 16**). If we assume that illuminances below 300 lux are not sufficient for task performance, the results imply a need for supplemental electrical lighting 43% of occupied hours for the case with fixed exterior shading (and only 9% for the case without). However, a UDI_{2000} value of 31% for the case without exterior shading indicates that nearly a third of the time daylight levels for this case are above 2000 lux, suggesting that visual discomfort may be a problem and may thus requires supplemental interior shading.

However, if we account for interior roller shade operation in the case without exterior shading, the frequency of illuminances above 2000 lux is greatly reduced.[38] Daylight levels for this case exceed 300 lux 79% of the year, considerably higher than for the case with fixed

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[36] The results revealed that the illuminance levels for both workstations were comparable, however illuminance levels at workstation #4 were slightly higher, as expected, since the workstation points sampled are closer to the facade.

[37] Weekdays between 8:00 and 18:00, excluding a one-hour break between 12:00 and 13:00

[38] This assumes that the middle roller shades are lowered across all four bays when the threshold of 50 W/m^2 is exceeded at any of the perimeter workstations. Once deployed, shades remain lowered for the remainder of the day and are raised when the occupant returns to the office the following day. Only the large middle shades are lowered; the smaller side shades remain open. For more information, see description of assumptions in 7.1.3 *Simulation procedure and assumptions.*

exterior shading (**Table 16**). Even if the shades remain closed throughout all occupied hours, daylight autonomy is still higher (64%) than for the case with fixed exterior shading (57%).[39]

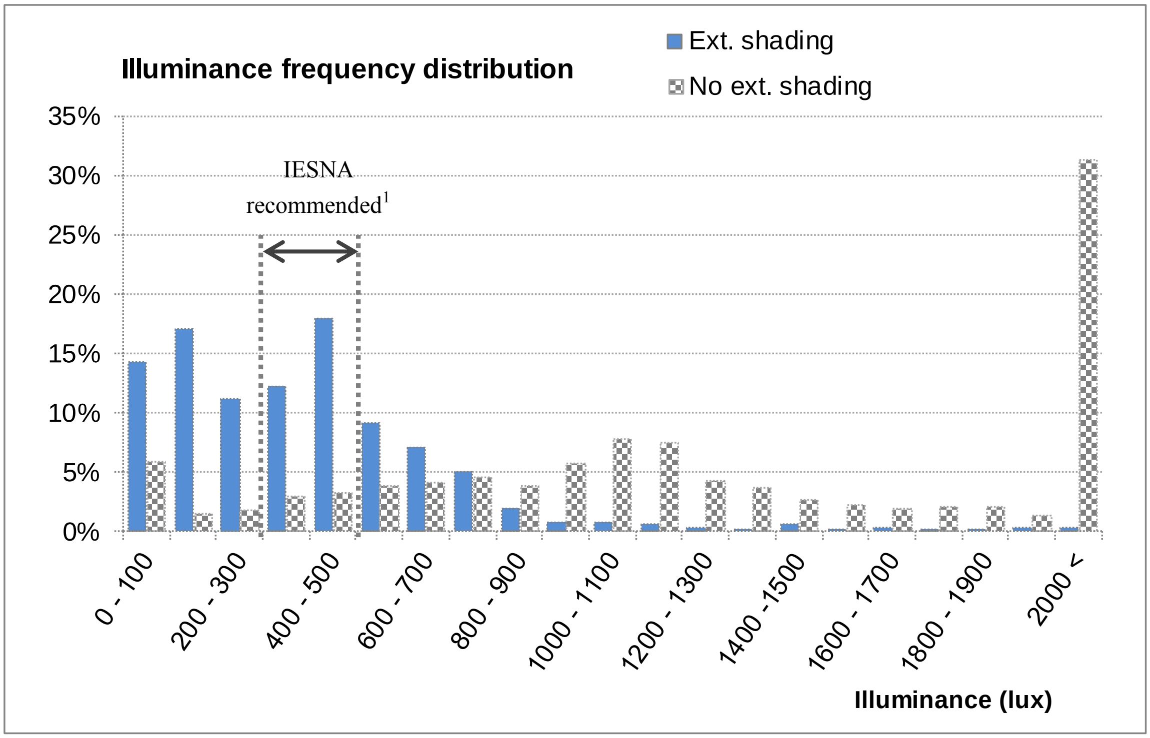
Illuminance levels are within the IESNA recommended range of 300 to 500 lux 30% of the time for the case with louvers, 5% for the case without louvers, and 19% for the case without louvers but with an interior roller shade. **Figure 77** and **Figure 78** show annual hourly illuminance frequency distributions. The diagrams illustrate that the illuminance levels for the shaded case are too low, while the illuminance levels for the case without louvers are too high when compared to the IESNA recommended range of 300 to 500 lux for computer-based tasks (**Figure 77**). For the case without louvers, illuminances are higher than 500 lux for 86% of occupied hours, and higher than 2000 lux for 31% of occupied hours. However, once we account for interior roller shading, the case without fixed exterior shading compares favorably to the case with shading since daylight autonomy levels are considerably higher, however the case with louvers still has a higher number of hours the 300 to 500 lux range recommended by IESNA (**Figure 78**).

Table 16 Daylight Autonomy and Useful Daylight Illuminance for workstations #2 and 4

Case	DA_{300}	DA_{500}	UDI_{100}	$UDI_{100\text{-}2000}$	UDI_{2000}
Ext. shading	57%	27%	14%	85%	0%
No ext. shading	91%	86%	6%	63%	31%
No ext. shading + RS: active user	79%	60%	7%	81%	12%
No ext. shading + RS: always down	64%	35%	9%	83%	8%

39 It should be noted that while the results for the case with fixed exterior shading do not assume any interior shading operation, the analysis of visual comfort (see following section, 7.2.3 *Luminance ratios*) indicated that visual discomfort is unlikely and thus the need for supplemental interior shading is minimal.

Figure 77 Illuminance frequency distributions: (1) ext. shading case and (2) no shading case



[1] 300-500 lux illuminance range recommended by IESNA for computer-based tasks

Figure 78 Illuminance frequency distributions: (1) ext. shading case and (2) interior RS case

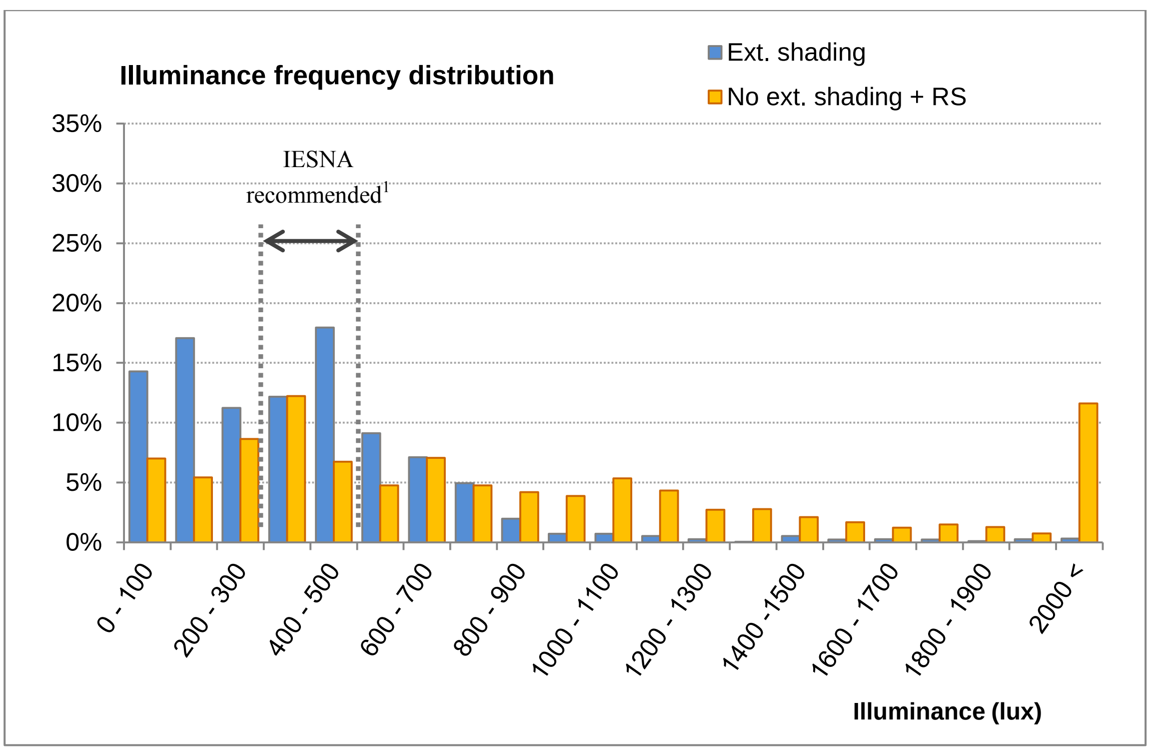


Figure 79 shows shade operation and electrical lighting need by season for the case without louvers assuming a target workplane illuminance at the perimeter workstations of 300 lux. Results indicate that interior roller shades are deployed approximately 64% of the time. It should be noted however, that the shading control algorithm may be overly conservative.[40] Despite the relatively high rate of shade deployment, the need for electrical lighting is limited to 25% of occupied hours, with a minimal need for lighting in the summer months (May - July) – less than 5% of the time, and a moderate need in the winter months (Nov. - Jan.) – 40%.

7.2.3. Luminance ratios

Luminance ratio results for both workstations are included in *Appendix J*. See discussion in section 7.1.4 *Data analysis* for a more detailed description of how the field of view was defined and the luminance ratios calculated.

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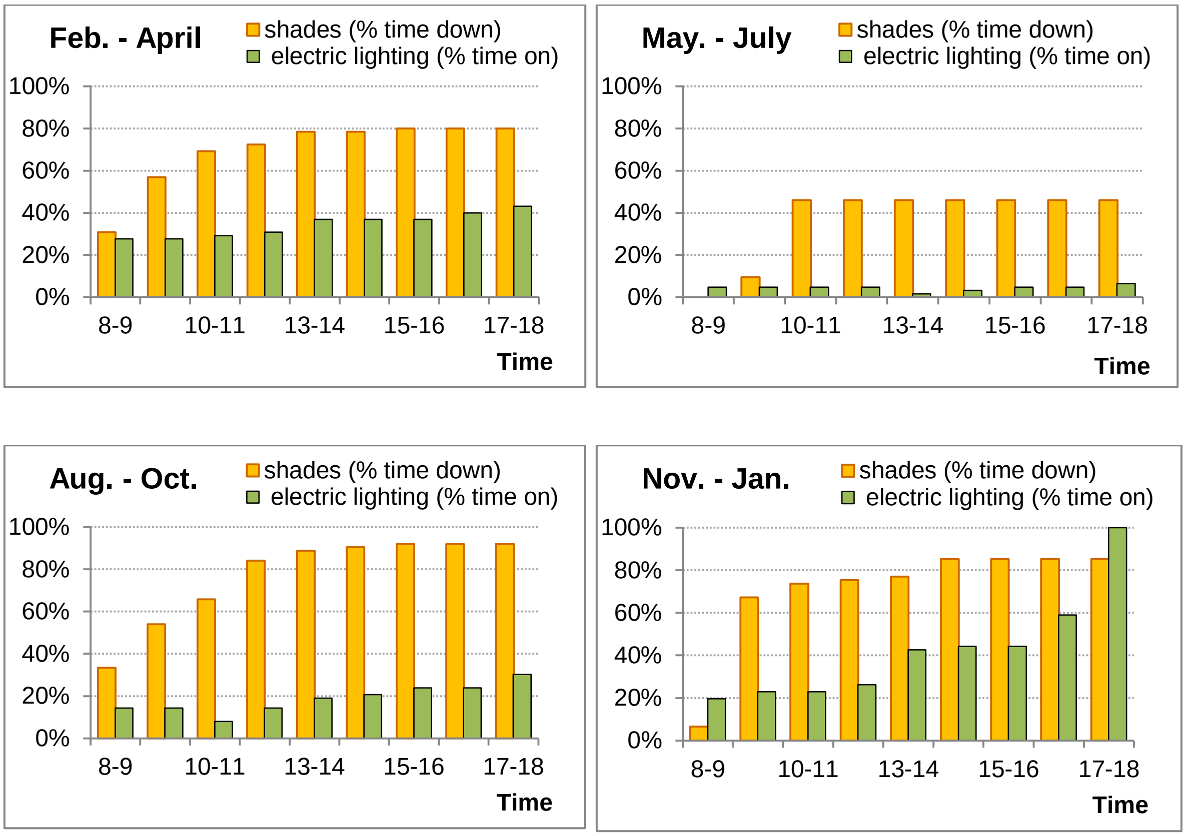
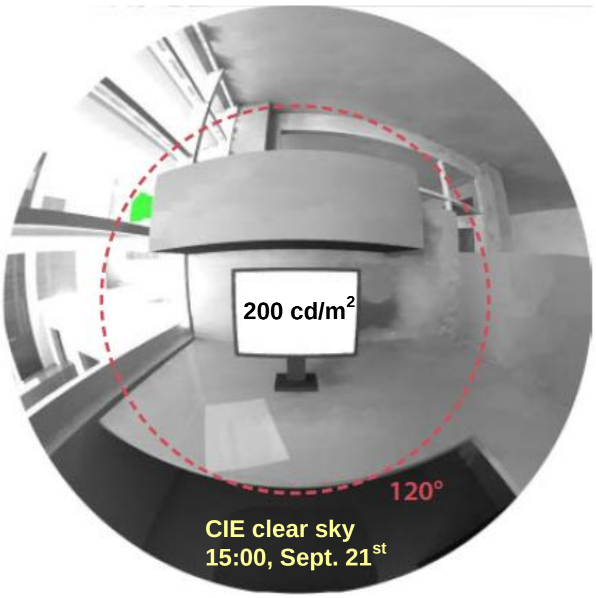
[40] The shading control model used for the simulation may be overly conservative due to the following:
(1) The model assumes that once deployed, shades remain lowered for the remainder of the day.
(2) If there is direct sun at any of the workstations, all of the roller shades are lowered, whereas in reality the occupant may only lower the shades closest to that particular workstation.
(3) The shade control model used in DAYSIM does not take into account the fact that occupants may tolerate short periods of direct sunlight. For example, the shading masks presented in the previous section reveal that in the case of workstation #2, duration of morning direct sunlight at the worksurface from Nov. to February is less than 30 minutes (**Figure 73**), however the roller shades were lowered from this point onward for the remainder of the day.

Figure 79 Shade deployment by season: No louvers + RS case



Case with louvers. The luminance ratios for the shaded case suggest that visual discomfort at either of the workstations is unlikely. There were no glare sources detected for workstation #2 and only one potential source at workstation #4. The detected glare source is part of a light-colored exterior wall belonging to an adjacent building (**Figure 80**). While this small glare source (solid angle of source is approximately 0.015 steradians) is present throughout most of occupied hours, it appears on the outer periphery of the 120° cone of vision. The median luminance ratio for the dates simulated between this glare source and the VDT is 17:1. Since no glare sources were detected at workstation #2, this position may be preferable in terms of visual comfort, however additional analysis would be required in order to determine whether veiling reflections on the computer screen at either of the two orientations could be an issue.



L_s = 3560 cd/m^2
ω = 0.125
L_s / L_{task} = 18:1

Figure 80 Glare source at workstation #4

Case without louvers. The probability of visual discomfort is greater for the case without exterior louvers. Target luminance ratios for the ergorama and panorama are exceeded during periods when direct sun falls on the work surface: Sept. 21st at 9:00 and 12:00 for both workstations. Moreover, the same glare source as the one noted for the case with shading (exterior wall of an adjacent building as seen through the window). However apart from these two cases, luminance ratios are within the targets recommended by IESNA, suggesting that for a large portion of the year visual discomfort is minimized due to shading from surrounding site obstructions. The results of the luminance ratio analysis suggest that direct sun can be used as a relatively good predictor of visual discomfort, however visual discomfort may also be present even if there is no direct sun, as is seen in the case of the bright wall of the adjacent building.

7.2.4. Glare

DGP was only calculated for workstation #4. Due to limitations of DGP and the fact that for a number of cases E_v and DGP fall below the lower limits of 380 lux and 0.20, respectively, DGP was only calculated for two cases with shading and five cases without shading (**Figure 81**).[41] For the case with shading, for both of the times analyzed (June 21st and Sept. 21st at 9 am), a DGP of 0.23 and 0.21, respectively, suggests that glare at this workstation is "imperceptible."[42] For the case without shading, DGP falls below the threshold value of 0.35 in June, however in September, the glare in the morning (DGP = 0.41) would be characterized as "disturbing," and as "perceptible" midday (DGP = 0.39), see **Figure 82**. Finally, while research has indicated that DGI is poorly correlated with occupant response to glare, the indices are what one would expect based on the DGP values: all of the dates/views analyzed have a DGI at or below 16 ("just perceptible"), with the exception of the two September times which have DGIs of 25 and 26, respectively ("uncomfortable") and a DGI of 17 at 9:00 in June ("just perceptible").

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[41] Validity range of DGP: DGP > 0.2 and E_v > 380 lux

[42] The DGP glare rating scale is subdivided in to the following ranges:
DGP ≤ 0.35 "A" - best class office: glare weaker than "imperceptible"
DGP ≤ 0.40 "B"- good class office: glare weaker than "perceptible"
DGP ≤ 0.45 "C" - reasonable class office: glare weaker than disturbing"

Figure 81 DGP and DGI at workstation 4 (case with louvers)

Date	Time	Sky	E_v (lux)[1]	DGP[2]	DGI	$L_{s\ ave}$ (cd/m^2)[3]	Σ ω (steradians)[4]
21-Jun	9:00	clear	489	0.23	17	3560	0.125
21-Jun	12:00	clear	(310)	(0.18)	3	2189	0.002
21-Jun	15:00	clear	261	(0.18)	3	2118	0.013
21-Sep	9:00	clear	549	0.21	15	3323	0.032
21-Sep	12:00	clear	(318)	(0.18)	4	2515	0.016
21-Sep	15:00	clear	(337)	(0.18)	7	3937	0.016
21-Dec	9:00	clear	(337)	(0.18)	7	3937	0.016
21-Dec	12:00	clear	(135)	(0.18)	8	3182	0.015
21-Dec	15:00	clear	(261)	(0.19)	11	6538	0.016
21-Jun	12:00	ov	(172)	(0.18)	6	2474	0.015

[1] E_v - vertical illuminance at eye (lux)

[2] DGP validity range: DGP > 0.2 and E_v > 380 lux

[3] $L_{s\ ave}$ - average luminance of all glare sources (cd/m2)

[4] Σ ω - sum of solid angles of all glare sources (steradians)

( ) value out of range

Figure 82 DGP and DGI at workstation 4 (case without louvers)

Date	Time	Sky	E_v (lux)[1]	DGP[2]	DGI	$L_{s\ ave}$ (cd/m^2)[3]	Σ ω (steradians)[4]
21-Jun	9:00	clear	611	0.23	16	3560	0.126
21-Jun	12:00	clear	494	0.21	13	3140	0.088
21-Jun	15:00	clear	436	(0.19)	2	2097	0.046
21-Sep	9:00	clear	3753	0.41	26	3775	1.208
21-Sep	12:00	clear	3192	0.39	25	5681	0.838
21-Sep	15:00	clear	714	0.21	13	3401	0.129
21-Dec	9:00	clear	(191)	(0.17)	-	-	-
21-Dec	12:00	clear	(287)	(0.18)	4	2586	0.063
21-Dec	15:00	clear	470	(0.19)	8	4459	0.055
21-Jun	12:00	ov	459	(0.19)	4	3207	0.148

7.3. Discussion

Simulation findings for the south-facing office space reveal that shading from structural concrete columns and surrounding site obstructions (especially midday shading from Oxford Plaza apartments during fall and winter months), minimizes the need for additional shading through fixed exterior aluminum louvers. While the uppermost two louvers effectively block midday (10:30 to 14:30) sun from April to October, the lower two louvers are not needed to block direct sun because the Oxford Plaza apartment building blocks midday sun from October through March (**Figure 74** and **Figure 76**). In fact, the exterior aluminum louvers reduce daylight levels considerably (DA = 57%) when compared with the unshaded case (DA = 91%). However, luminance ratios for the latter case indicate a slightly higher frequency of visual discomfort, suggesting interior roller shade use would somewhat increase.

While interior roller shade operation can considerably affect daylight levels, results indicate that for the simulated office space, daylight autonomy is higher for the case without exterior louvers regardless of how interior roller shades are operated. For example, if we assume that that the user is more actively involved in shade operation and that they retract shades every morning upon returning to the office, daylight autonomy is considerably higher (DA = 79%) than for the case with fixed exterior shading. On the other hand, if roller shades remain closed throughout the year, daylight autonomy is 64%, which is still higher than for the case with fixed exterior louvers, but considerably lower than for the case without louvers but with an active user.[43] It should be noted that the relatively high daylight autonomy for the case without louvers and with roller shades lowered throughout the year is attained in part due to the fact that only the wide middle interior roller shade is deployed while the narrow

43 This could be considered a fairly conservative assumption since the majority of time no direct sunlight reaches the facade, so one could reasonably expect that occupants would be more engaged in shade operation in order to take advantage of daylight and view to the outside.

side shades remain raised.[44] This suggests that installing several smaller roller shades rather than one large shade could result in higher daylight levels.

While the daylight levels are higher for the case without exterior louvers, increased reliance on roller shades to block direct sunlight results in a high frequency of window occlusion, resulting in fewer times with a view to the outside. The simulations indicate that view is blocked approximately 2/3 of the time, however the shading control algorithm may be somewhat conservative since it does not account for the fact that occupants may tolerate short periods of direct sunlight. For example, at workstation #2, the duration of morning direct sunlight during fall and winter months (Oct. to March) does not exceed 30 minutes (**Figure 73**) and there is no direct sunlight until mid-afternoon, which, once again, is very brief (less than 30 minutes in duration).

Despite the relatively high rate of shade deployment, the need for electrical lighting is limited to 25% of occupied hours. This can be once again attributed to the fact that only the wide roller shade is lowered in the simulations, allowing some daylight to enter the space through the unoccluded portion of the window.[45]

Finally, partitions oriented perpendicular to a south-facing facade may positively contribute to occupant visual and thermal comfort by blocking low-angle morning or afternoon sun. However, the relatively large shading effect from these partitions suggests that interior partitions may have a noticeable effect on daylight and should thus be carefully

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[44] Effective fenestration occlusion with lowered shades is 60%. See more detailed discussion of assumptions in 7.1.3 *Simulation procedure and assumptions*.

[45] It is estimated that when the wider middle roller shade is lowered, approximately 20% of daylight is transmitted through the shaded area, while the remaining 80% is transmitted through the unoccluded portion of the window.

analyzed in the context of the space daylighting strategy. This would be especially important if the partitions were oriented parallel rather than perpendicular to the facade, were relatively high and/or positioned close to the facade.

8. CONCLUSION AND FUTURE WORK

The goal of this study was to determine the reasons why the design team implemented fixed exterior louvers on the south facade of the David Brower Center and to evaluate the louvers' impact on performance. The interviews addressed the first question and the occupant comfort survey and simulations addressed the second. While the field study also provided information on the louvers' impact on performance, its primary purpose was to help shape the assumptions for the computer simulations. The findings from the interviews, occupant comfort survey, field study and simulations were discussed in considerable detail in previous chapters. This section of the thesis will focus on contextualizing the findings in the broader context of building design through a discussion of daylight design and analysis considerations. Recommendations for future research are provided as well.

8.1. CONCLUSION

Facade design in office spaces is particularly complex due to the need to balance increasingly stringent energy code requirements with the well-being and comfort of the building's occupants. While the south facade of the David Brower Center effectively controls solar loads, minimizing the need for cooling, the combination of fixed exterior louvers, concrete structural columns and site obstructions to the south result in a considerable reduction in daylight levels. Daylight levels in the perimeter zone of a representative south-facing office (an office with highly variably occupancy where occupants are frequently away from their workstation) meet the IESNA recommended 300 to 500 lux illuminance range for computer-based offices for 30% of occupied hours but are frequently below (43% of hours) this range. While higher daylight levels could have likely been attained without exterior louvers (and with manually-operated interior fabric roller shades), the illuminances would have been frequently above the target (60% of hours), and within the range for only 19% of occupied hours. This assumes that in the presence of direct sunlight occupants would lower the wide middle roller shade only and that that a narrow (28"-wide) window area on either side of this shade would remain unoccluded. Shades are raised the following day upon the occupant's return to the office.

For the case without exterior louvers, there is a relatively large spread in hourly illuminance distributions (from less than 100 lux to approximately 1300 lux) throughout the year. This suggests that without advanced daylighting strategies (lightshelves, prismatic glazing) it may be quite difficult for a similar side-lit office space (27'-deep with 11'-9" floor-to-ceiling height and light-colored walls and ceiling) to meet the stringent illuminance and visual comfort requirements of VDT offices. In fact, it is reasonable to expect that supplemental electrical lighting in side-lit open plan offices will typically be needed for at least a portion of the year to either increase illuminance levels or improve light uniformity in the space. At the same time, since daylight is critical to health and well-being and occupants prefer daylight to electrical lighting, it is imperative that the electrical lighting system design aim to achieve maximum integration with daylighting in the space. Whereas properly calibrated daylight dimming systems offer best performance in terms of energy savings, results from the field monitoring phase, however brief, indicate that bi-level lighting with a separate switch leg along the perimeter of the zone provided substantial savings.

While the exterior louvers provide the opportunity to minimize interior shading use and maximize the view out (the occupant comfort survey and field study revealed that roller shades are lowered infrequently), the office space studied appears somewhat gloomy. Indeed, two out of the sixteen respondents sitting in offices with exterior louvers who took the survey, complained of a lack of direct sunlight in the space (these two occupants were situated within 5 ft of a window). Respondents did not specifically state why they desired direct sunlight, however past research has indicated that, from a daylighting perspective, small bright areas provide a degree of visual interest in the space (Loe et al., 1994; Newsham & Veitch, 2001) and allow for periodic eye relaxation (IESNA, 1993). Boubekri, Hull & Lester (1991) and Wang & Boubekri (2011) suggest that small patches of direct sunlight may have a positive impact on occupant mood and satisfaction in offices.

If an automated exterior shading system had been installed in place of the exterior louvers, it could have provided a means to provide shading only at times when direct sunlight hits the window and thus still maintain low cooling loads while maximizing daylight. However, automated systems require considerably more maintenance, especially when installed on the exterior. Seasonally-adjusted exterior shading, on the other hand, may provide a simpler alternative to automated systems, and may deliver comparable performance in terms of visual comfort and cooling load reduction (Lee & Selkowitz, 2009). A manually-adjusted exterior system, designed to only shade the upper part of the window (the lower half is largely shaded by Oxford Plaza apartments), would have permitted higher daylight levels and a greater degree of control than the fixed exterior louvers, and an opportunity to introduce small amounts of sunlight. This in turn, could have provided the occupants with a better connection to the outdoor environment and a sense of temporal variation due to greater daylight variation in the space throughout the day and seasons. The interior roller shades would have provided an additional layer of solar control and helped ensure that visual comfort needs of occupants are met at all times. Installing several narrower interior roller shades, such as the ones installed at the David Brower Center, rather than a single wide shade could provide a way to avoid a situation where shades are deployed across entire bays of windows. Even if a few of the roller shades are deployed, the unoccluded portions of the window can provide some daylight and view out. This approach could be more effective in cases where some shading, either through outside obstructions or inside furnishings (buildings, facade elements, partitions, etc.) is provided.

8.2. FUTURE WORK

8.2.1. BRIEF PERIODS OF DIRECT SUNLIGHT AND SHADING CONTROL

In this study of a representative south-facing office space it was discovered that due to the geometry of exterior shading and site obstructions, there are times in the morning and afternoon when the sun hits the facade for a relatively short time (30 minutes). Past studies have indicated that once interior shading is deployed it remains lowered for extended periods of time. Many of the studies on occupant interior shading control reviewed in this thesis were conducted in offices without external shading. Yet in offices with shading from exterior obstructions or facade elements occupants may be more conscious in operating interior shades if they know that visual or thermal discomfort will not last long.

Even though the periods of direct sunlight are quite brief, the DAYSIM shading control algorithm assumes that the occupant lowers the shades in response to direct sunlight and that these shades remain lowered until the next day. This is part of the reason why the simulated case without louvers was characterized by a high frequency of window occlusion (2/3 of occupied hours) due to lowered roller shades. By not accounting for the fact that occupants may tolerate short periods of direct sunlight, the shading control algorithm may be overly conservative for cases such as this one, where there is typically limited direct sunlight throughout the day. It would be helpful if the algorithm incorporated an option for specifying the acceptable duration of direct sun or glare (for simulations using annual Daylight Glare Probability, aDGP), or if it had in-built assumptions about how occupants operate shades in response to the duration of direct sunlight. The latter option may require additional field research on how occupants operate roller shades (i.e. if they are less likely to lower shades) in offices when exposed to brief periods of direct sunlight. If studies of occupant shade use in heavily shaded environments have been conducted, a comprehensive review of existing literature on the subject would be useful.

8.2.2. Visual comfort in low-daylight environments

While daylight glare probability (DGP) was used to analyze visual comfort for some of the simulated cases, the limitations for the applicability of this metric (DGP > 0.2 and vertical eye illuminance, $E_v > 380$ lux) greatly limited the cases to which the visual comfort metric could be applied. Expanding the applicability range of this metric so that it includes lower vertical eye illuminances, e.g. as low as 150 lux, is needed in order to account for cases with increased shading of the facade and overcast sky conditions. This would require field monitoring of the visual environment and occupant shading operation in spaces with relatively low daylight levels (e.g. 100 to 500 lux): spaces with a well-shaded exterior facade, tinted glazing and/or smaller window-to-wall ratios.

8.2.3. SHADING MASKS

The Ecotect shading masks (overlays superimposed on a stereographic sun diagram) used in this study played a central role in understanding the effect of exterior shading, surrounding site obstructions, and even the effect of interior partitions on shading of the workplane. Shading masks, which are simple and intuitive to understand, could serve as a valuable early design tool for architects. Unfortunately however, this feature is not available to most designers since Ecotect is not typically used by architectural firms. The implementation of this feature in either the form of a plug-in for commonly used 3-D CAD programs, and/or as an added feature in existing building analysis tools such as COMFEN (Commercial Fenestration), an early facade analysis tool, could be of great value to the design community. Features such as the ability to create different colored shading overlays for each layer, to rearrange or reorder the overlays, and adjust the transparency of the overlay, would be particularly useful. The tool should allow the user to specify the shaded point anywhere on the facade or in the space (e.g. at workplane level, occupant eye level, or level of the monitor).

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Appendix A: Key building features

The following summary of David Brower Center's design features and performance data was taken from Zelenay et al. (2011).

KEY PROJECT FEATURES

Location	Berkeley, CA
Date of completion	2009
Architect	Daniel Solomon Design Partners (formerly Solomon WRT)
Mechanical Engineer	Integral Group (formerly Rumsey Engineers)
Daylighting consultant	Loisos + Ubbelohde
Building type	4-story mixed-use building with office, conference and event spaces
Project size	38,500 ft^2
Passive design strategies	Building massing and orientation, moderate WWR with exterior shading, operable windows, thermal mass and night-time purging, daylight controls
HVAC system	Cooling tower with radiant slab hydronic heating and cooling, low pressure ventilation via under floor air distribution (UFAD) system
Window-to-wall ratio	41% (South), 54% (North), 51% (East), 6% (West), 2% (roof)
Floor depth	60 ft
Glazing specifications	PPG Solarban 60 or equivalent, typical
Exterior shading type	Fixed exterior white-painted aluminum louvers on 2nd and 3rd floors, awning at ground floor, photovoltaic canopy at 4th floor
Occupancy	150 people, 40 hr/person/week
Predicted EUI [1]	38.4 kBtu/ft^2/yr (121.1 kWh/m^2/yr) – *54% savings over Title 24-2005*
Actual EUI [2]	47.3 kBtu/ft2/yr (149.2 kWh/m^2/yr) – *44% savings over Title 24-2005*
PV production [3]	8.92 kBtu/ft^2/yr (28.1 kWh/m^2/yr)

[1] Excludes restaurant energy use. Includes the following end uses (in kBtu/ft2/yr): cooling (2.23), heating (13.26), indoor fans (1.73), lighting (9.23), heat rejection (0.48), pumps (1.51), DHW (3.39), and receptacle energy use (6.56).

[2] Excludes restaurant energy use. Calculated based on utility bills for the first year of occupancy (July 2009 to June 2010). While most of the restaurant systems and equipment is separately submetered, minor adjustments to the utility bill numbers were made by the mechanical engineer in order to exclude the portion of energy used by restaurant for systems shared by the base building and restaurant (e.g. condenser water from base building for heat pumps). Does not include contribution of photovoltaic array.

[3] Based on photovoltaic array electricity generation data obtained from the building dashboard (http://buildingdashboard.com/clients/brower/) for the first year of occupancy (July 2009 to June 2010). The electricity generated by the array offset approximately 50% of the building's electricity demand during this period.

Appendix B: Interview guide

Three one-hour-long interviews with design team members were conducted in July 2010 in an effort to collect information on which social, economic and environmental factors drove the implementation of exterior shading at the David Brower Center. Interviewees included the architect, mechanical engineer, and daylighting consultant. The interview questions are listed below.

1. What were the major factors driving the design of the facade at the David Brower Center?
2. Were there any specific performance objectives for the facade? Is so, what were they?
3. When was the fixed exterior shading system introduced into the project and why?
4. Were alternative strategies (reduced window-to-wall ratio, electrochromic glazing, etc. considered?
5. What tools and methods used to evaluate the impact of shading on performance?
6. What was the impact of shading on performance?
7. Which factors drove the design of the exterior shading (i.e. the specific color, shape, and spacing of the louvers, custom vs non-custom, ease of installation)?
8. Was a payback or ROI for the shading ever calculated? If so, what were the assumptions (cost of energy, discount rate, occupancy period, etc.)?
9. Was there a VE phase? If so, which facade systems were eliminated and which remained? Why did the exterior shading remain?

Appendix C: Occupant comfort survey

The following pages contain select responses from the Center for the Built Environment (CBE) comfort survey, which was administered to the David Brower Center occupants in March 2010. Out of 150 total building occupants, 49% (73 respondents) completed the anonymous web-based survey, however, only responses for respondents sitting in 2nd or 3rd floor south-facing offices (offices with fixed exterior aluminum louvers), N=16, are included here. While the CBE survey covers a number of areas, ranging from occupant workspace description and satisfaction with interior furnishings to indoor air quality and thermal comfort, only sections specifically related to the research question are included here; sections on background, workspace description, lighting, visual comfort, and interior shading operation.

Survey Methods

This report presents the results of an Occupant Satisfaction Survey. Occupant responses are collected via the Internet and recorded to a secure server database using SQL technology (SQL is a standardized query language used for requesting information from a database). To protect the confidentiality of participants, the online report contains only aggregated, anonymous results.

The survey is comprised of a core survey and optional survey modules. Each organization using the survey has the option of employing the core survey or customizing the survey to include additional modules that support their information needs. The core survey includes modules for office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, and building cleanliness and maintenance. Examples of optional modules include wayfinding, safety and security, and air diffusers. Core questions stay consistent from survey to survey to maintain data integrity for the purposes of benchmarking and trend analysis.

The survey has been extensively tested and refined, and facility managers and designers to have evaluated the reporting format to determine the utility of various report designs. An established in-depth pre-testing method called cognitive interviewing was used by the Survey Research Center at the University of California, Berkeley to assess how well respondents were able to comprehend and accurately report answers to survey questions (Eisenhower, 2000). Cognitive interviews allow researchers to examine the thought processes that affect the quality of answers provided to survey questions. The primary technique used was the concurrent think aloud whereby respondents were asked to comment out loud about anything crossing their mind as they read, interpreted and answered each question. This technique was supplemented by paraphrasing (asking the respondents to put something in their own words) and systematic probing. Seven people participated in this testing. Results were used to refine the survey organization, question text, graphic design of the scales, and the process required to access the survey website.

The time to completion has been monitored, and occupants have evaluated the length of each section of the survey. Approximate time to completion for the core survey is 5-12 minutes; time to completion varies depending on the number of branching questions and comments answered. This length of time has not been regarded as an impediment to completion in most (but not all) of the buildings surveyed to date. Surveys that include several customized modules in addition to the core survey have had completion times of up to 20 minutes. Organizations that choose to implement longer surveys are briefed regarding the potential negative effect that longer time to completion can have on response and completion rates.

The survey implementation process typically begins with an email informing building occupants of the survey web site address, start date and end date. This email is drafted and sent either by CBE or the sponsoring agency. Subjects can open the survey at their convenience. After linking to the survey, respondents see a welcome screen informing them of the purpose of the survey. The welcome page also advises them of the amount of time it should take to complete the survey, and their rights as a research participant. Participation in the survey is voluntary and anonymous. Upon starting the survey, participants click through a series of questions asking them to evaluate their "satisfaction" with different aspects of their work environment. Satisfaction is rated on a 7-point scale ranging from "very satisfied" to "very dissatisfied" (see Figure 1). In most cases, respondents who indicate dissatisfaction (the lowest three points on the scale) with a particular aspect of their work environment are branched to a follow-up screen probing them for more information about the nature of their dissatisfaction. Respondents who indicate neutrality or satisfaction (the upper four points on the scale) move directly to the next survey topic. When applicable, respondents are also asked to assess the impact of environmental factors on their effectiveness in getting their job done.

Figure 1. Sample occupant satisfaction question (screen shot of web-based survey)

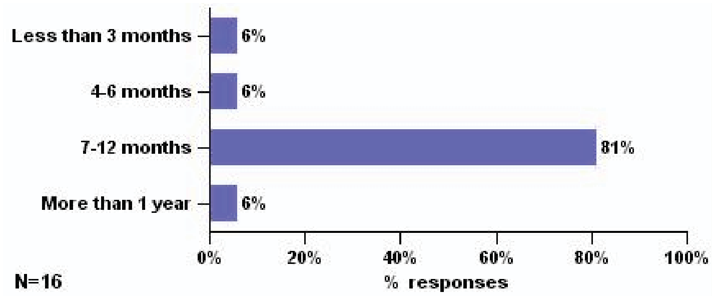
A survey typically stays open for 1-2 weeks. The rate of participation is monitored; if it is going slowly, reminder emails may be sent. After the survey is closed, the data is cleaned. Responses of participants who answer less than 15 questions are removed from the final data set.

Satisfaction ratings are tabulated for each point on the scale, and are also summarized into three bins: satisfied (top three points), neutral (middle point) and dissatisfied (bottom 3 points). This summary is particularly useful to managers that need to see a top-level overview of occupant feedback. Comments are also listed in totality for each question.

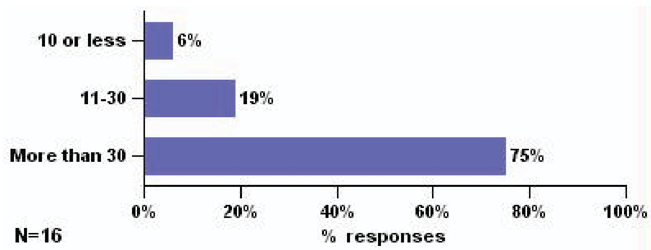
For more information, please send us an e-mail or contact us at (510) 642-6574.

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

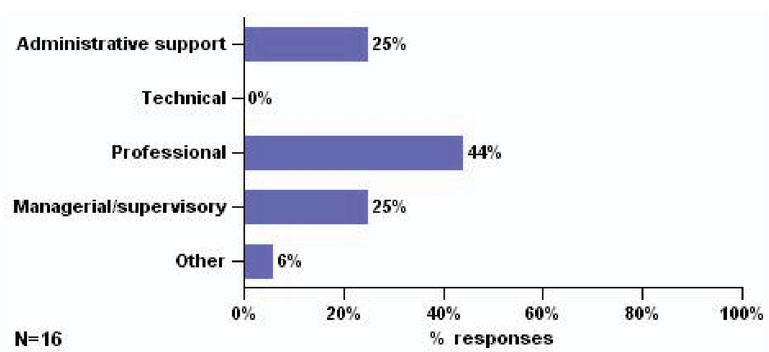
1.1 How long have you been working at your present workspace?



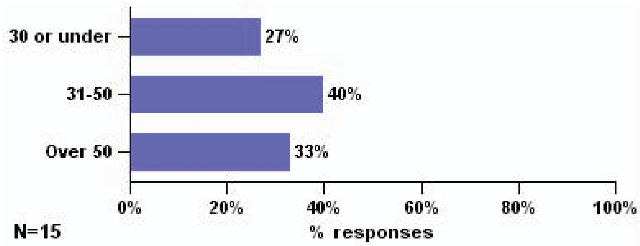
1.2 In a typical week, how many hours do you spend in your workspace?



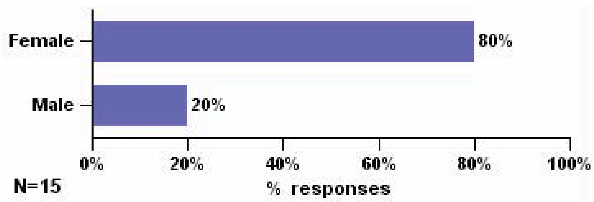
1.3 How would you describe the work you do?



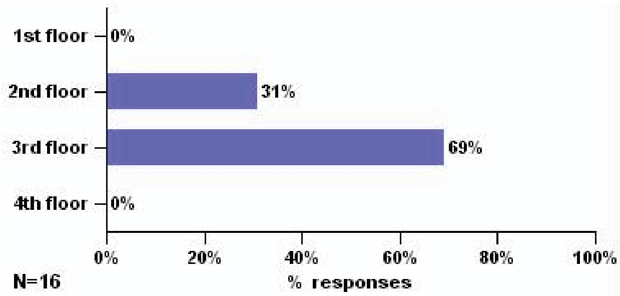
1.4 What is your age?



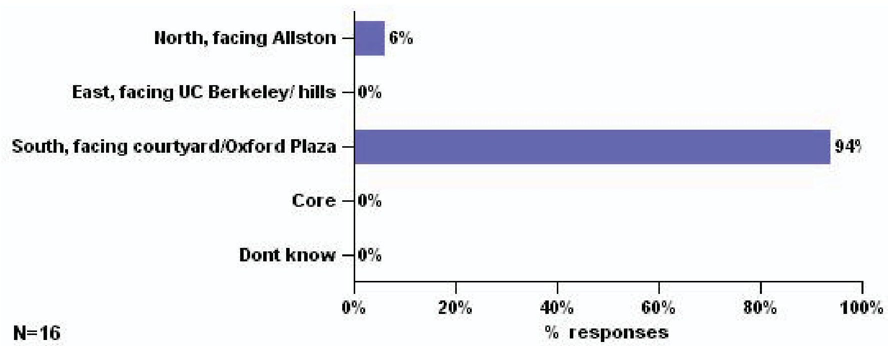
1.5 What is your gender?



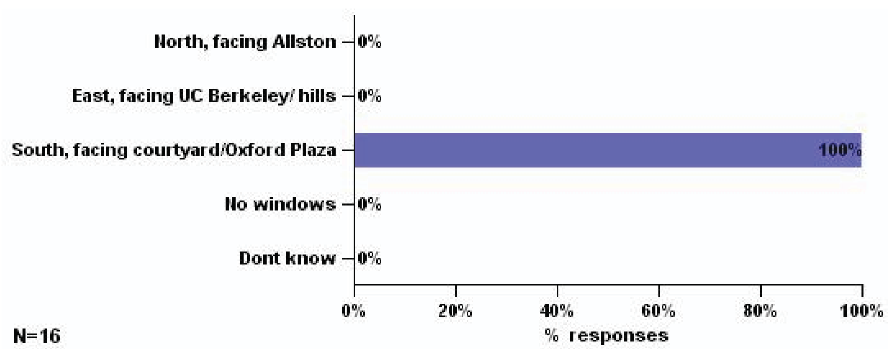
2.1 On which floor is your workspace located?



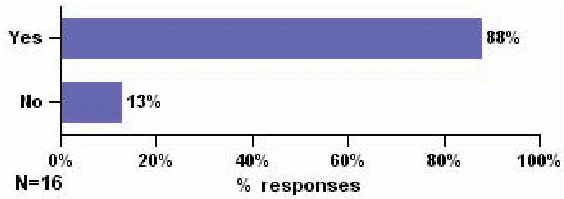
2.2 In which area of the building is your workspace located?



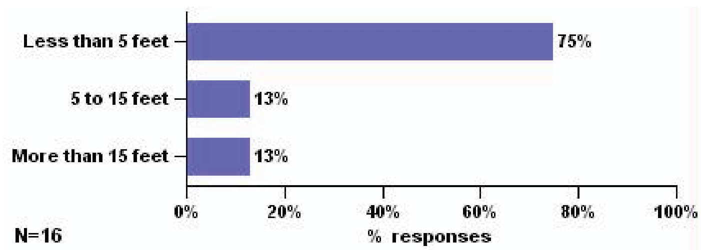
2.3 To which direction do the windows closest to your workspace face?



2.4 Are you near an exterior wall (within 15 feet)?

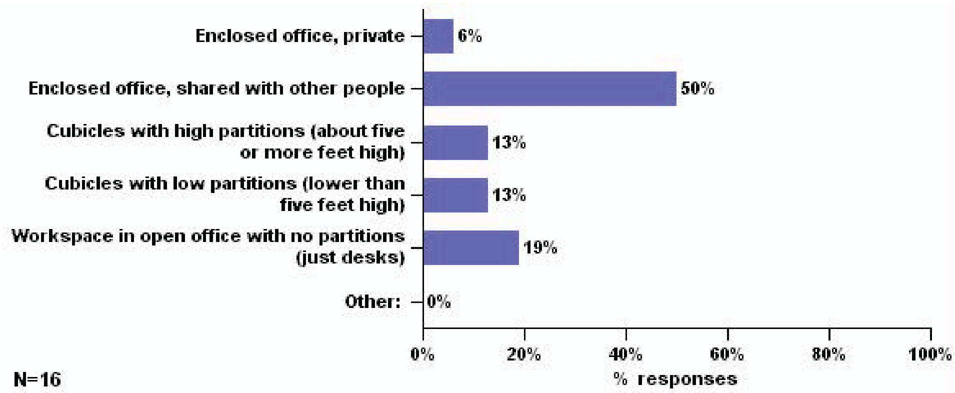


2.5 Are you near a window? **(5ft is equal to the length of a medium-sized desk)**



Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

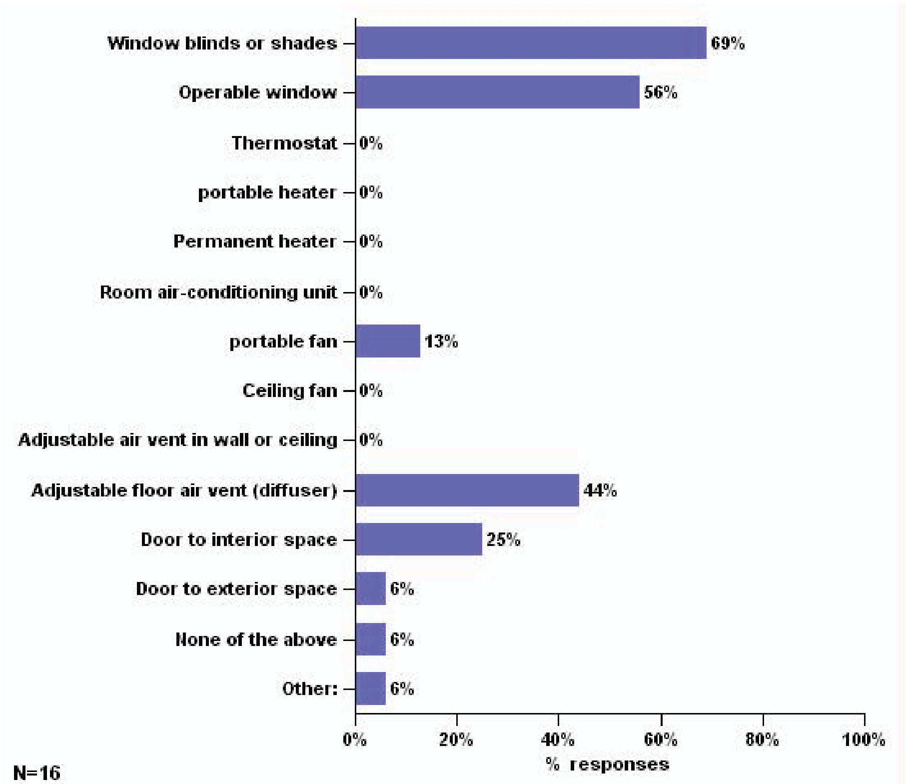
3.1 Which of the following best describes your personal workspace?



[No comments]

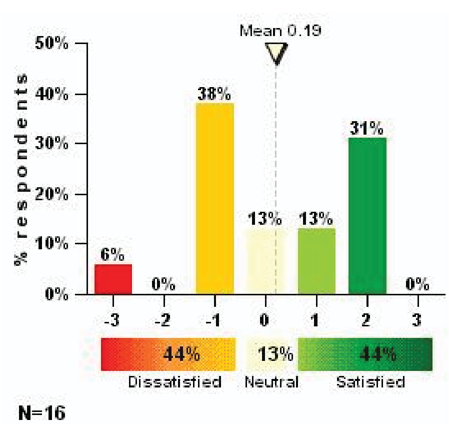
Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

4.1 Which of the following do you personally adjust or control in your workspace? (check all that apply)



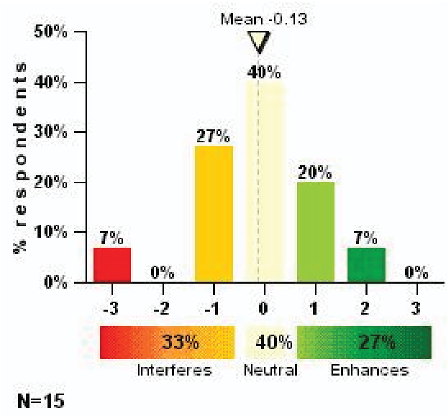
View 'Other:' responses

4.2 How satisfied are you with the temperature in your workspace?



View follow-up question for dissatisfied occupants

4.3 Overall, does your thermal comfort in your workspace enhance or interfere with your ability to get your job done?



Comments:

4.1.14 Which of the following do you personally adjust or control in your workspace?

(answer: Other:)

- it can be extremely hot in my workspace which isn't near a window,

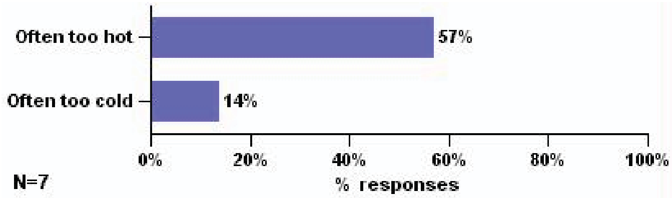
return to question

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

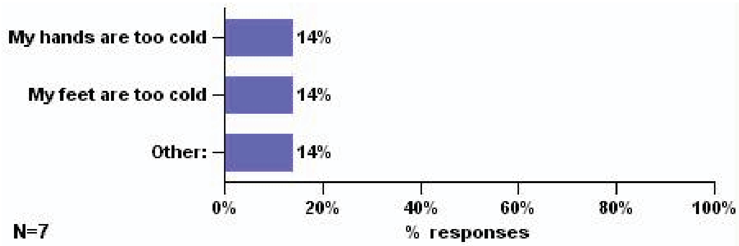
Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

You have said that you are dissatisfied with the temperature in your workspace. Which of the following contribute to your dissatisfaction?

5.1 In warm/hot weather, the temperature in my workspace is: (check all that apply)

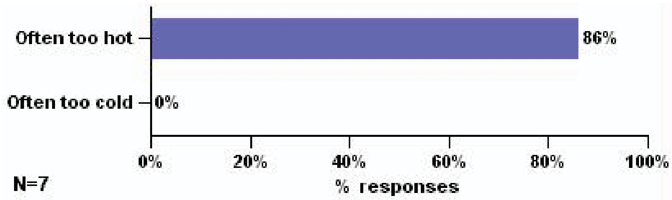


5.2 In warm/hot weather... (check all that apply)

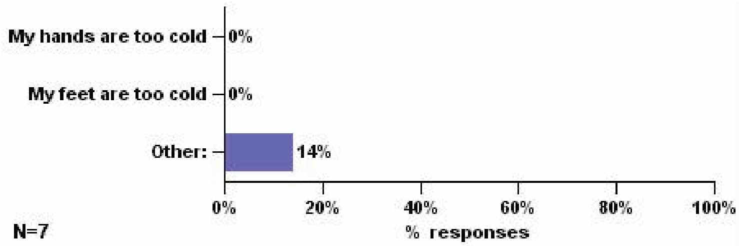


View 'Other:' responses

5.3 In cool/cold weather, the temperature in my workspace is: (check all that apply)

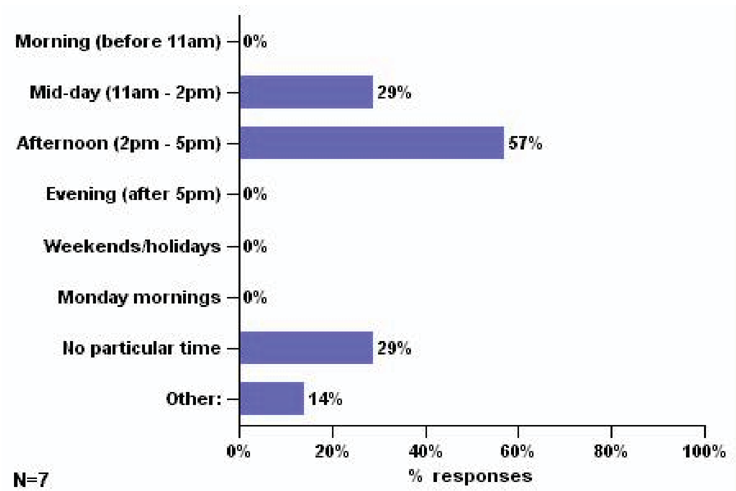


5.4 In cool/cold weather... (check all that apply)



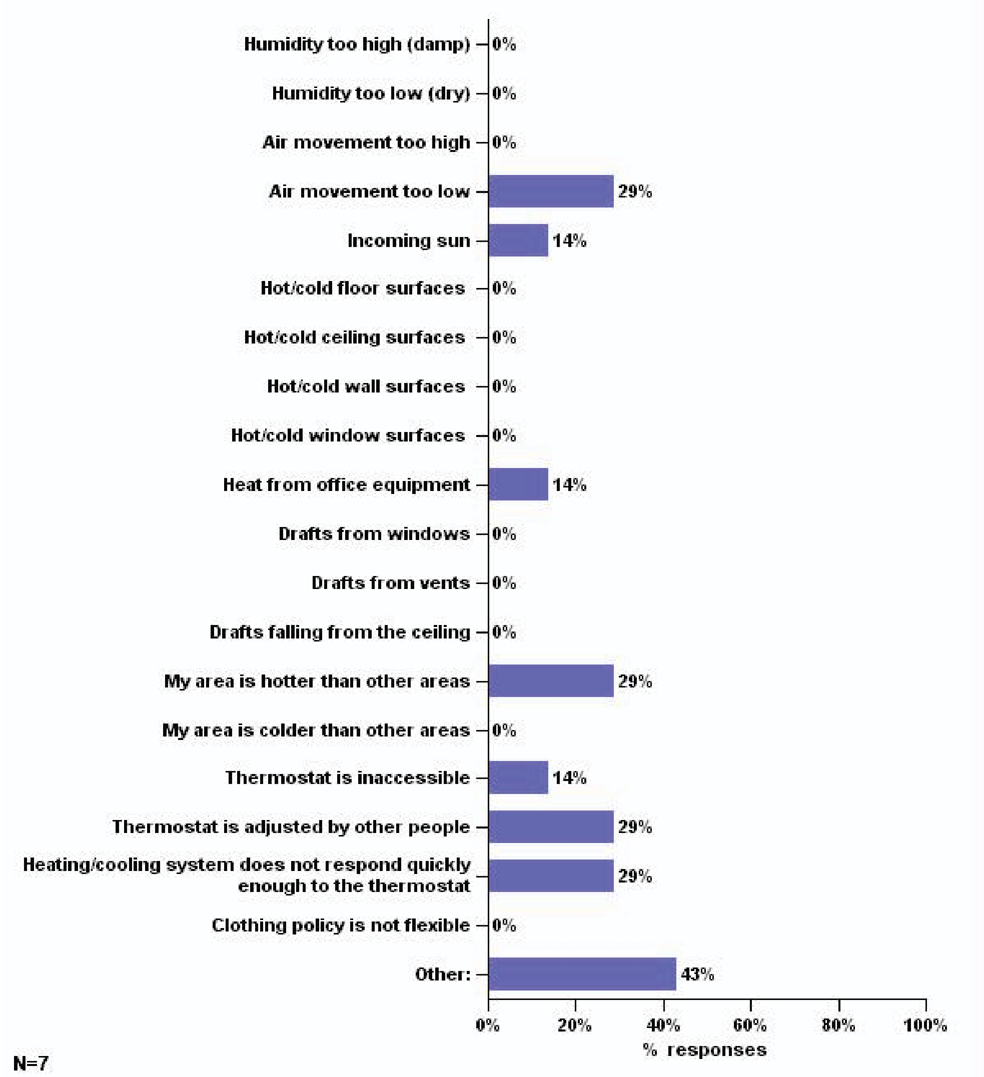
View 'Other:' responses

5.5 When is this most often a problem? (check all that apply)



View 'Other:' responses

5.6 How would you best describe the source of this discomfort? (check all that apply)



View 'Other:' responses

5.7 Please describe any other issues related to being too hot or too cold in your workspace.

View responses for this question

Comments:

5.2.3 In warm/hot weather...

(answer: Other:)

- just too hot, but temp is improving

return to question

5.4.3 In cool/cold weather...

(answer: Other:)

- just too hot, but temp is improving

return to question

5.5.8 When is this most often a problem?

(answer: Other:)

- too hot in pm; too cold all day

return to question

5.6.20 How would you best describe the source of this discomfort?

(answer: Other:)

- ambient temp too warm

- thermostat is already set at the coolest and can't be adjusted

- stuffy and hot

return to question

5.7.0 Please describe any other issues related to being too hot or too cold in your workspace.

- For months, Suite 280 was just too warm, but Brower staff is working on it, and the comfort level has improved.

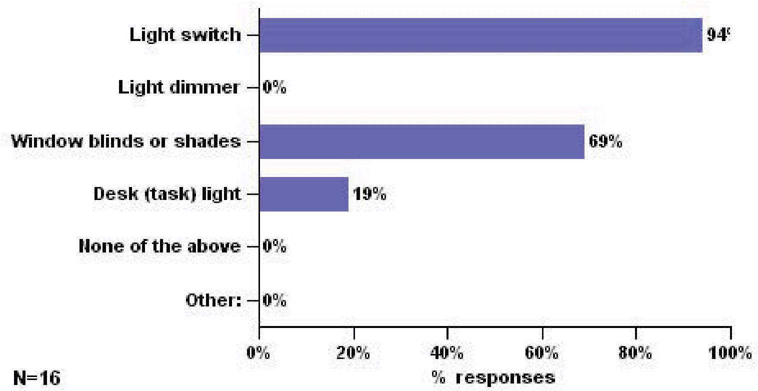
- Our library has a ceiling fan which is great at cooling down that space but unfortunately I don't have that option.

- Hot and stuffy in 2nd floor hallway and our Cluster; it seems much better lately in Spring

return to question

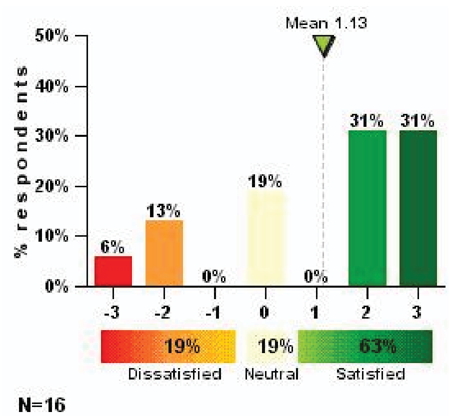
Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

8.1 Which of the following controls do you have over the lighting in your workspace? (check all that apply)



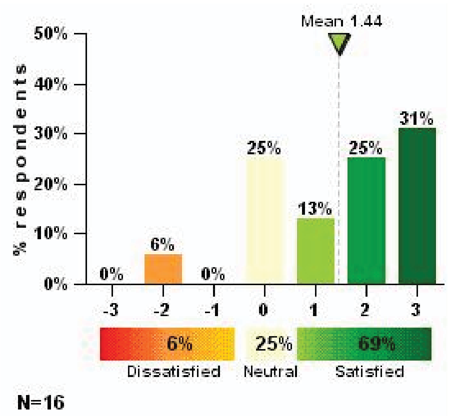
[No comments]

8.2 How satisfied are you with the amount of daylight in your workspace?



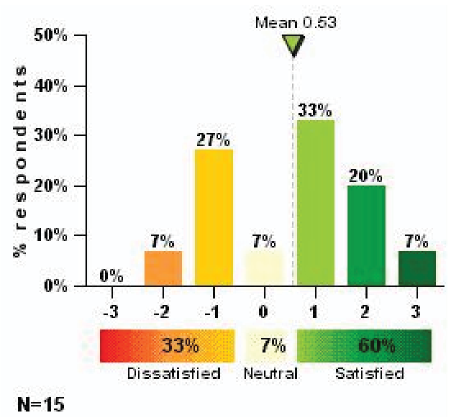
View follow-up question for dissatisfied occupants

8.3 How satisfied are you with the amount of electric light in your workspace?



View follow-up question for dissatisfied occupants

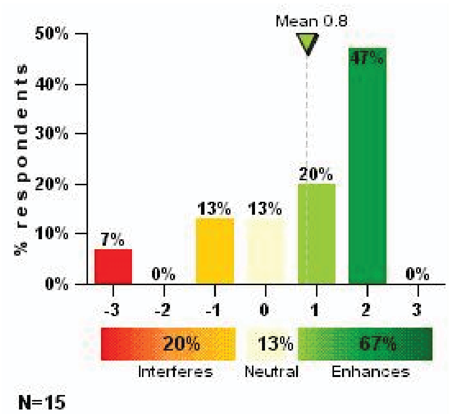
8.4 How satisfied are you with the visual comfort of the lighting (e.g., glare, reflections, contrast)?



View follow-up question for dissatisfied occupants

8.5 Overall, does the lighting quality enhance or interfere with your ability to get your job done?

CBE Survey: Lighting (0-2653-0)



Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

You have said that you are dissatisfied with the amount of daylighting in your workspace. Which of the following contribute to your dissatisfaction?

9.1 Too much daylight (check all that apply)

Due to the number of limited responses to this question, its statistics are not displayed

[No comments]

9.2 Not enough daylight (check all that apply)

Due to the number of limited responses to this question, its statistics are not displayed

View 'Other:' responses

Comments:

9.2.4 Not enough daylight

(answer: Other:)

- Not enough DIRECT sunlight. horizontal exterior installations block it.
- very little direct sunlight; don't see sun during day except early morning

return to question

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

10.1 You have said that you are dissatisfied with the amount of electric lighting in your workspace. Which of the following contribute to your dissatisfaction? **(check all that apply)**

Due to the number of limited responses to this question, its statistics are not displayed

View 'Other:' responses

Comments:

10.1.5 You have said that you are dissatisfied with the amount of electric lighting in your workspace. Which of the following contribute to your dissatisfaction?

(answer: Other:)

- I don't like the overhead lighting but the task lighting is too hot and I don't have enough natural light from the windows.

return to question

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

11.1 You have said that you are dissatisfied with the visual comfort of the lighting in your workspace. Which of the following contribute to your dissatisfaction? **(check all that apply)**

Due to the number of limited responses to this question, its statistics are not displayed

View 'Other:' responses

Comments:

11.1.9 You have said that you are dissatisfied with the visual comfort of the lighting in your workspace. Which of the following contribute to your dissatisfaction?

(answer: Other:)

- automatic light goes on and off too much
- The flourescent lighting gives me a headache.

return to question

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

12.1 Please describe any other issues related to lighting that are important to you.

View responses for this question

Comments:

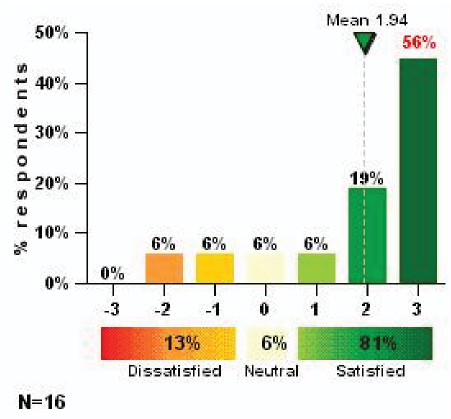
12.1.0 Please describe any other issues related to lighting that are important to you.

- It's good that lights turn off if there is no movement, but the sensors should be more sensitive. Annoying if I have to get up and walk around every 15 minutes or so to keep the lights on.
- We have had significant problems with photovoltaic and motion sensors, but Brower staff tended to them, and they appear to be solved.
- I need direct sunlight at my desk in the early afternoon/late morning. How can this be fixed?
- The timed lights are hard to get reactivated, so at night, it is challenging to work beyond natural daylight hours because the lights cause frequent interruption to work flow and require walking over to the wall to reactivate. I very much enjoy the natural daylight of this space.
- Daylight controls did not work for the first 6 months, but seem to be working now. In early afternoon, I get a large amount of direct sunlight into my office & I have to close the shades all the way in order to work.
- Reflection of sunlight off the Oxford Plaza windows can be blinding; the shades don't do much to help, but they're better than nothing.

return to question

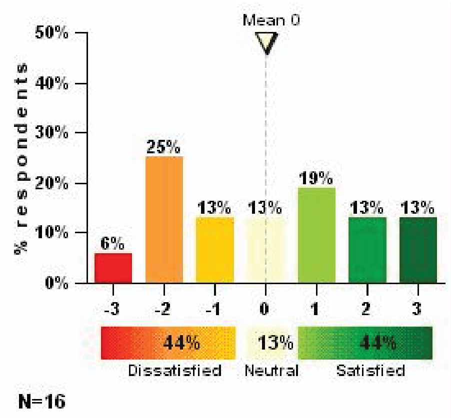
Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

13.1 How satisfied are you with your access to a window view from your workspace?



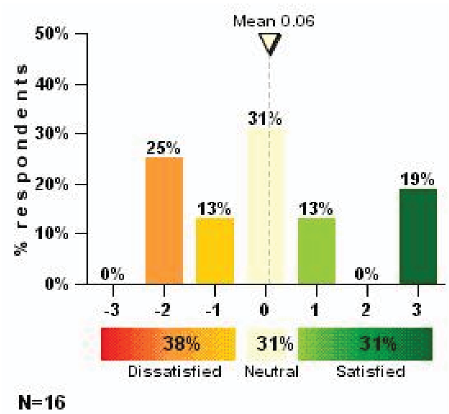
View follow-up question for dissatisfied occupants

13.2 How satisfied are you with the content of the window view from your workspace (i.e. the scene that you see when you look out the window)?



View follow-up question for dissatisfied occupants

13.3 How satisfied are you with the sense of connection to the outside while sitting at your workspace?


Mean 0.06
50%
40%
30%
20%
10%
0%
% respondents
0%
25%
13%
31%
13%
0%
19%
-3
-2
-1
0
1
2
3
38%
31%
31%
Dissatisfied
Neutral
Satisfied
N=16

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

14.1 You have said that you are dissatisfied with your access to a window view. Which of the following contribute to your dissatisfaction? (check all that apply)

Due to the number of limited responses to this question, its statistics are not displayed

View 'Other:' responses

Comments:

14.1.7 You have said that you are dissatisfied with your access to a window view. Which of the following contribute to your dissatisfaction?

(answer: Other:)

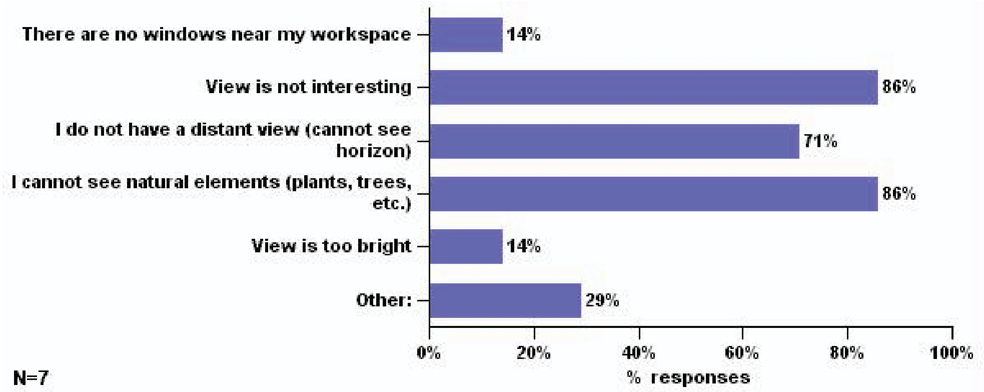
- look out on adjacent building and some foliage
- the view is of an apartment building

return to question

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

15.1 You have said that you are dissatisfied with the <u>content</u> of the window view. Which of the following contribute to your dissatisfaction? **(check all that apply)**



View 'Other:' responses

Comments:

15.1.6 You have said that you are dissatisfied with the <u>content</u> of the window view. Which of the following contribute to your dissatisfaction?

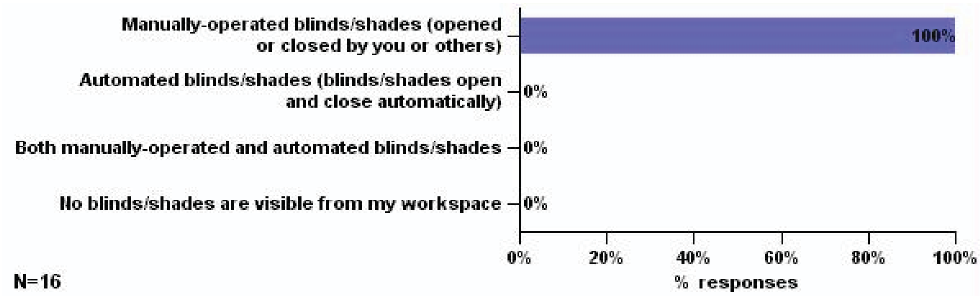
(answer: Other:)

- Our view is of the roof and next-door building wall; needs plants, a mural, something.
- all concrete, no direct sun, very little nature or humans

return to question

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

16.1 What type of <u>movable</u> blinds/shades (interior or exterior) are closest to your workspace?



View followup question for people who selected the answer ' Manually-operated blinds/shades (opened or closed by you or others)'

View followup question for people who selected the answer ' Automated blinds/shades (blinds/shades open and close automatically)'

View followup question for people who selected the answer ' Both manually-operated and automated blinds/shades'

View followup question for people who selected the answer ' No blinds/shades are visible from my workspace'

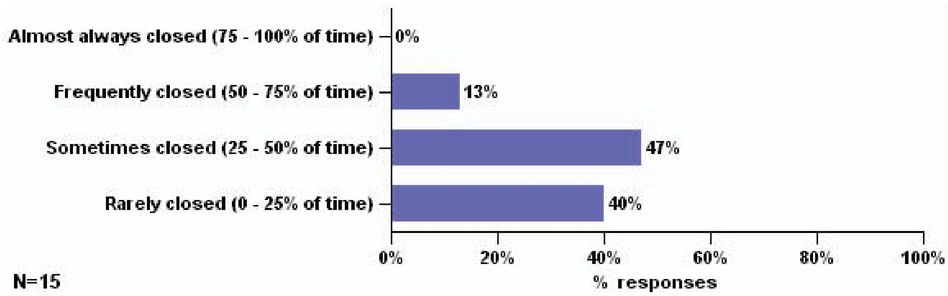
View followup question for people who selected the answer 'undefined'

View followup question for people who selected the answer 'undefined'

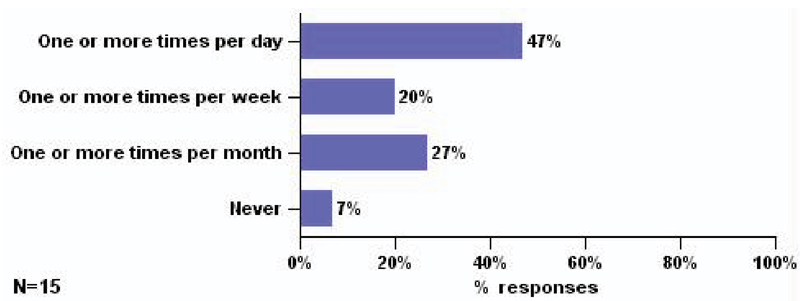
Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

17.1 Throughout the year, blinds/shades near your workspace are generally:



17.2 Please indicate how frequently you adjust the blinds/shades.

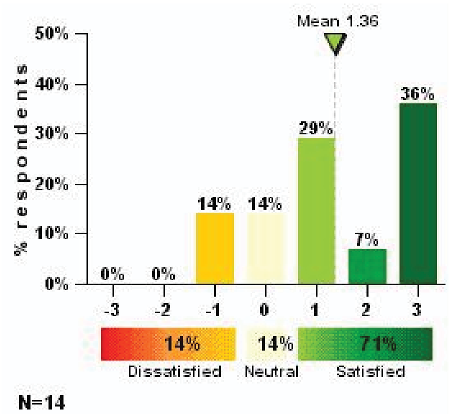


View followup question for people who selected an answer that was not equal to the answer 'One or more times per day'

How satisfied are you with the blinds/shades in terms of the following?

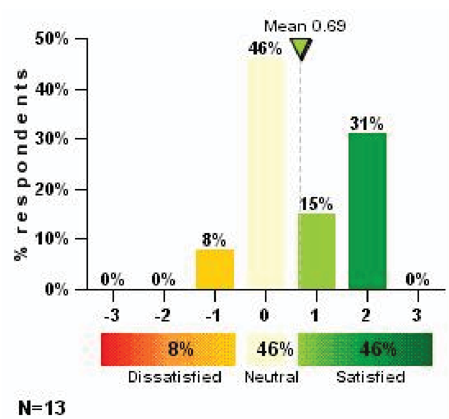
17.3 Daylight

View



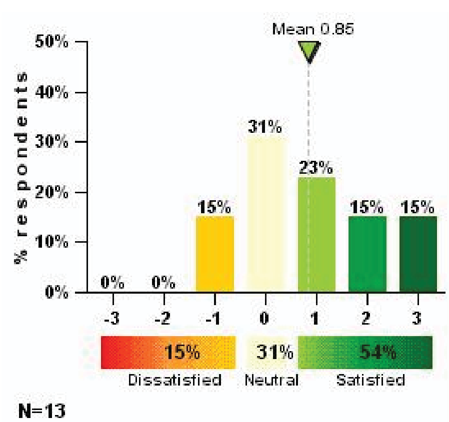
follow-up question for dissatisfied occupants

17.4 Thermal comfort



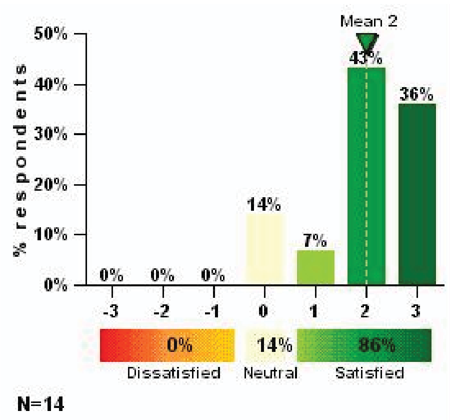
View follow-up question for dissatisfied occupants

17.5 View to outside



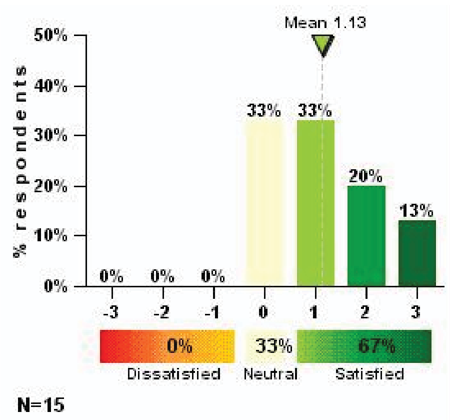
View follow-up question for dissatisfied occupants

17.6 Your ability to control



View follow-up question for dissatisfied occupants

17.7 Overall



View follow-up question for dissatisfied occupants

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

18.1 Throughout the year, blinds/shades near your workspace are generally:

Due to the number of limited responses to this question, its statistics are not displayed

---

18.2 Please indicate how frequently you adjust the blinds/shades.

Due to the number of limited responses to this question, its statistics are not displayed

View followup question for people who selected an answer that was not equal to the answer 'One or more times per day'

How satisfied are you with the blinds/shades in terms of the following?

18.3 Daylight

Due to the number of limited responses to this question, its statistics are not displayed

View follow-up question for dissatisfied occupants

18.4 Thermal comfort

Due to the number of limited responses to this question, its statistics are not displayed

View follow-up question for dissatisfied occupants

18.5 View to outside

Due to the number of limited responses to this question, its statistics are not displayed

View follow-up question for dissatisfied occupants

18.6 Your ability to control

Due to the number of limited responses to this question, its statistics are not displayed

View follow-up question for dissatisfied occupants

18.7 Overall

Due to the number of limited responses to this question, its statistics are not displayed

View follow-up question for dissatisfied occupants

18.8 How satisfied are you with the automated control of the blinds/shades (i.e. blinds/shades operate smoothly and when needed)?

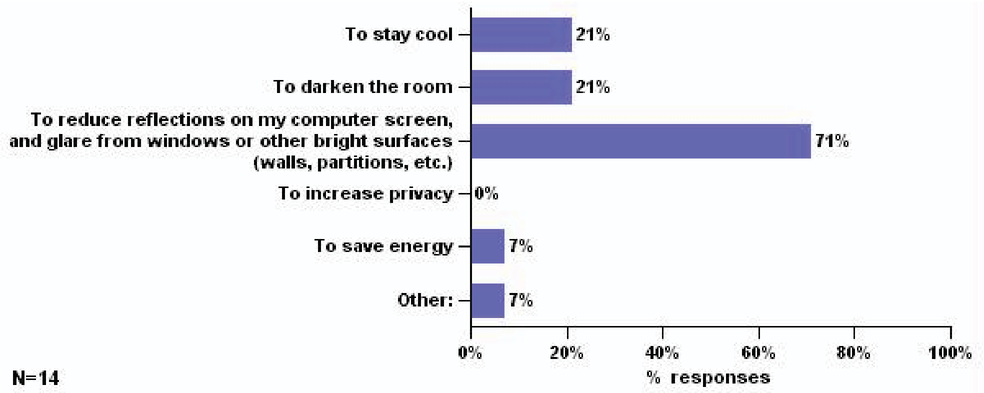
Due to the number of limited responses to this question, its statistics are not displayed

View follow-up question for dissatisfied occupants

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

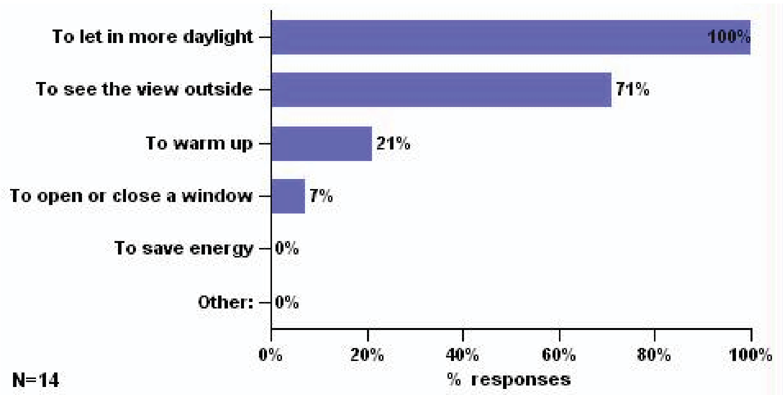
Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

19.1 If you close the blinds/shades, please list the reasons why you do so. **(check all that apply)**



View 'Other:' responses

19.2 If you open the blinds/shades, please list the reasons why you do so. **(check all that apply)**



[No comments]

Comments:

19.1.6 If you close the blinds/shades, please list the reasons why you do so.

(answer: Other:)

- My boss complains about the sun in her eyes

return to question

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

20.1 You have indicated that you are dissatisfied with the blinds/shades. Which of the following contribute to your dissatisfaction? (check all that apply)

Due to the number of limited responses to this question, its statistics are not displayed

[No comments]

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

21.1 If you close the blinds/shades, please list the reasons why you do so. **(check all that apply)**

Due to the number of limited responses to this question, its statistics are not displayed

[No comments]

21.2 If you open the blinds/shades, please list the reasons why you do so. **(check all that apply)**

Due to the number of limited responses to this question, its statistics are not displayed

[No comments]

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

22.1 You have indicated that you are dissatisfied with the blinds/shades. Which of the following contribute to your dissatisfaction? (check all that apply)

Due to the number of limited responses to this question, its statistics are not displayed

[No comments]

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

23.1 Please describe any other issues related to the operation of blinds/shades that are important to you.

View responses for this question

Comments:

23.1.0 Please describe any other issues related to the operation of blinds/shades that are important to you.

- I don't use them much, daylight is so important to the space, other than heat issues from the sun, we generally don't lower them.

return to question

Filters are : ON
South-facing/Floor > 1/Floor < 4 (all)

Percentages based on the number of those respondents who, because of their response to an earlier question, saw this page.

24.1 Have you been instructed on how to operate the shading system? **(check all that apply)**

Due to the number of limited responses to this question, its statistics are not displayed

[No comments]

24.2 Please describe any other issues related to the operation of blinds/shades that are important to you.

[No comments]

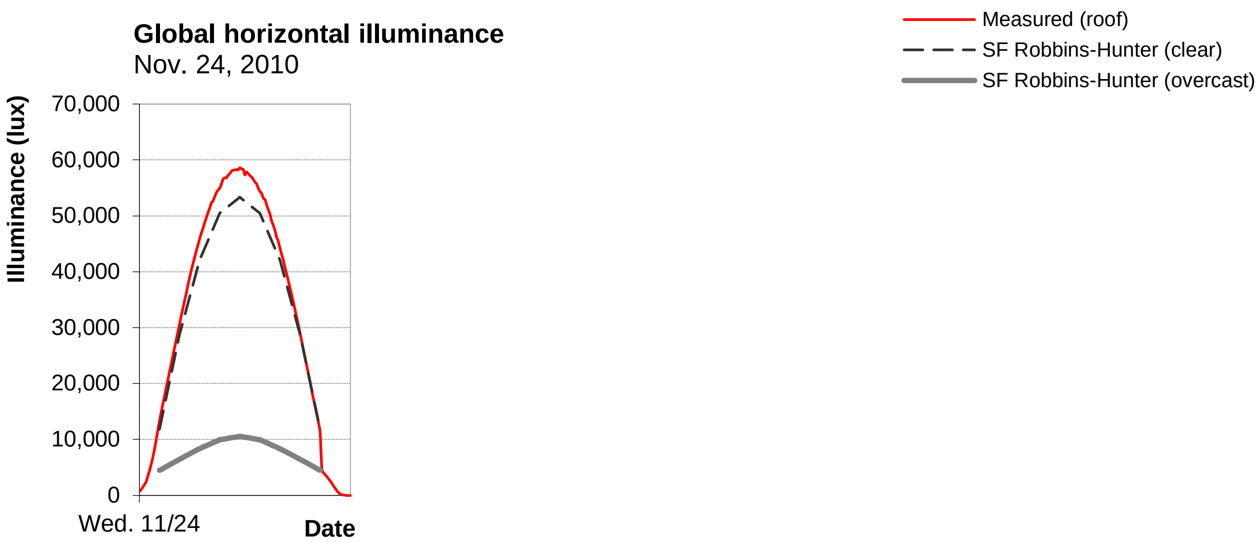
Appendix D: Exterior illuminance data

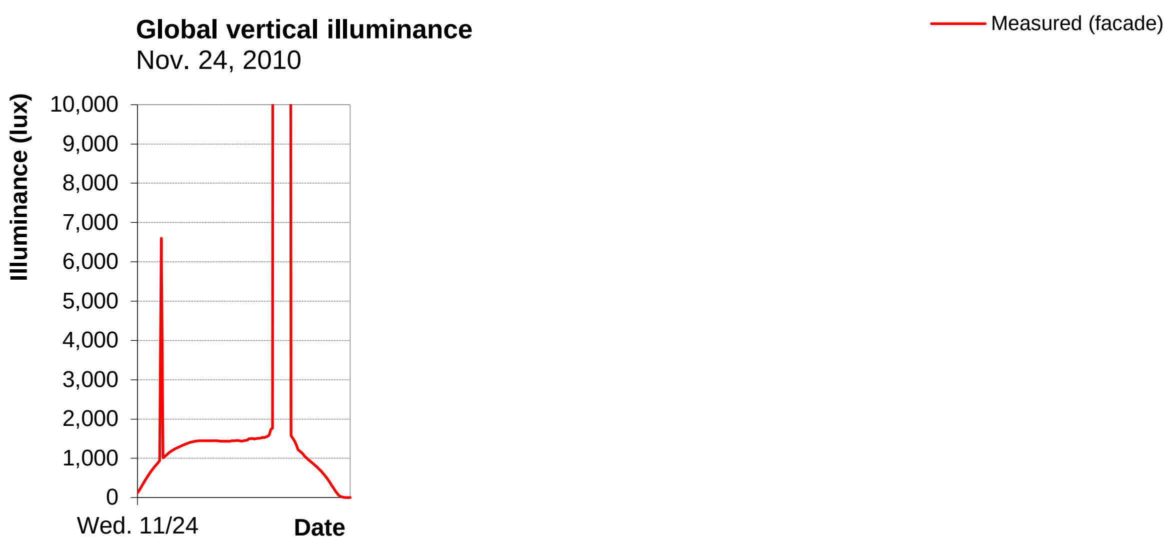
This appendix contains global horizontal roof illuminance and vertical facade illuminance data collected at the David Brower Center during the three-week monitoring period (Nov. 24 - Dec. 15, 2010).

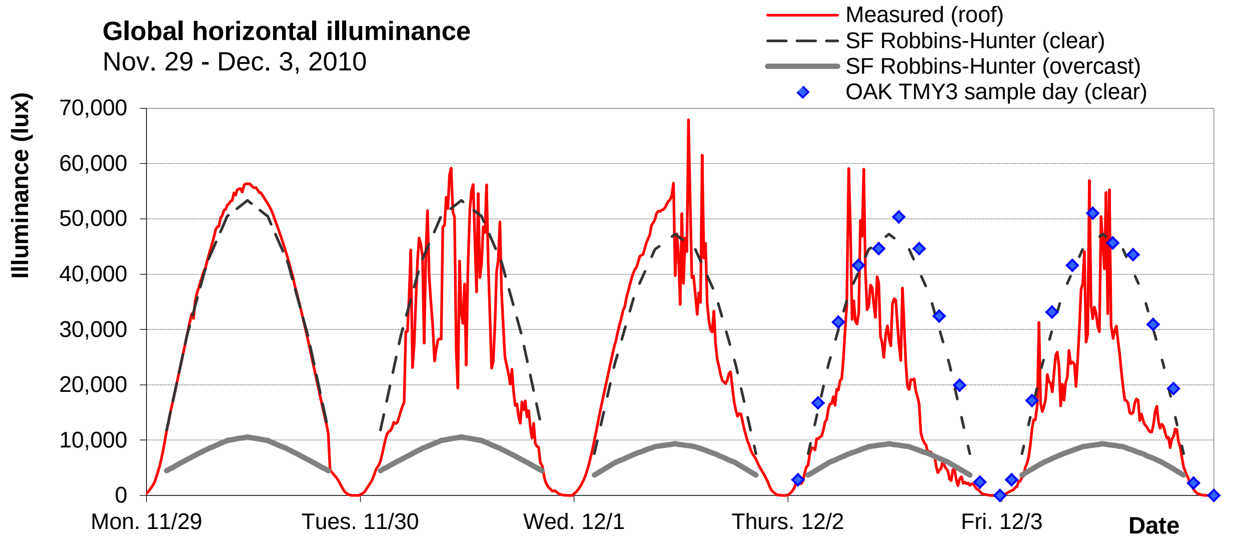
NOTE: Reference global horizontal illuminance levels for perfectly clear and overcast skies (labeled SF Robbins-Hunter) were taken from daylight availability tables for San Francisco, which are included in *Appendix E*.

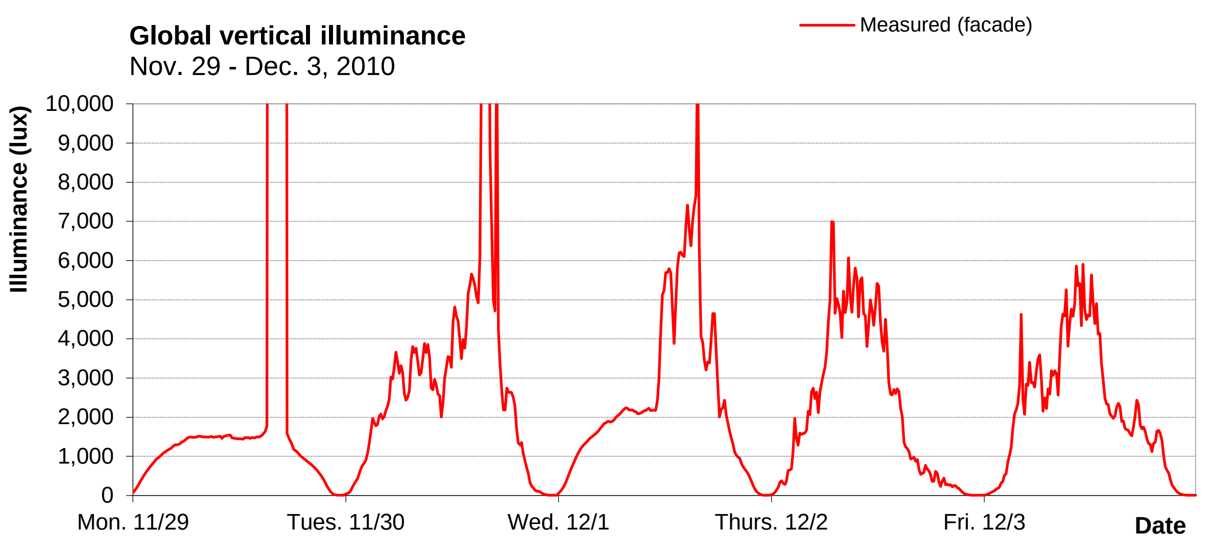
Measured global horizontal and vertical facade illuminance (weekdays)

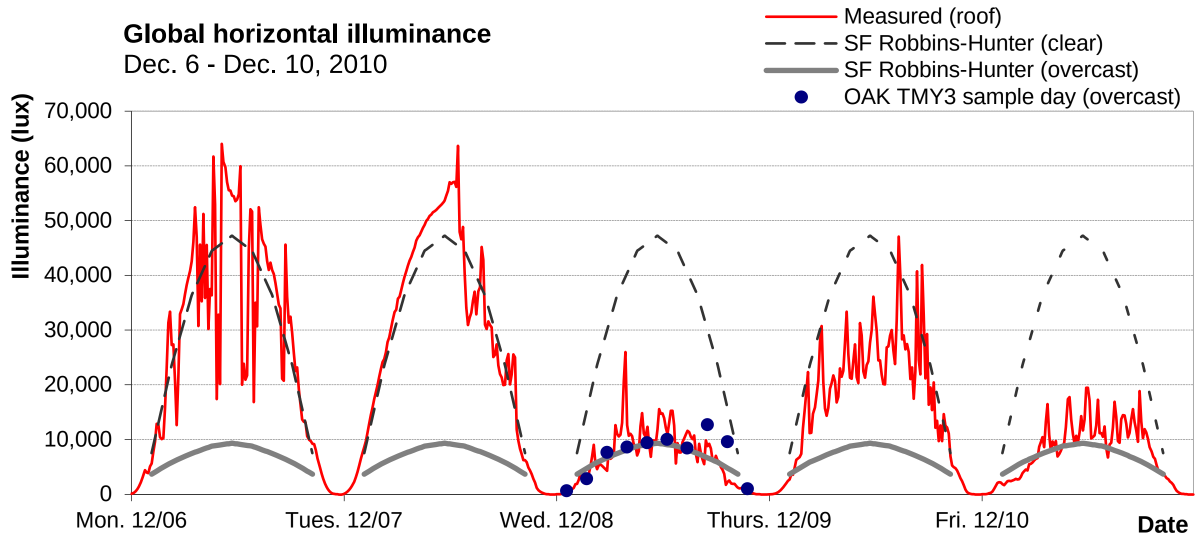
Nov. 24 – Dec. 15, 2010

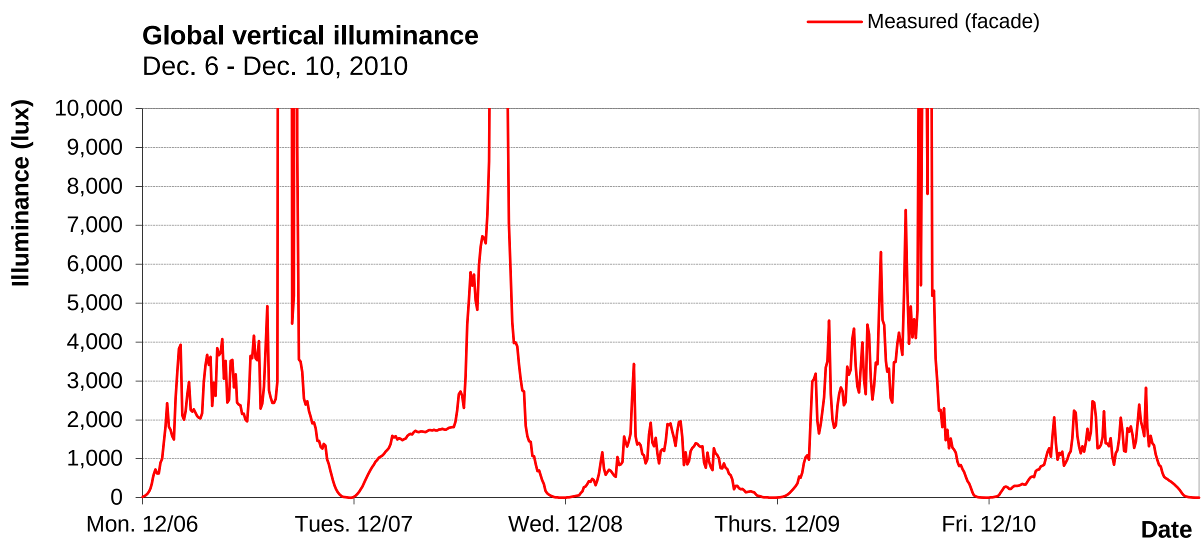


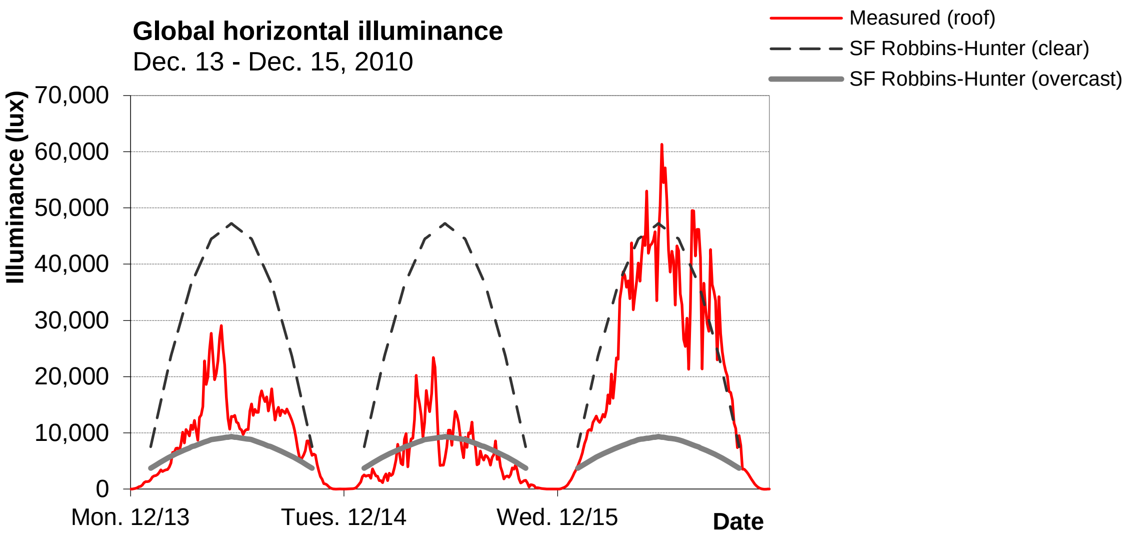


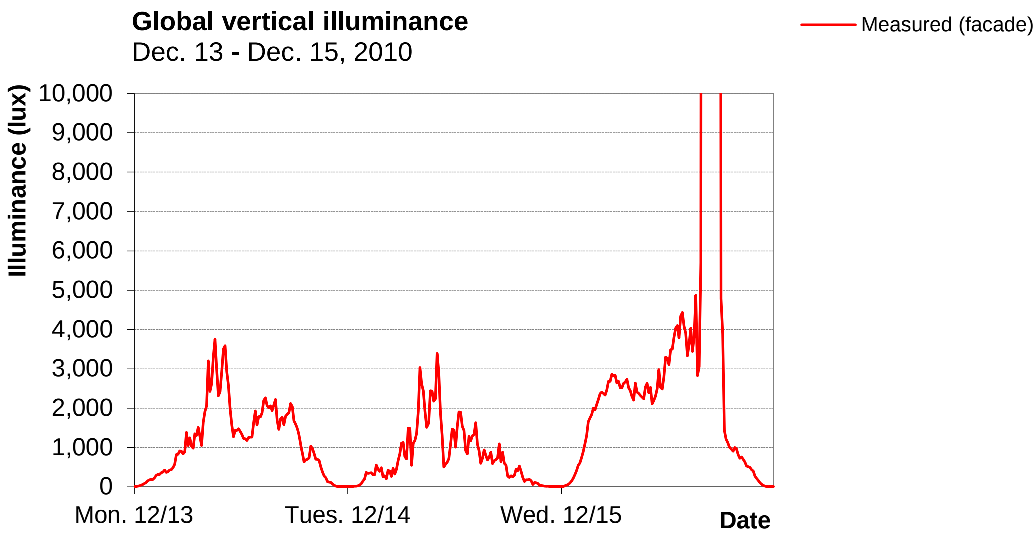

Global horizontal illuminance
Nov. 29 - Dec. 3, 2010
Measured (roof)
SF Robbins-Hunter (clear)
SF Robbins-Hunter (overcast)
OAK TMY3 sample day (clear)
Illuminance (lux)
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Mon. 11/29
Tues. 11/30
Wed. 12/1
Thurs. 12/2
Fri. 12/3
Date


Global vertical illuminance
Nov. 29 - Dec. 3, 2010
Measured (facade)
Illuminance (lux)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Mon. 11/29
Tues. 11/30
Wed. 12/1
Thurs. 12/2
Fri. 12/3
Date


Global horizontal illuminance
Dec. 6 - Dec. 10, 2010
Measured (roof)
SF Robbins-Hunter (clear)
SF Robbins-Hunter (overcast)
OAK TMY3 sample day (overcast)
Illuminance (lux)
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Mon. 12/06
Tues. 12/07
Wed. 12/08
Thurs. 12/09
Fri. 12/10
Date

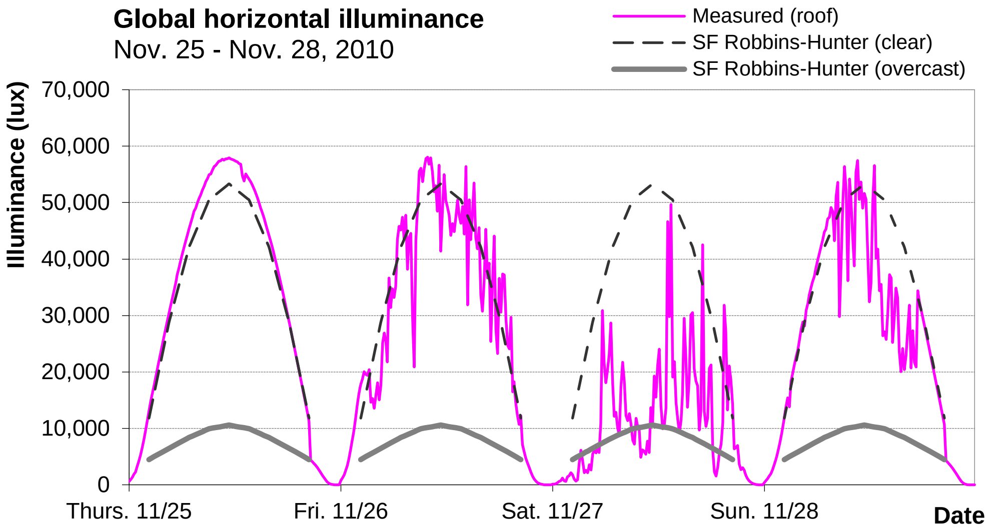

Global vertical illuminance
Dec. 6 - Dec. 10, 2010
Measured (facade)
Illuminance (lux)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Mon. 12/06
Tues. 12/07
Wed. 12/08
Thurs. 12/09
Fri. 12/10
Date

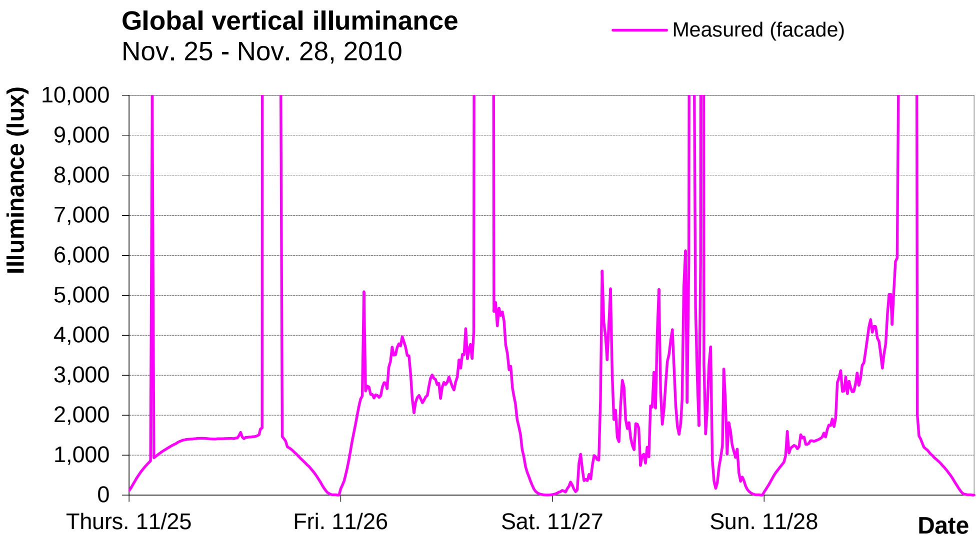

Global horizontal illuminance
Dec. 13 - Dec. 15, 2010
Measured (roof)
SF Robbins-Hunter (clear)
SF Robbins-Hunter (overcast)
Illuminance (lux)
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Mon. 12/13
Tues. 12/14
Wed. 12/15
Date

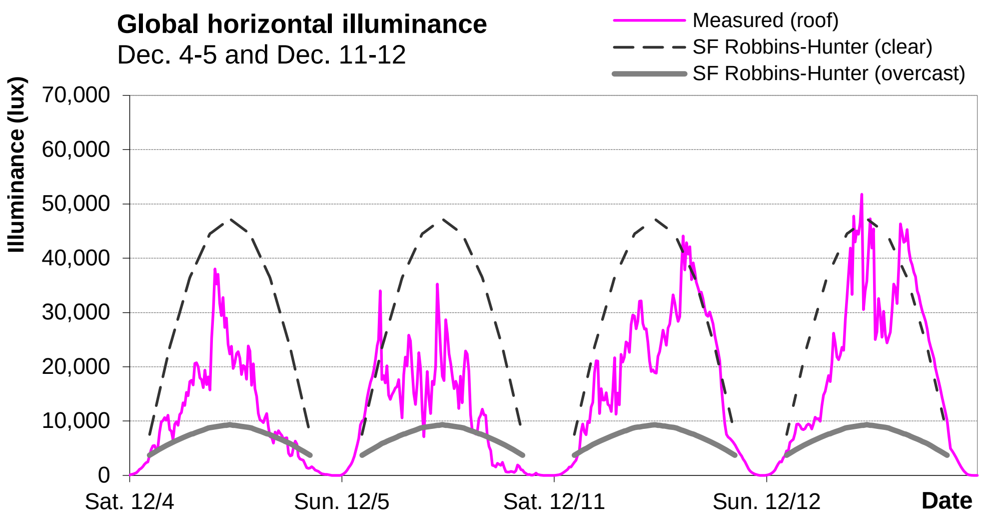

Global vertical illuminance
Dec. 13 - Dec. 15, 2010
Measured (facade)
Illuminance (lux)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Mon. 12/13
Tues. 12/14
Wed. 12/15
Date

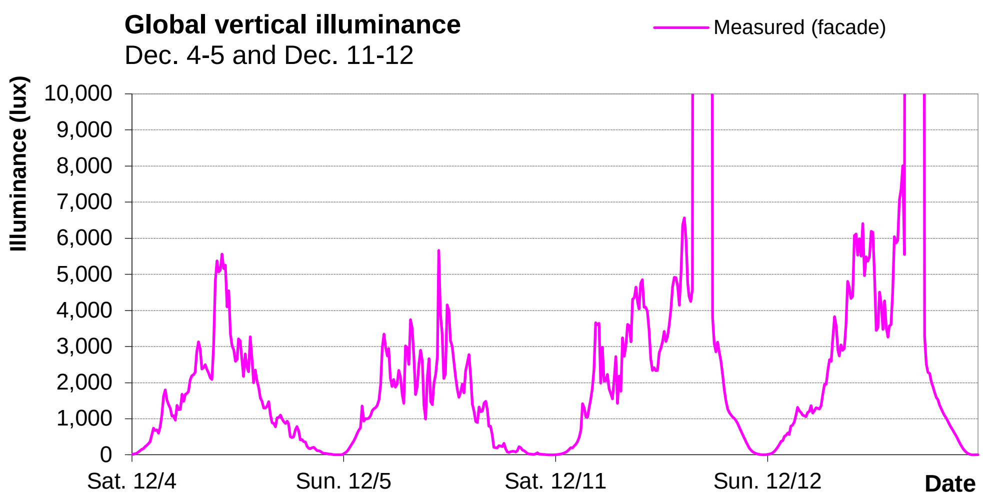
Measured global horizontal and vertical facade illuminance (weekends)

Nov. 24 – Dec. 15, 2010






Global horizontal illuminance
Dec. 4-5 and Dec. 11-12
Measured (roof)
SF Robbins-Hunter (clear)
SF Robbins-Hunter (overcast)
Illuminance (lux)
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Sat. 12/4
Sun. 12/5
Sat. 12/11
Sun. 12/12
Date


Global vertical illuminance
Dec. 4-5 and Dec. 11-12
Measured (facade)
Illuminance (lux)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Sat. 12/4
Sun. 12/5
Sat. 12/11
Sun. 12/12
Date

Appendix E: Daylight availability data

The following table contains illluminance data for San Francisco, CA from *Daylighting: Design and Analysis* by C. L. Robbins. The illuminance data is calculated based on the Robbins-Hunter daylight prediction model which accounts for location, cloud cover, sky clearness, turbidity, altitude above sea level, and a series of extraterrestrial illuminance monthly constants (Robbins, 1996).

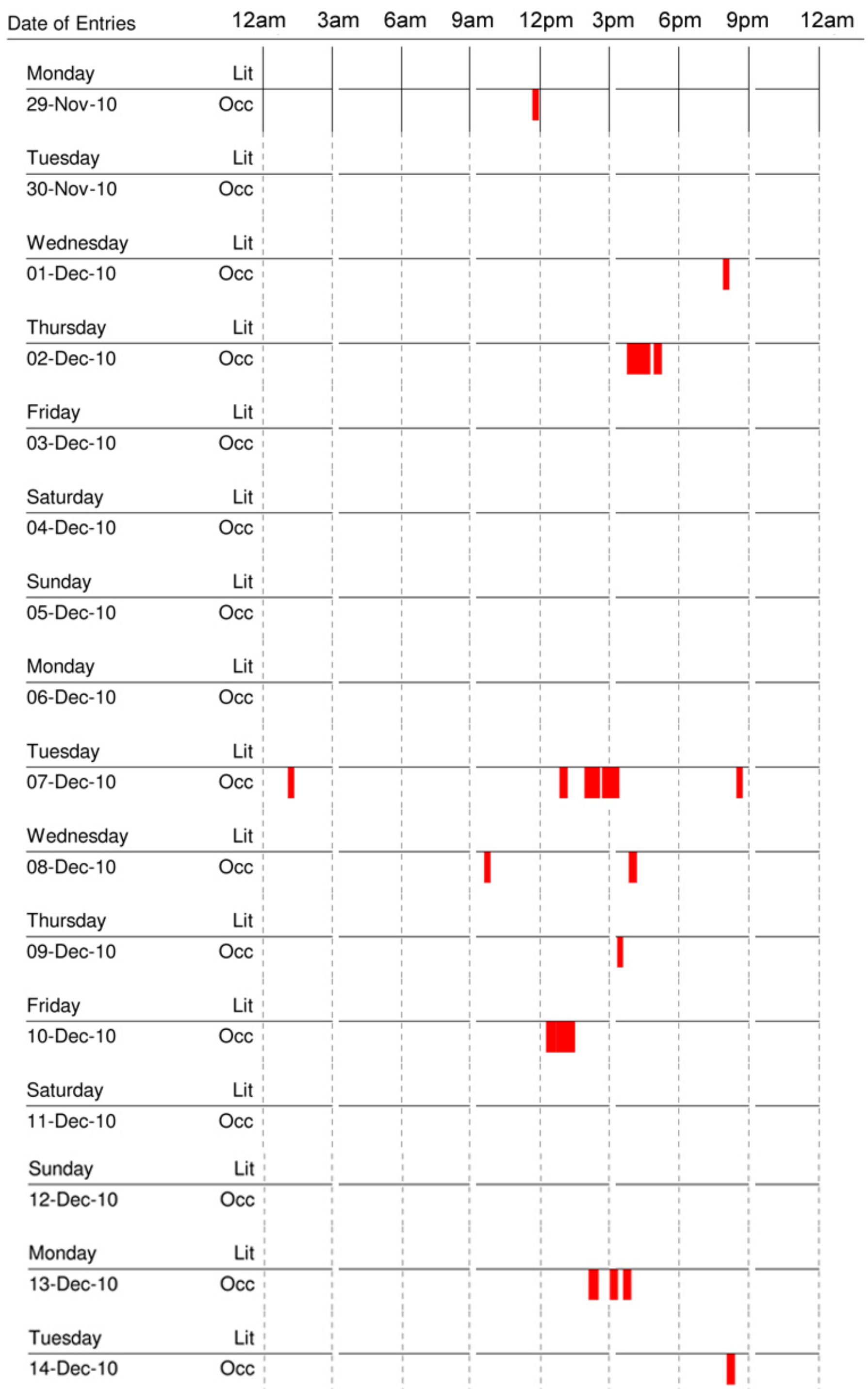
SAN FRANCISCO, CA

	TIME	DIRECT NORMAL CLEAR (LUX)	NORTH VERTICAL GLOBAL CLEAR (LUX)	NORTHEAST VERTICAL GLOBAL CLEAR (LUX)	EAST VERTICAL GLOBAL CLEAR (LUX)	SOUTHEAST VERTICAL GLOBAL CLEAR (LUX)	SOUTH VERTICAL GLOBAL CLEAR (LUX)	VERTICAL GLOBAL OVERCAST (LUX)	HORIZONTAL GLOBAL CLEAR (LUX)	HORIZONTAL DIFFUSE CLEAR (LUX)	HORIZONTAL GLOBAL OVERCAST (LUX)	TIME	
	5	750	1570	4450	4010	1340	920	290	160	140	950	19	
	6	42130	18510	46440	50330	27470	4750	2150	16840	7800	5170	18	
	7	65330	18960	63070	75470	49700	8990	3860	38650	12100	7810	17	
	8	76190	12460	61540	81630	62430	13130	5860	58700	14110	11850	16	
	9	81960	14040	49910	75720	66230	26260	7980	75740	15180	16360	15	
	10	85170	14960	33530	62030	63630	37370	10060	88740	15780	20200	14	
	11	86810	15120	16960	42740	56230	46060	12300	96880	16080	24850	13	
JUL	12	87320	14480	15600	17550	40720	51170	13730	99660	16180	28710	12	JUL
	13	86810	15120	14120	15360	19420	46060	12300	96880	16080	24850	11	
	14	85170	14960	13390	13520	15170	37370	10060	88740	15780	20200	10	
	15	81960	14040	11950	11420	12780	26260	7980	75740	15180	16360	9	
	16	76190	12460	9770	9050	9810	13130	5860	58700	14110	11850	8	
	17	65330	18960	7400	6580	6860	8990	3860	38650	12100	7810	7	
	18	42130	18510	4370	3700	3760	4750	2150	16840	7800	5170	6	
	19	750	1570	830	1160	1140	920	290	160	140	950	5	
	6	24390	7720	26360	31920	19420	2870	1400	7380	4250	3860	18	
	7	58660	8410	52340	69920	51250	7600	3130	29510	10230	6620	17	
	8	72920	10520	52310	79590	67340	21730	5020	50300	12720	10060	16	
	9	79930	12250	40960	74950	73050	36230	7060	67950	13940	14450	15	
	10	83650	13200	24260	61630	71560	48520	8950	81420	14590	18210	14	
	11	85530	13440	15390	41650	63540	57500	10520	89860	14920	21030	13	
AUG	12	86100	12750	14310	16430	48580	62170	11250	92730	15020	22480	12	AUG
	13	85530	13440	12810	14530	27190	57500	10520	89860	14920	21030	11	
	14	83650	13200	11600	12440	14500	48520	8950	81420	14590	18210	10	
	15	79930	12250	10370	10260	12010	36230	7060	67950	13940	14450	9	
	16	72920	10520	8340	7820	9000	21730	5020	50300	12720	10060	8	
	17	58660	8410	5660	5120	5620	7600	3130	29510	10230	6620	7	
	18	24390	7720	2550	2220	2370	2870	1400	7380	4250	3860	6	
	6	280	70	1210	3850	1180	70	60	40	40	190	18	
	7	48170	4640	35870	57180	47490	13040	2110	16330	6250	5110	17	
	8	70990	7900	40200	76460	73230	32260	3800	37630	9220	7710	16	
	9	80590	9860	29100	74200	82420	49430	5600	55940	10460	11280	15	
	10	85300	10900	13160	60870	81790	63040	7260	69950	11070	14880	14	
	11	87570	11270	13250	39740	72800	71630	8450	78740	11370	17290	13	
SEP	12	88250	10690	12460	14660	57780	75550	8900	81730	11460	18130	12	SEP
	13	87570	11270	11160	13110	36890	71630	8450	78740	11370	17290	11	
	14	85300	10900	9460	11010	14770	63040	7260	69950	11070	14880	10	
	15	80590	9860	8300	8760	10740	49430	5600	55940	10460	11280	9	
	16	70990	7900	6350	6220	7590	32260	3800	37630	9220	7710	8	
	17	48170	4640	3610	3330	3930	13040	2110	16330	6250	5110	7	
	18	280	70	830	670	830	70	60	40	40	190	6	
	7	20110	1730	12400	24590	22960	8970	970	3800	2120	2890	17	
	8	61870	5210	25230	63970	68790	36900	2630	23290	6510	5880	16	
	9	76620	7360	16060	67520	84450	57670	4120	41180	8060	8280	15	
	10	83110	8600	10580	55770	85580	72070	5490	54930	8740	11060	14	
	11	86070	8990	10860	36020	77640	80860	6480	63570	9050	13200	13	
OCT	12	86940	8560	10310	12450	63500	84400	6830	66520	9150	13980	12	OCT
	13	86070	8990	9240	11180	43910	80860	6480	63570	9050	13200	11	
	14	83110	8600	7710	9300	22570	72070	5490	54930	8740	11060	10	
	15	76620	7360	6130	6990	8840	57670	4120	41180	8060	8280	9	
	16	61870	5210	4230	4400	5550	36900	2630	23290	6510	5880	8	
	17	20110	1730	1520	1460	1700	8970	970	3800	2120	2890	7	
	8	46800	3070	12980	45830	54050	32530	1720	11810	4150	4470	16	
	9	70820	5400	6820	58640	80500	59530	3040	28790	6270	6470	15	
	10	80190	6760	8390	50020	85160	75850	4160	42090	7100	8360	14	
	11	84230	7200	8890	32300	79070	85380	4960	50470	7460	9940	13	
NOV	12	85390	6890	8550	10440	66140	88950	5260	53330	7560	10560	12	NOV
	13	84230	7200	7630	9390	47730	85380	4960	50470	7460	9940	11	
	14	80190	6760	6220	7690	27240	75850	4160	42090	7100	8360	10	
	15	70820	5400	4420	5420	7470	59530	3040	28790	6270	6470	9	
	16	46800	3070	2480	2770	3450	32530	1720	11810	4150	4470	8	
	8	36800	2200	8310	35230	43100	27040	1330	7540	3100	3710	16	
	9	66400	4590	5690	53150	75750	57640	2630	23600	5590	5880	15	
	10	77290	5920	7340	46450	82520	75000	3670	36390	6510	7480	14	
	11	81830	6320	7940	30010	77490	84790	4400	44470	6890	8810	13	
DEC	12	83120	5990	7730	9340	65360	88380	4670	47230	7000	9340	12	DEC
	13	81830	6320	6830	8430	47810	84790	4400	44470	6890	8810	11	
	14	77290	5920	5460	6870	28080	75000	3670	36390	6510	7480	10	
	15	66400	4590	3690	4710	8940	57640	2630	23600	5590	5880	9	
	16	36800	2200	1710	2030	2460	27040	1330	7540	3100	3710	8	
				NORTHWEST VERTICAL (LUX)	WEST VERTICAL (LUX)	SOUTHWEST VERTICAL (LUX)							

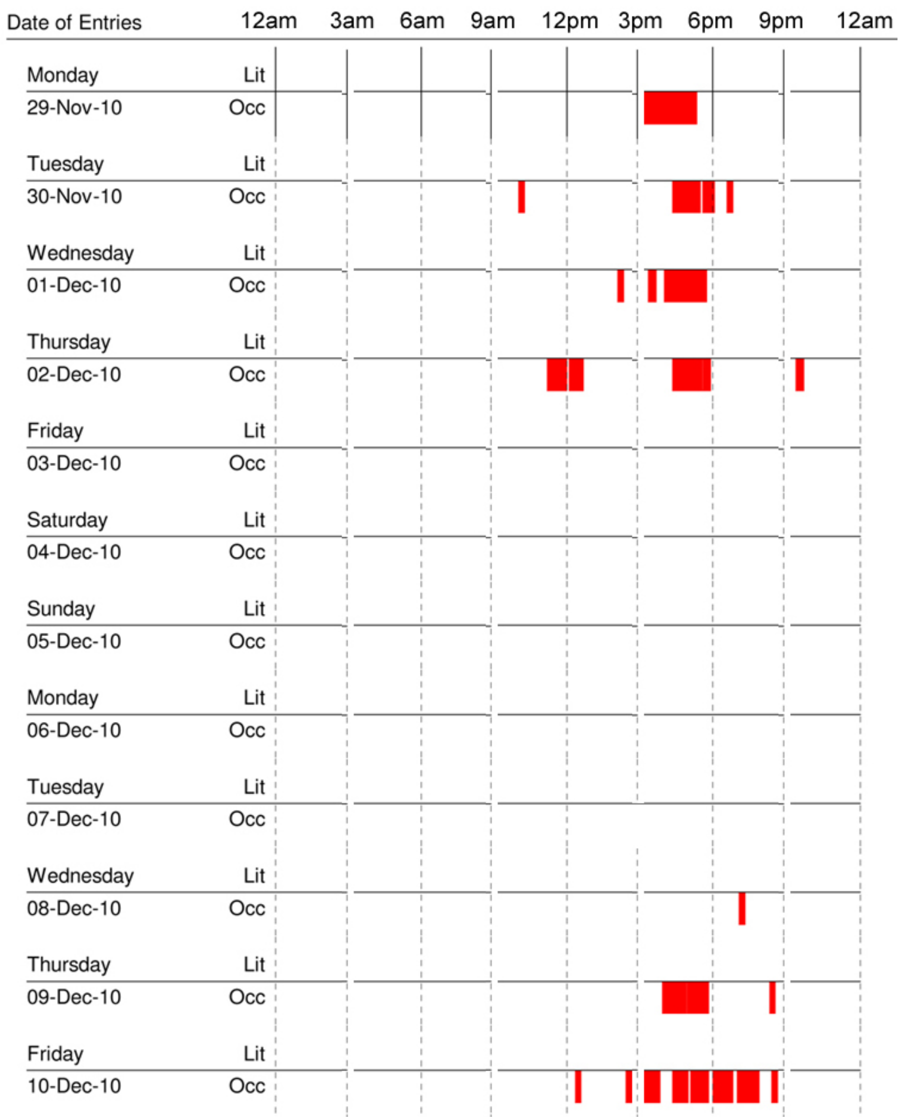
Appendix F: Occupancy data

The following appendix contains occupancy data for the three-week monitoring period (Nov. 24 - Dec. 15, 2010) for four perimeter workstations.

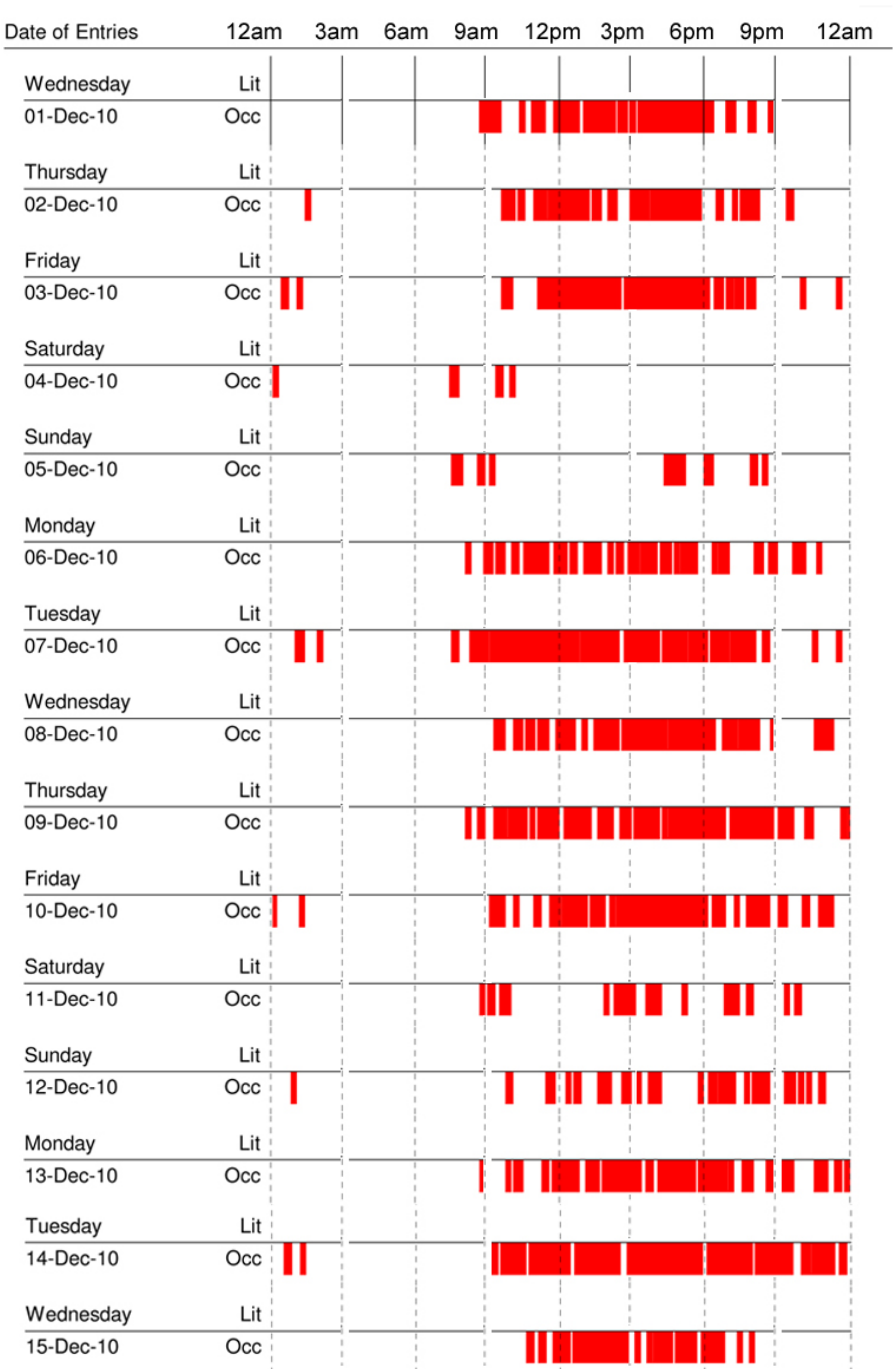
Workstation 1 occupancy



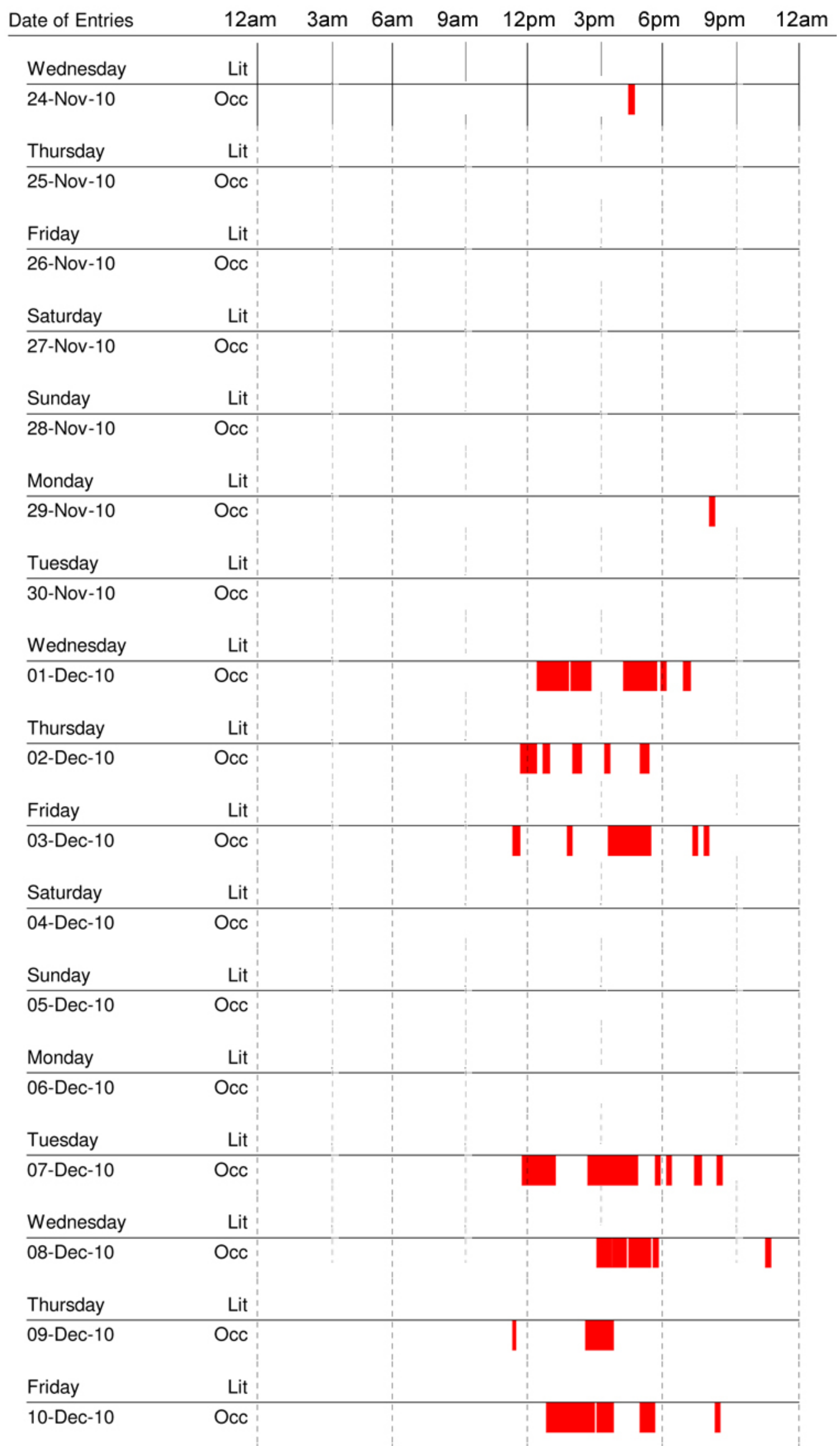
Workstation 2 occupancy



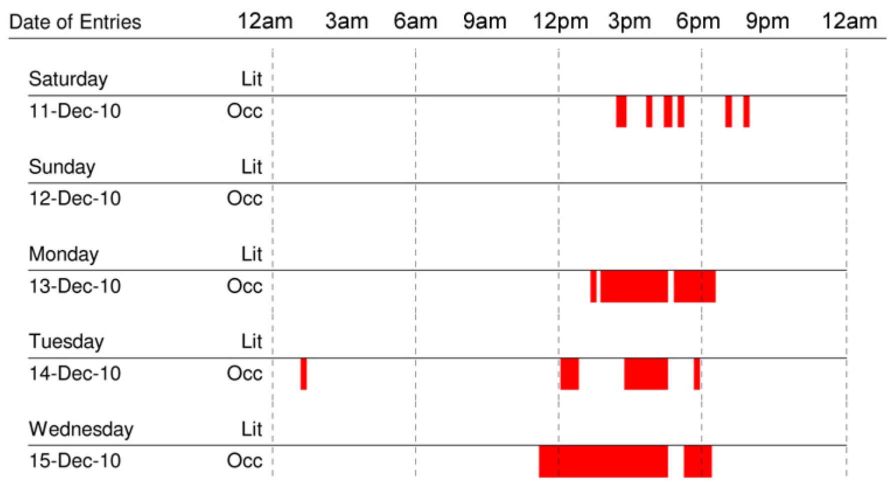
Workstation 3 occupancy



Workstation 4 occupancy



Workstation 4 occupancy (ctd.)

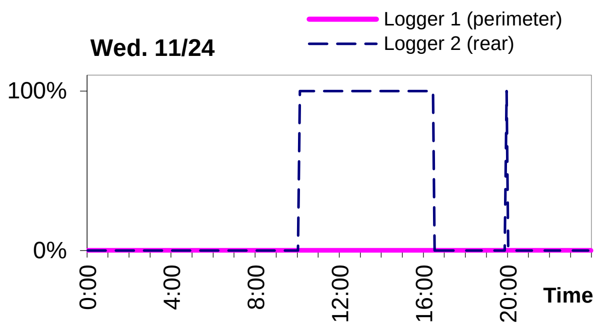


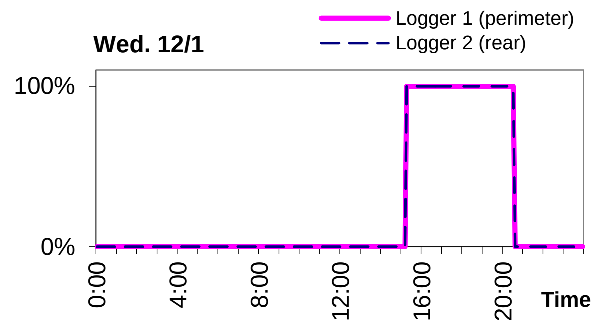
Appendix G: Lighting control data

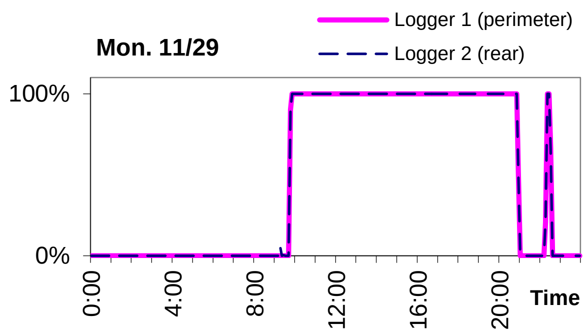
This appendix contains overhead fixture lighting data from the three-week field monitoring period. Lighting loggers were mounted below both rows of fixtures.

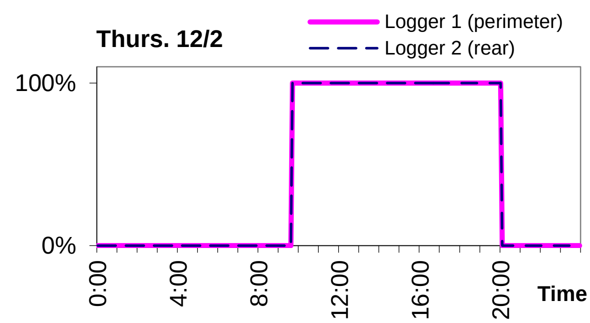
DENT lighting control data (weekdays only)

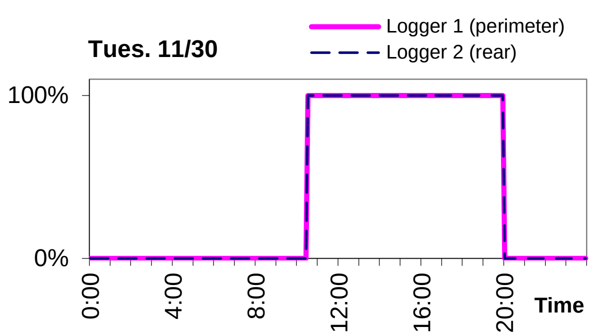
Nov. 24 – Dec. 2, 2010





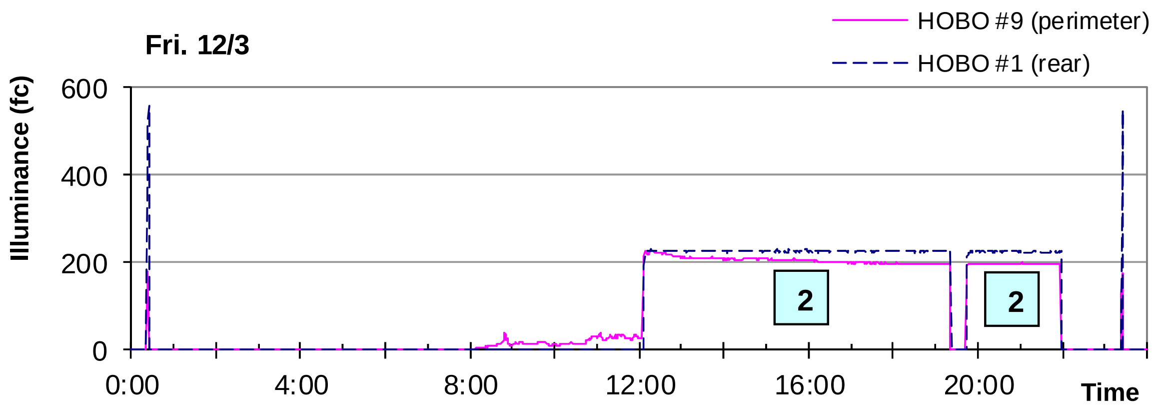


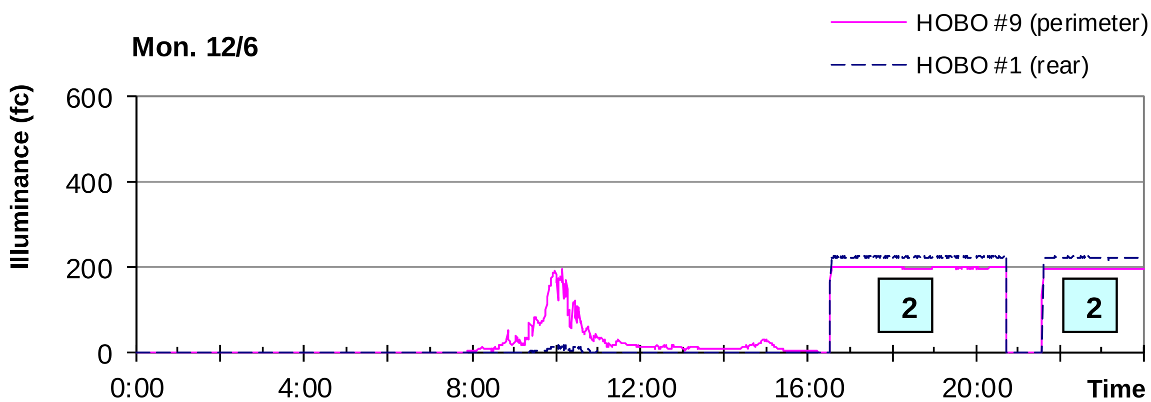


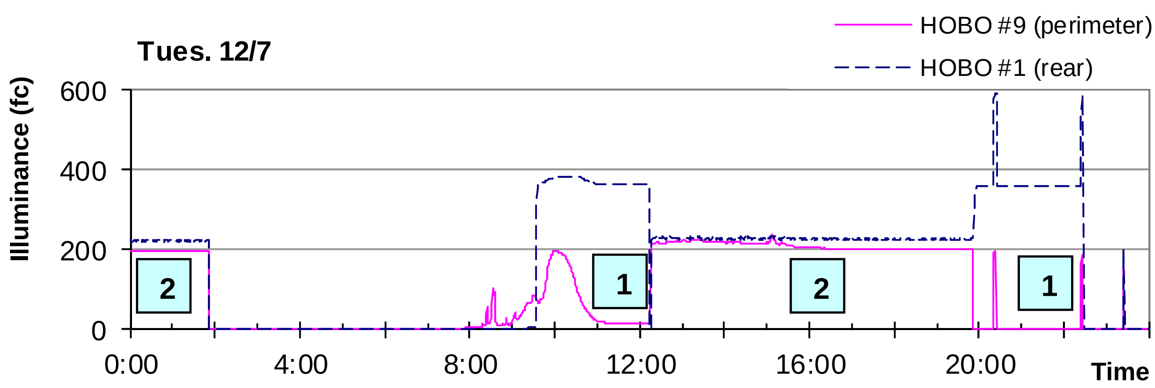


HOBO lighting control data (weekdays only)

Dec. 3 – Dec. 15, 2010

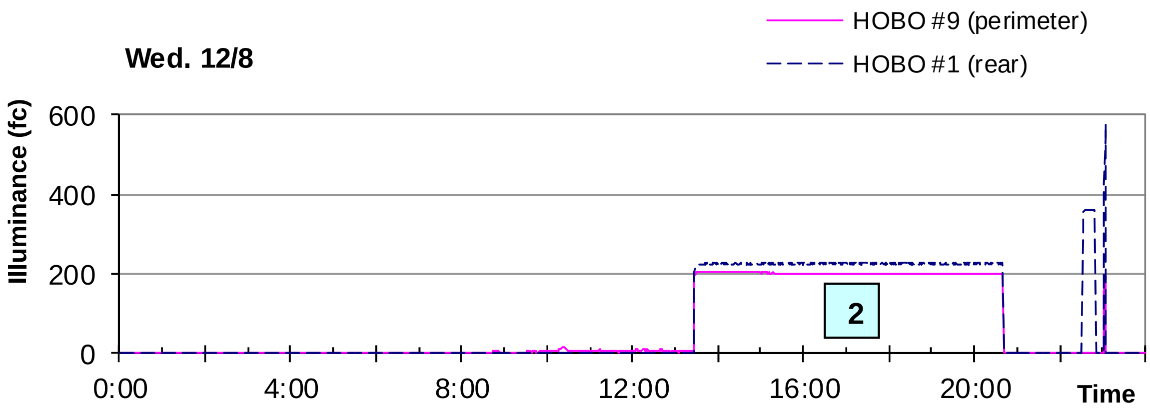


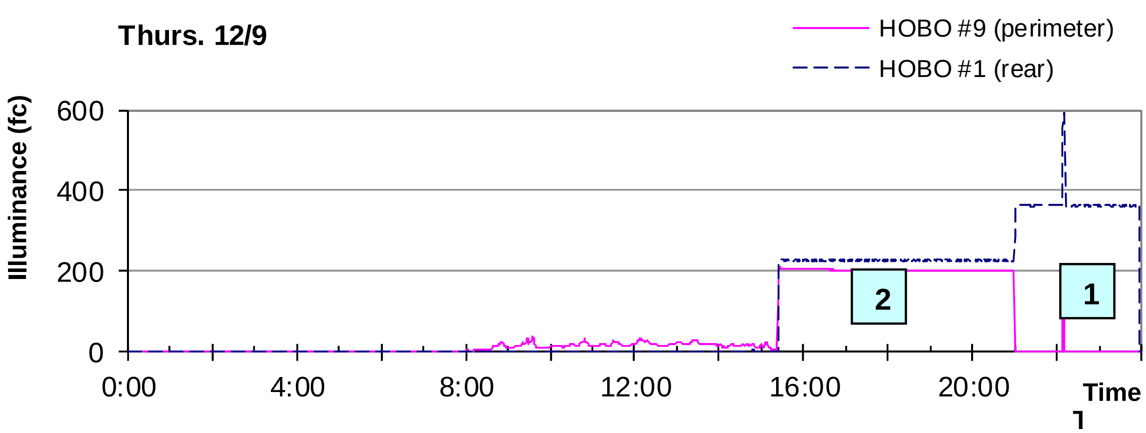


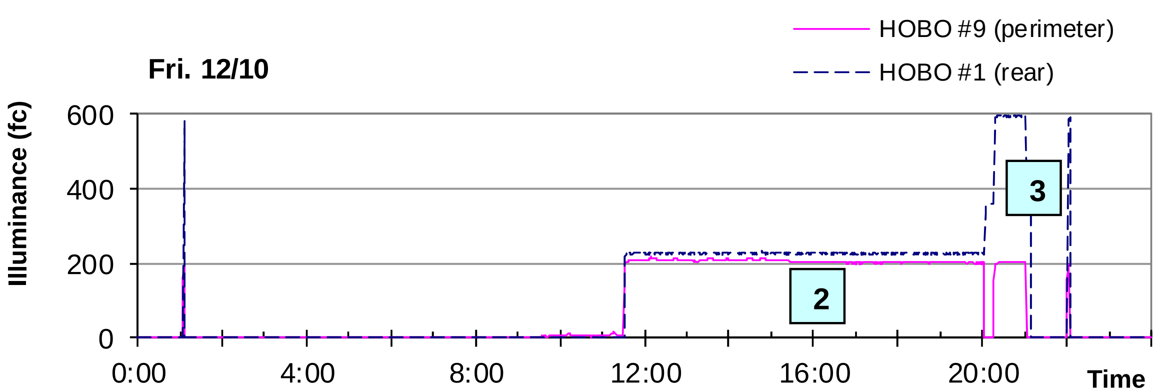


HOBO lighting control data (weekdays only)

Dec. 3 – Dec. 15, 2010

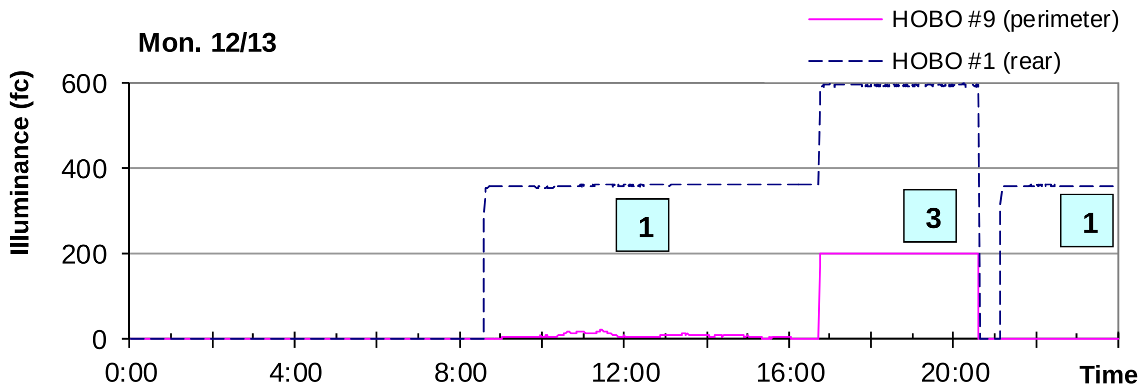


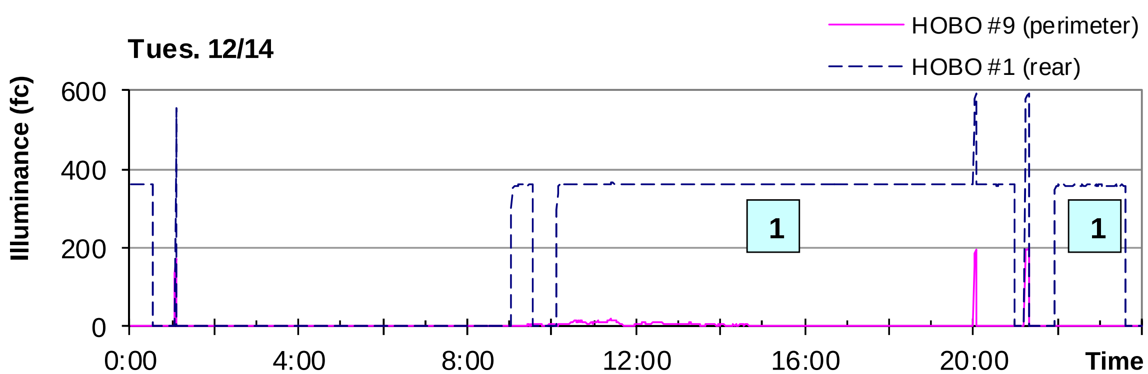


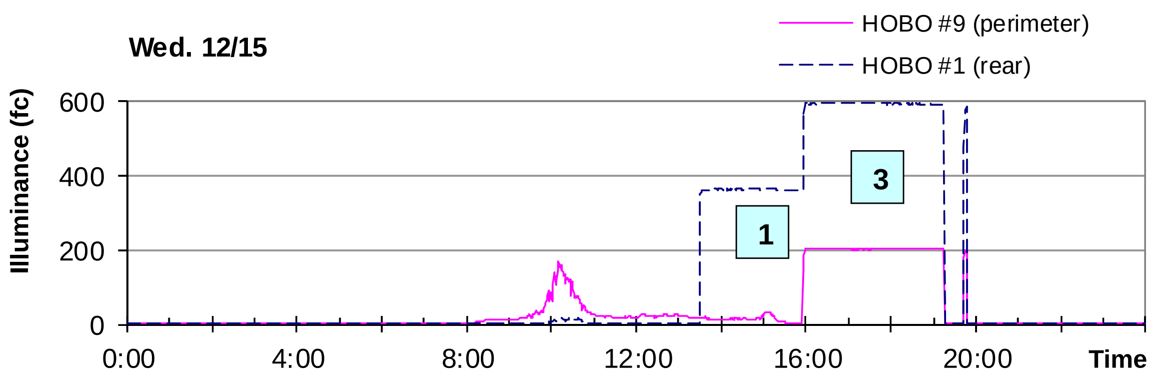


HOBO lighting control data (weekdays only)

Dec. 3 – Dec. 15, 2010





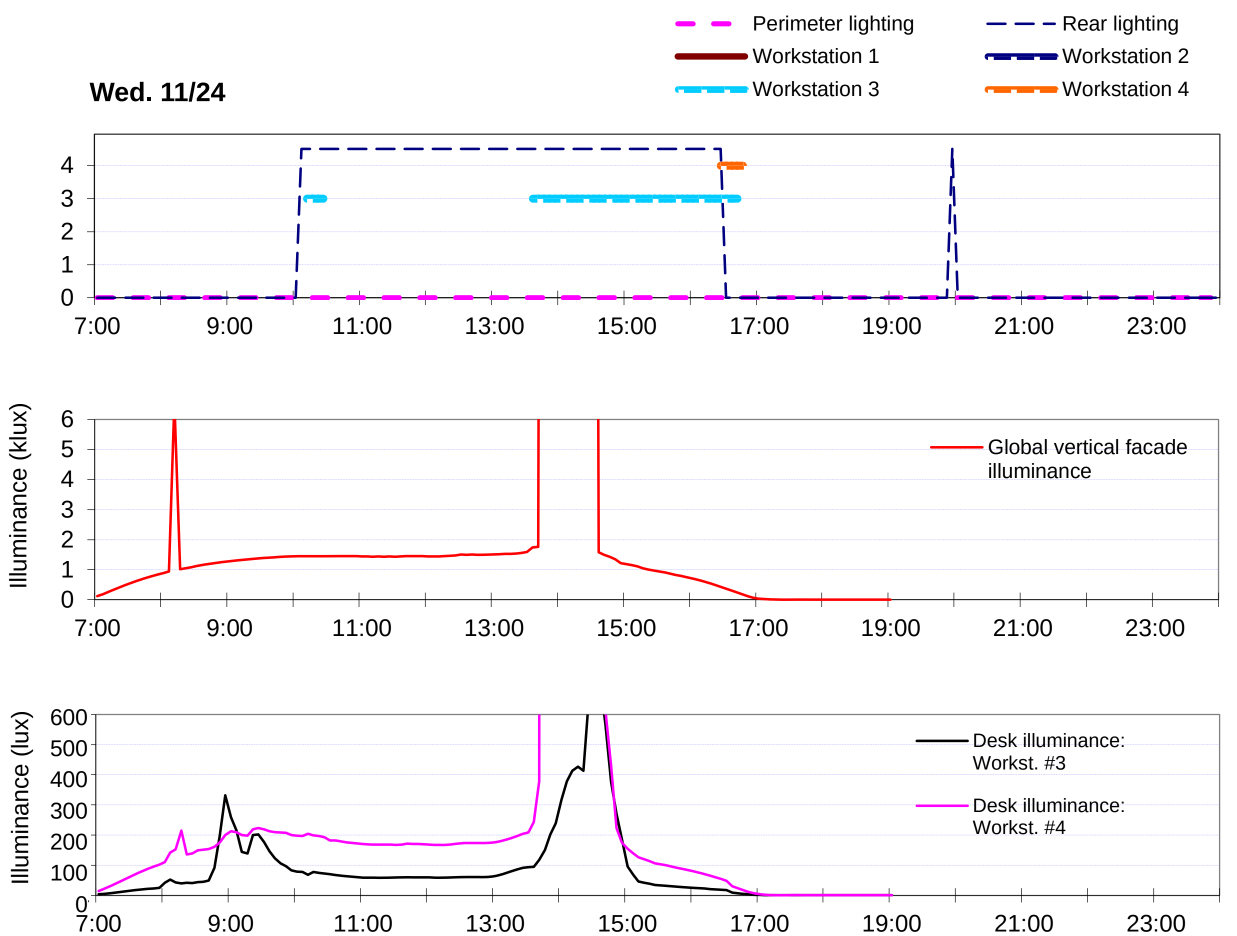


Appendix H: Hourly graphs

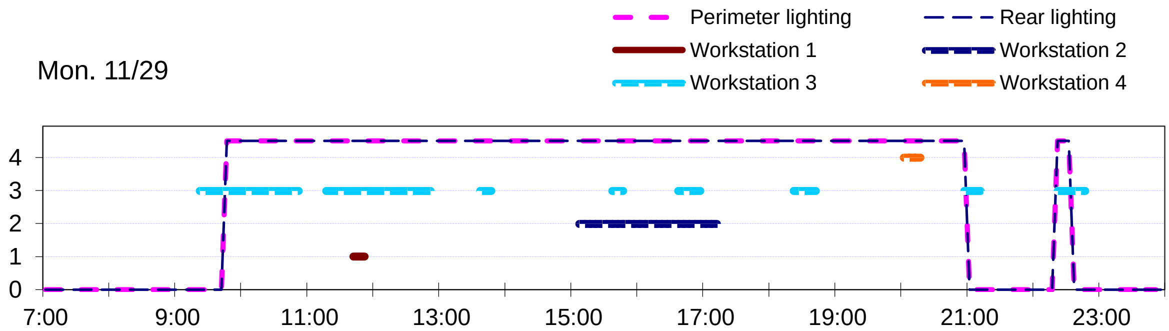
This appendix contains hourly data for the three-week monitoring period (Nov. 24 - Dec. 15, 2010). Occupancy data for perimeter workstations is presented next to overhead lighting control data; global facade illuminance and illuminance levels measured at two points inside the space.

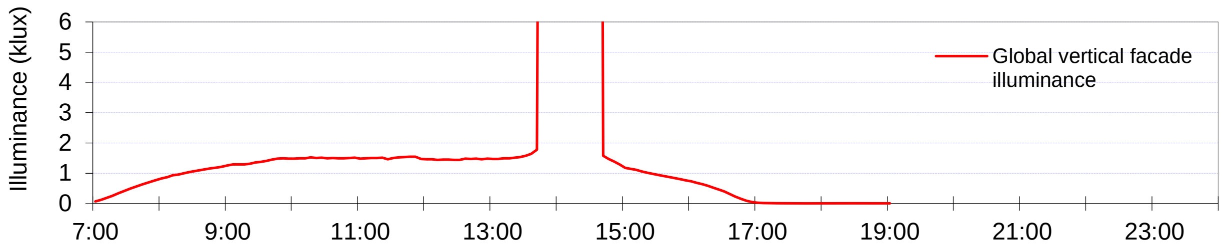
Hourly lighting and occupancy graphs (weekdays only)

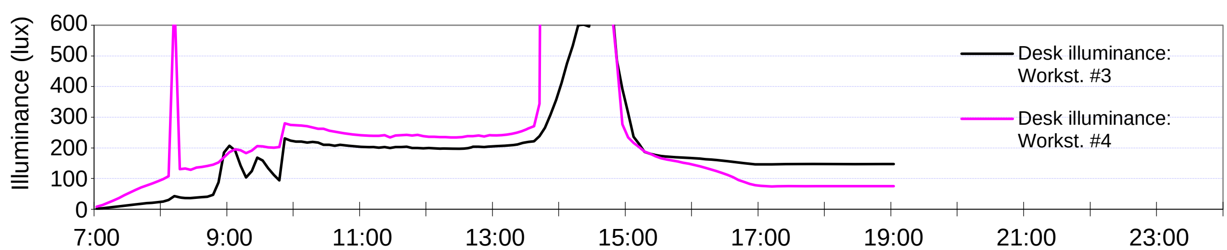
Nov. 24 – Dec. 15, 2010



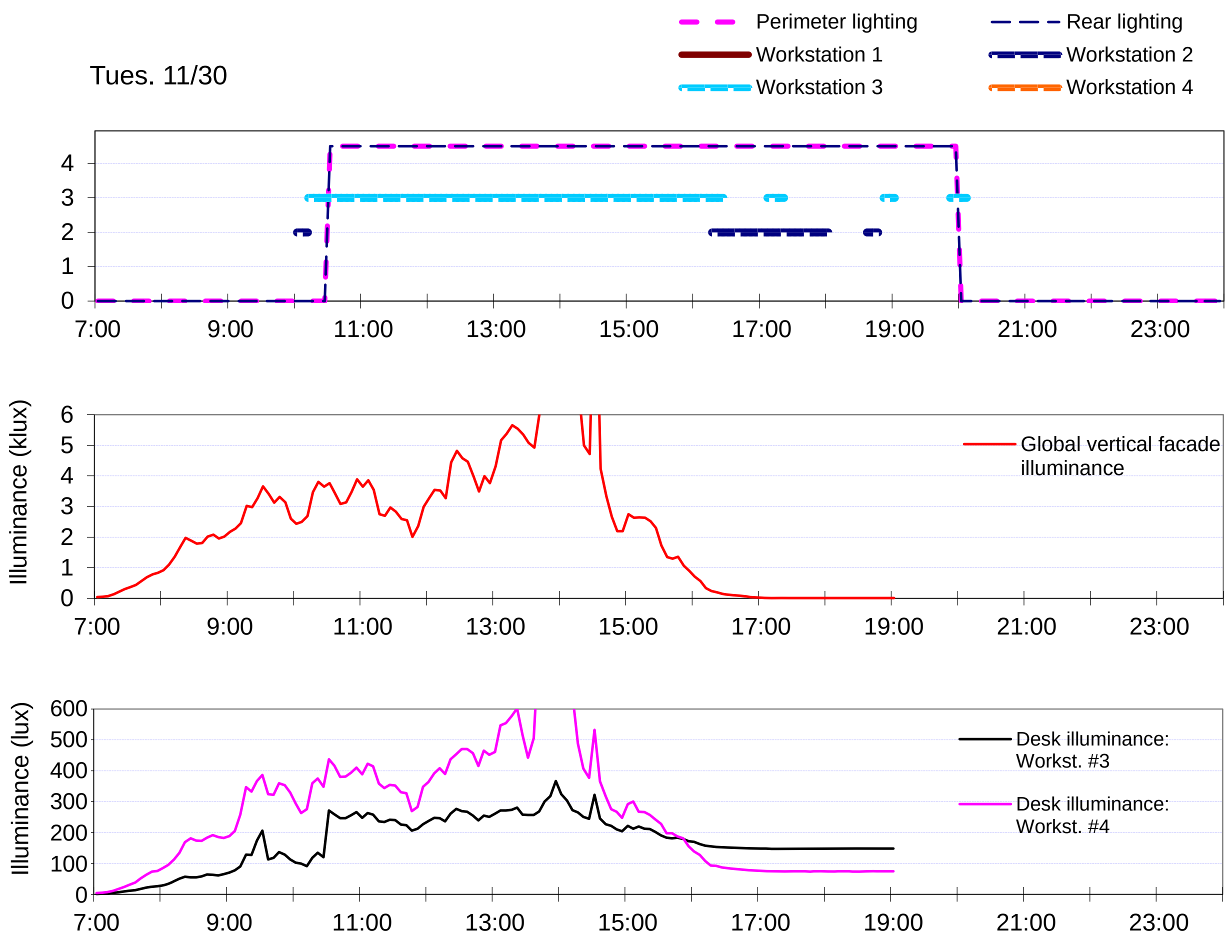
Hourly lighting and occupancy graphs (ctd.)



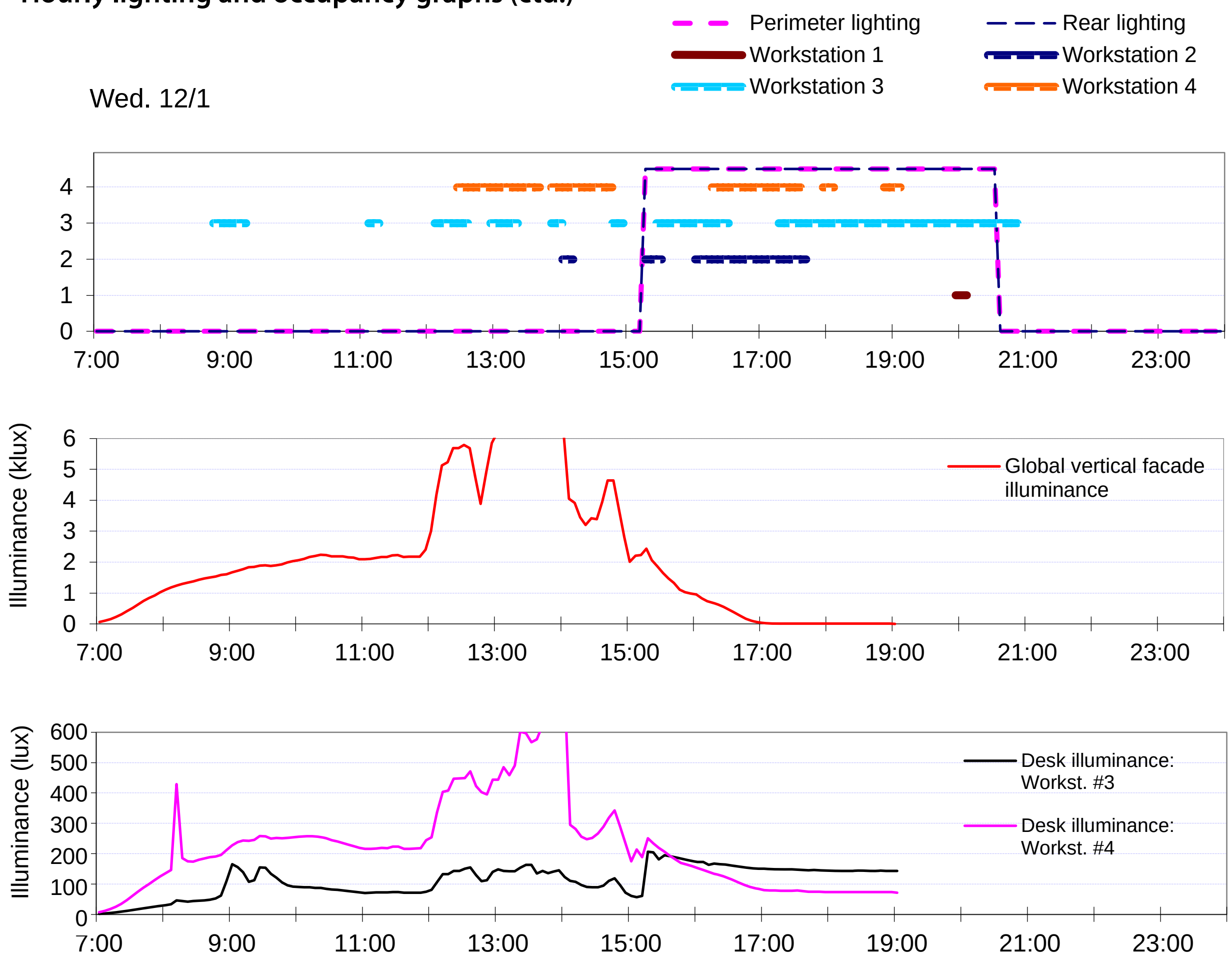




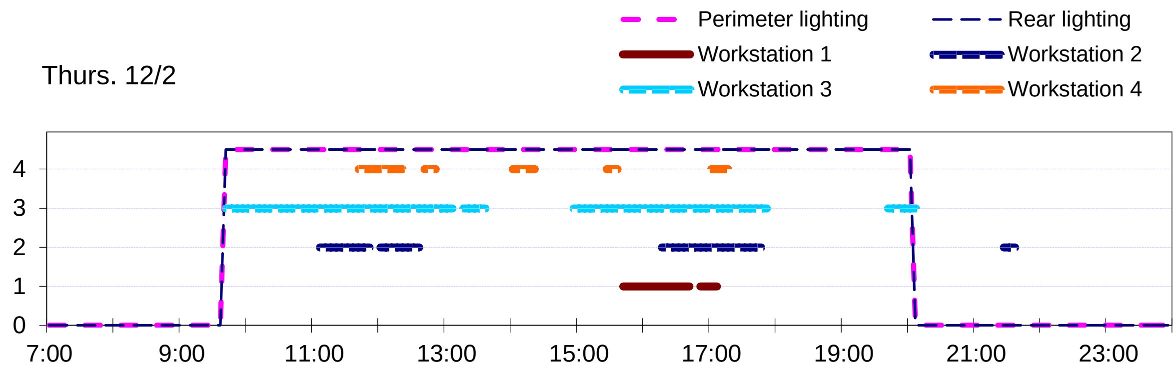
Hourly lighting and occupancy graphs (ctd.)

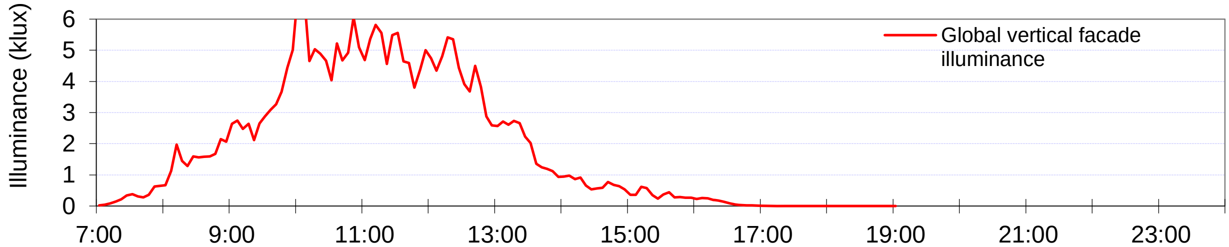


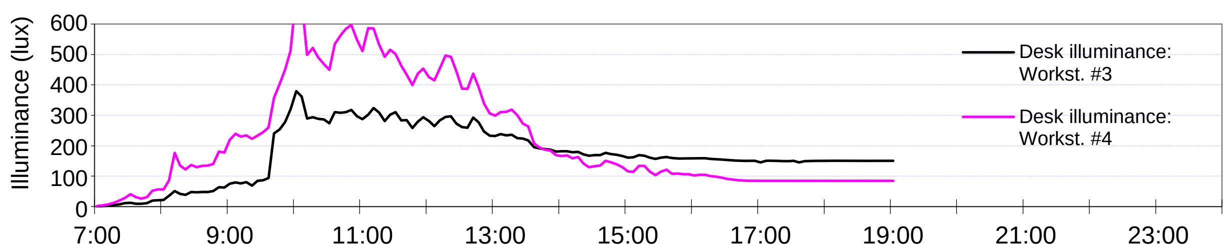
Hourly lighting and occupancy graphs (ctd.)



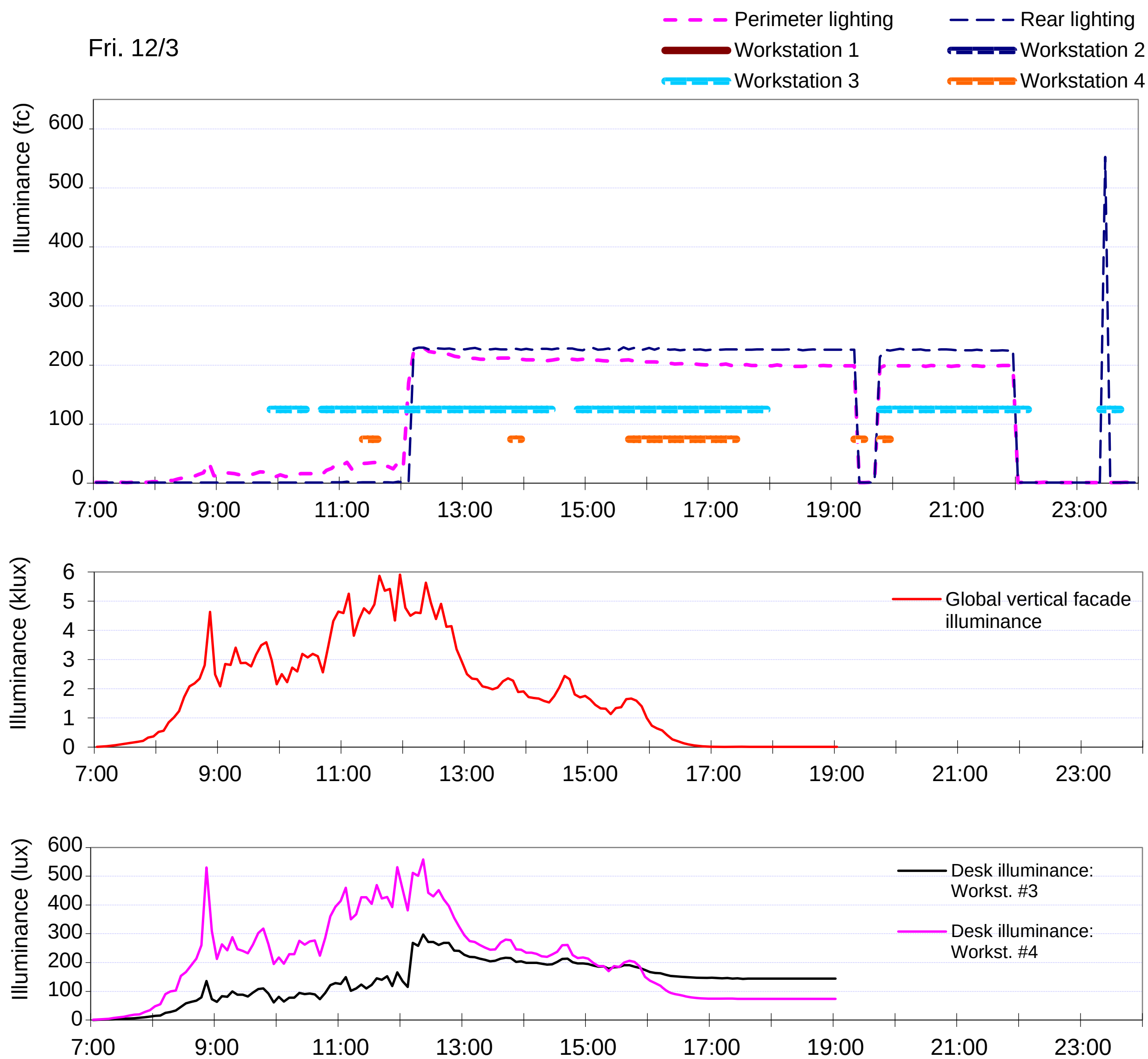
Hourly lighting and occupancy graphs (ctd.)



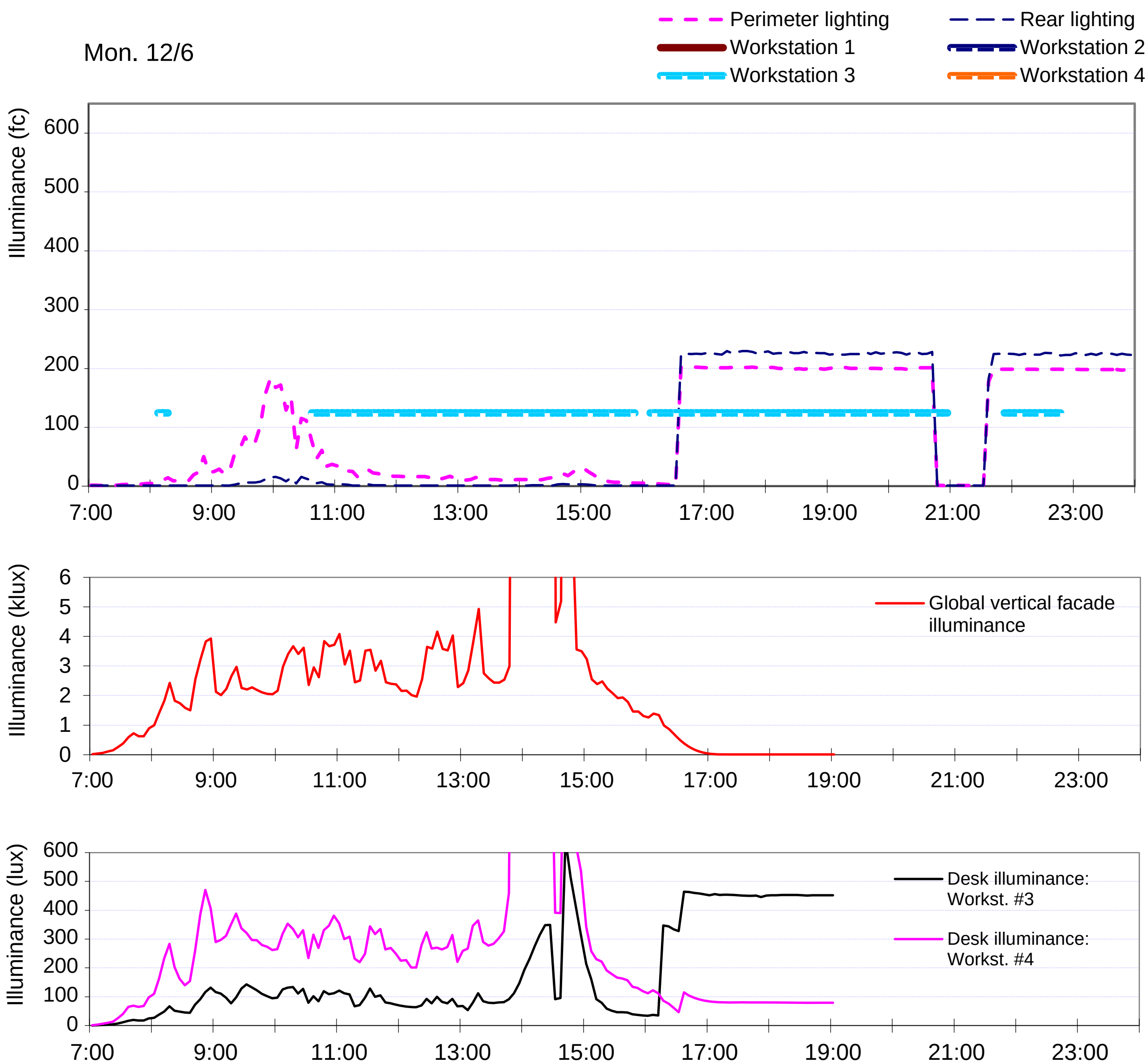




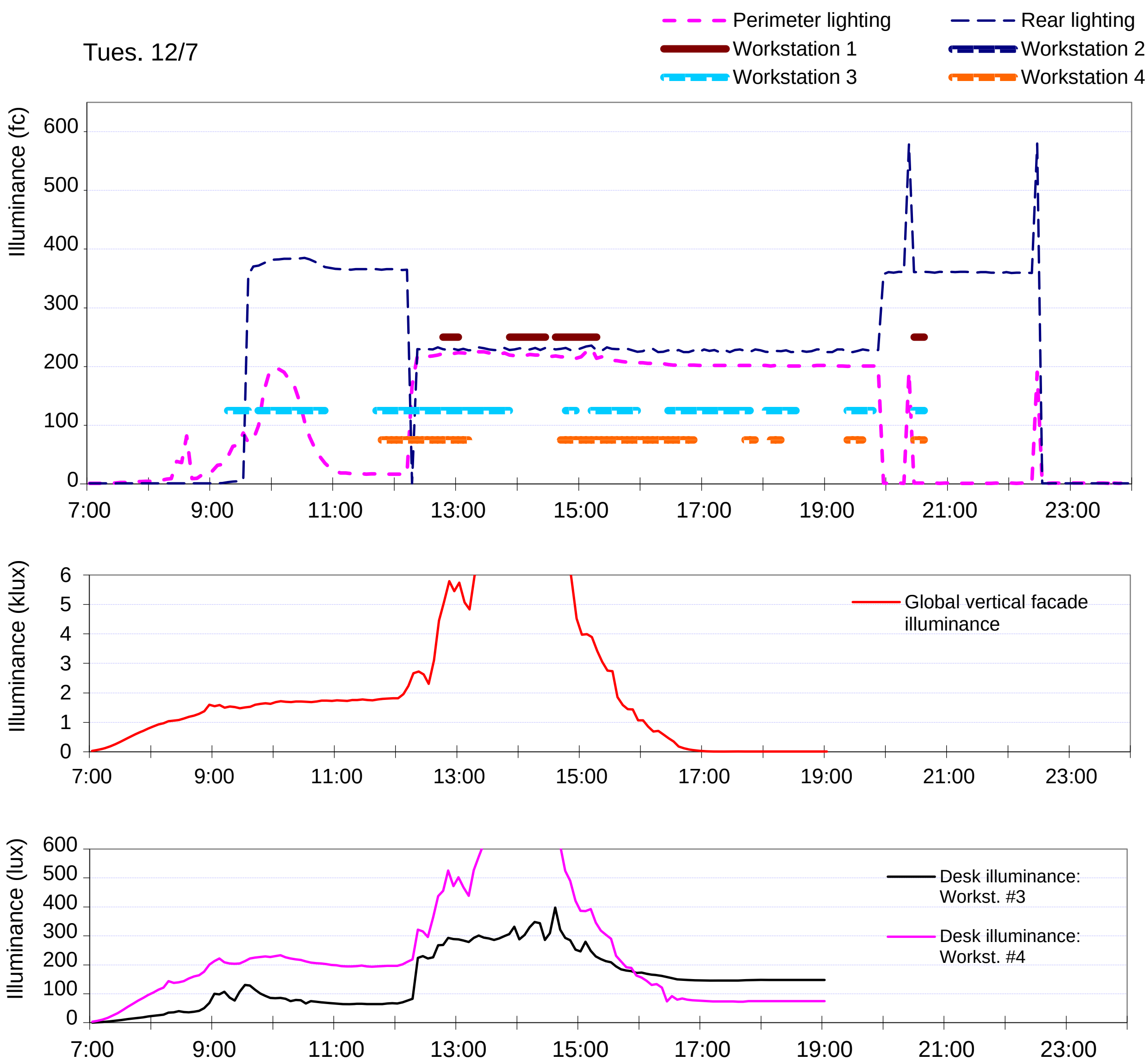
Hourly lighting and occupancy graphs (ctd.)



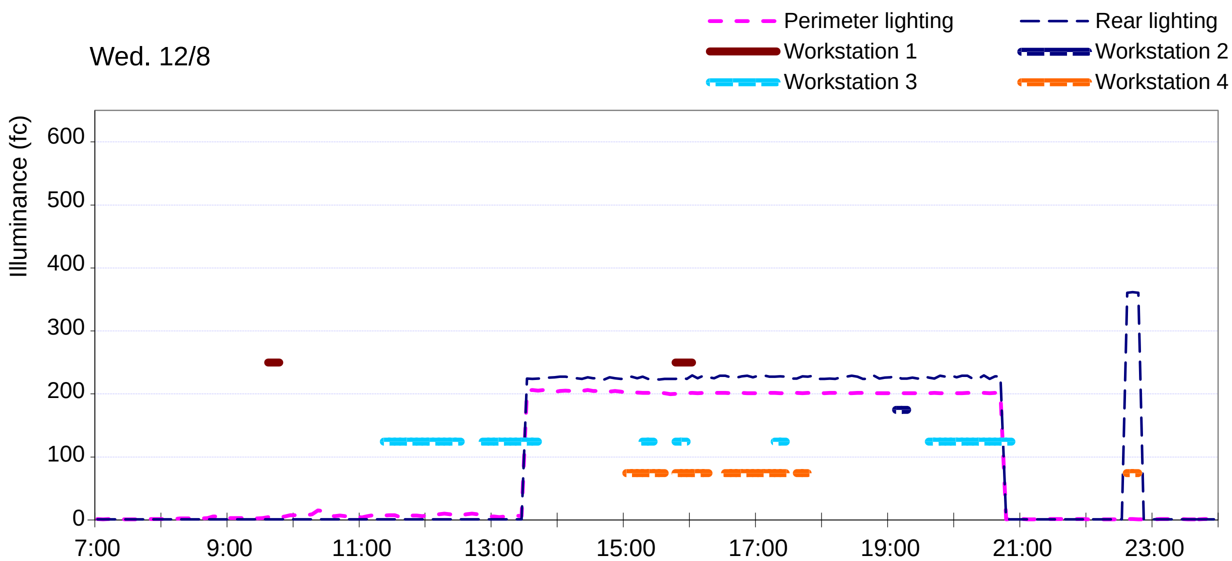
Hourly lighting and occupancy graphs (ctd.)

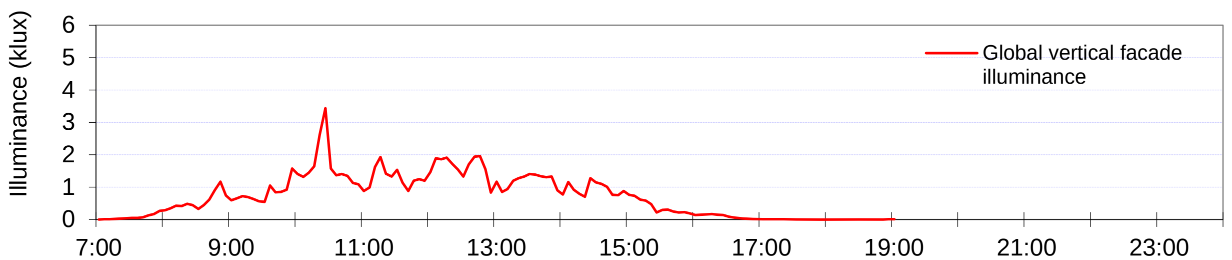


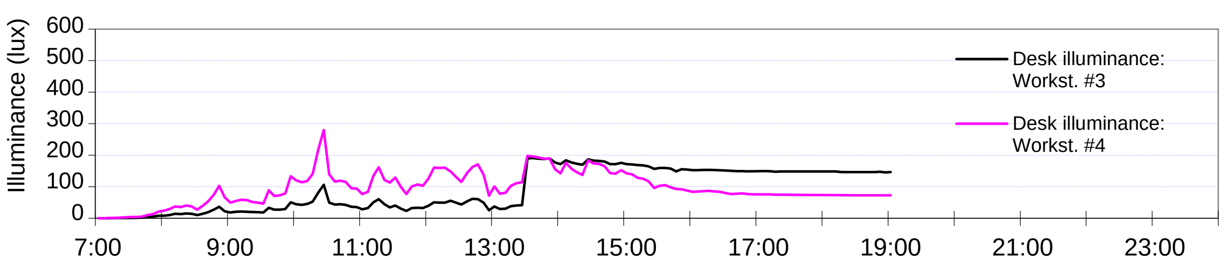
Hourly lighting and occupancy graphs (ctd.)



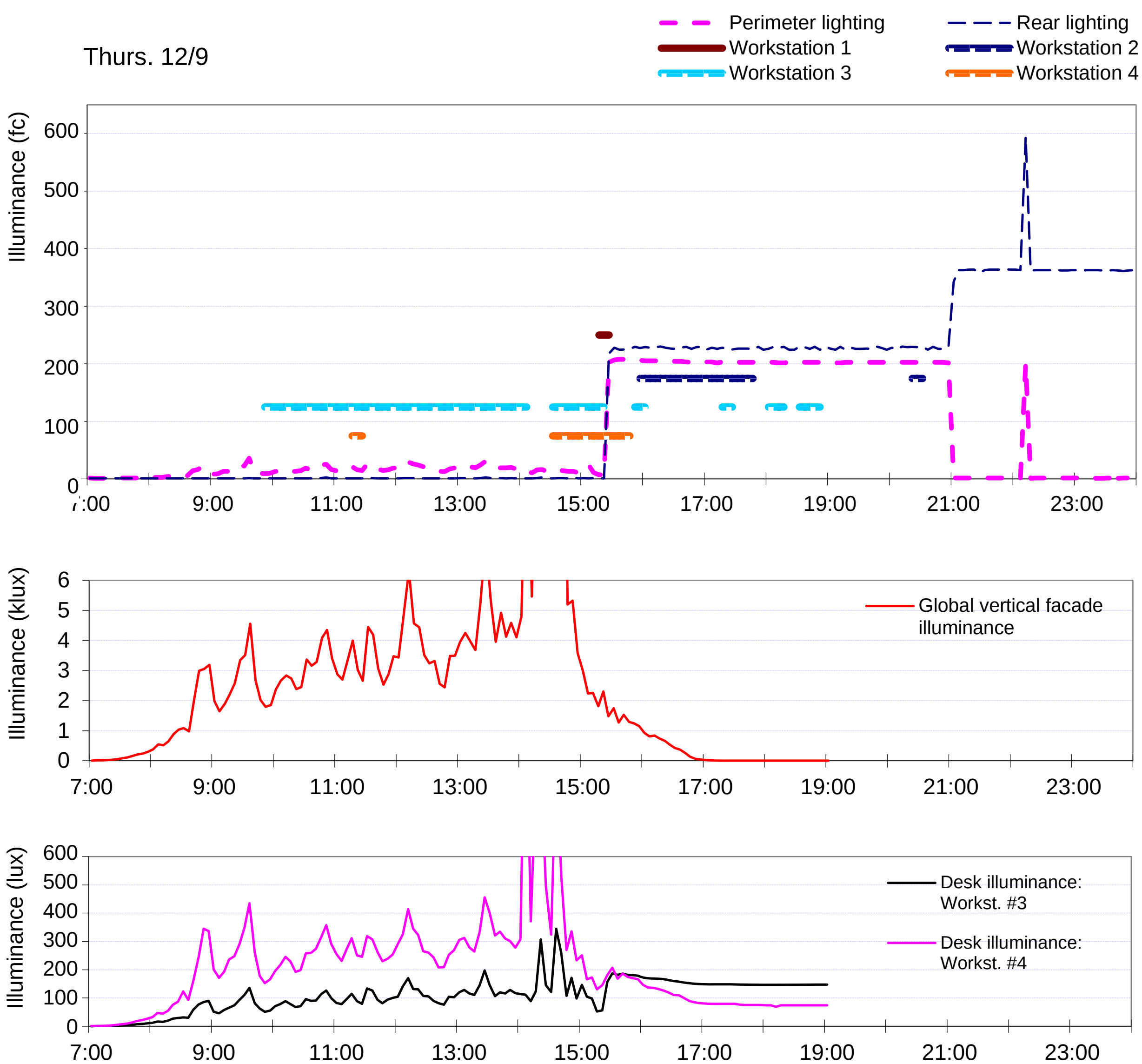
Hourly lighting and occupancy graphs (ctd.)



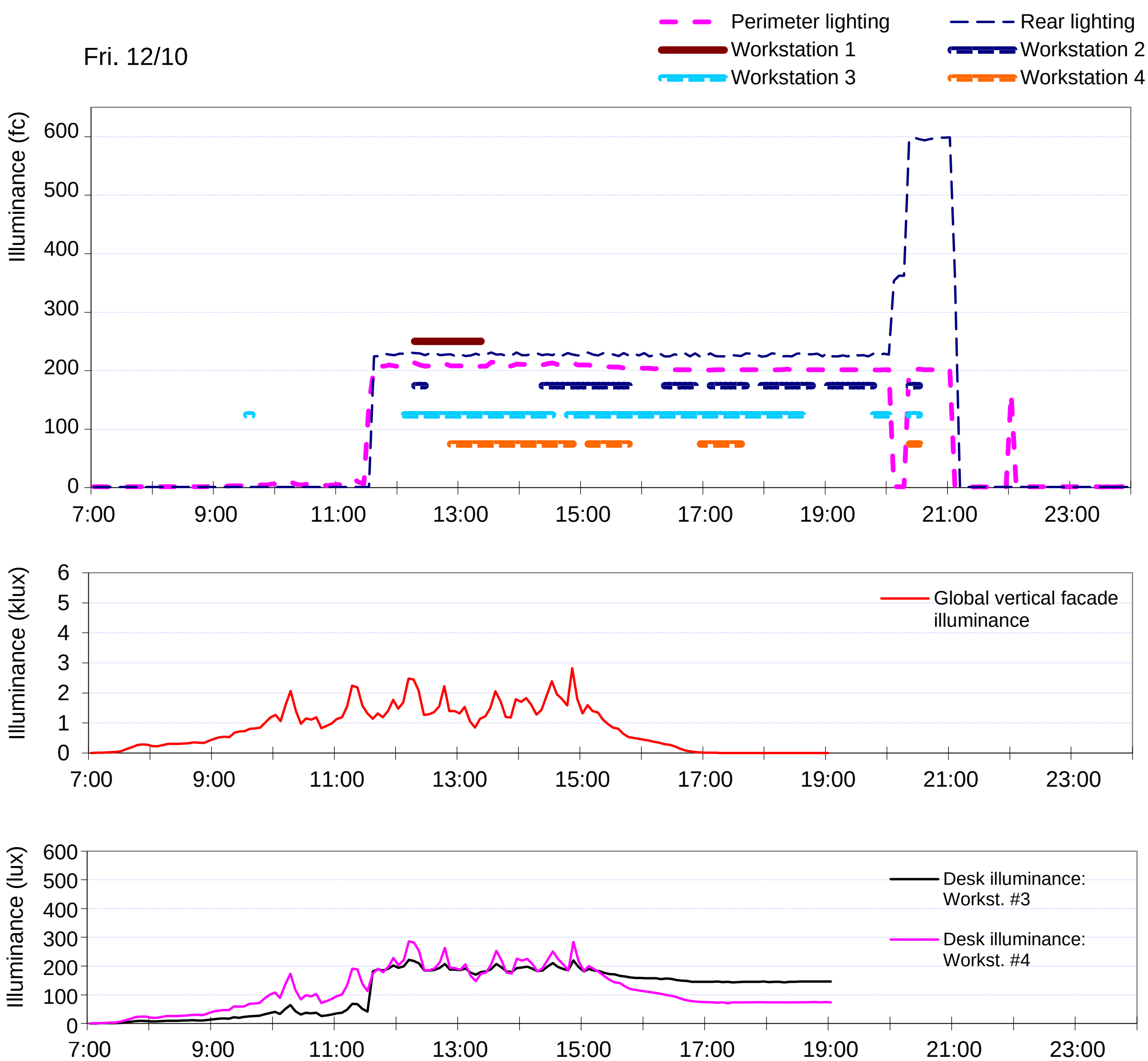




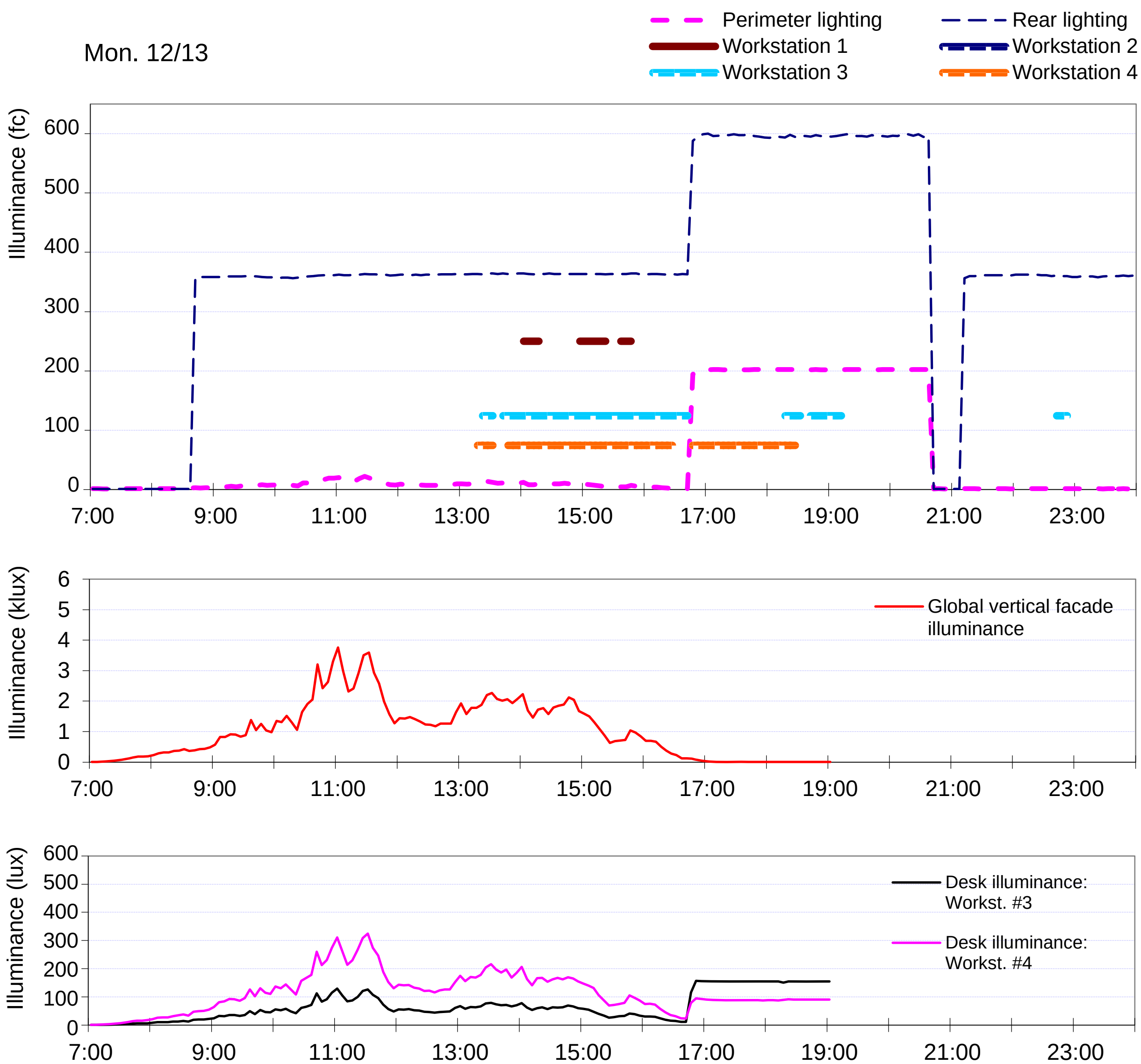
Hourly lighting and occupancy graphs (ctd.)



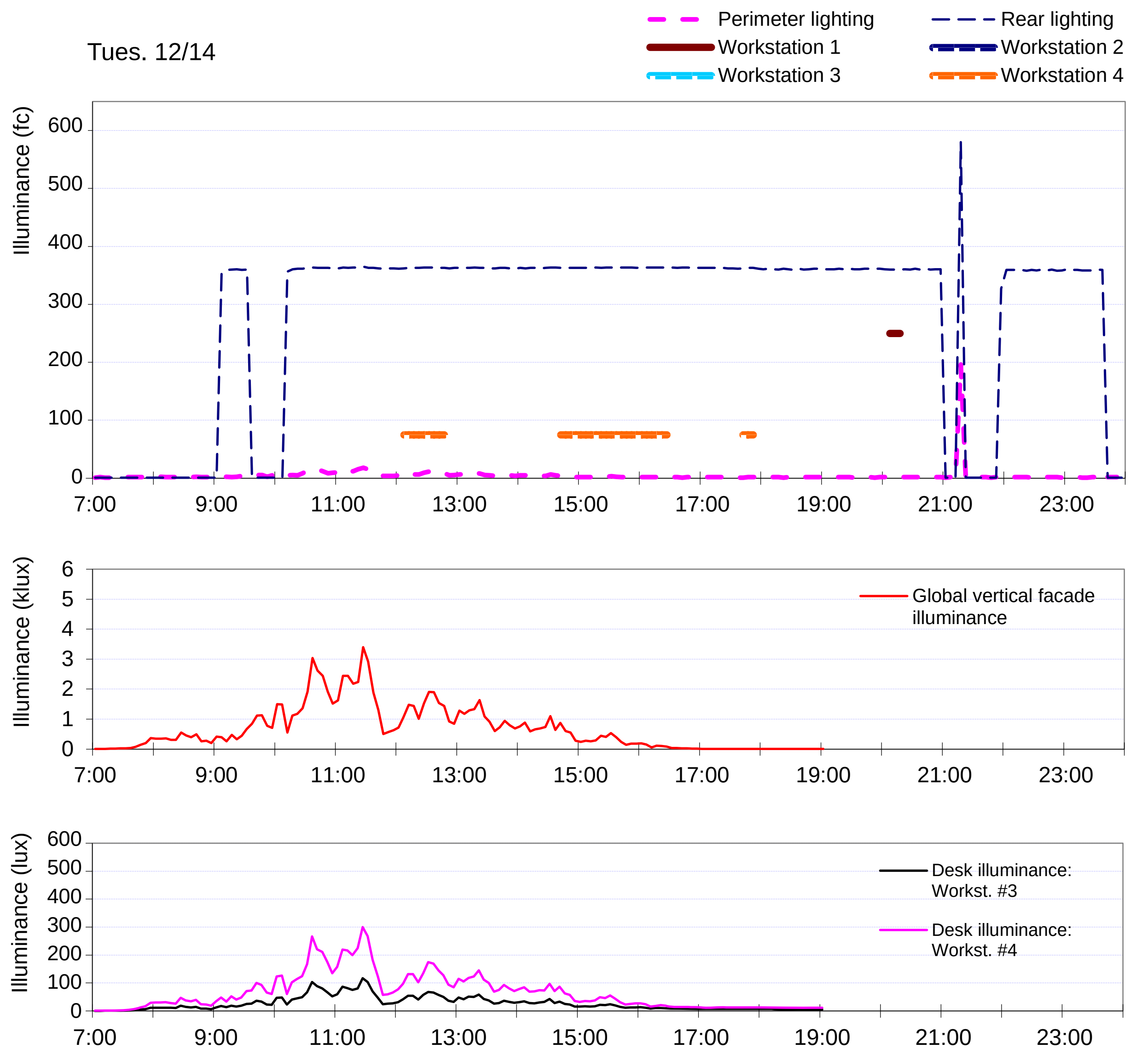
Hourly lighting and occupancy graphs (ctd.)



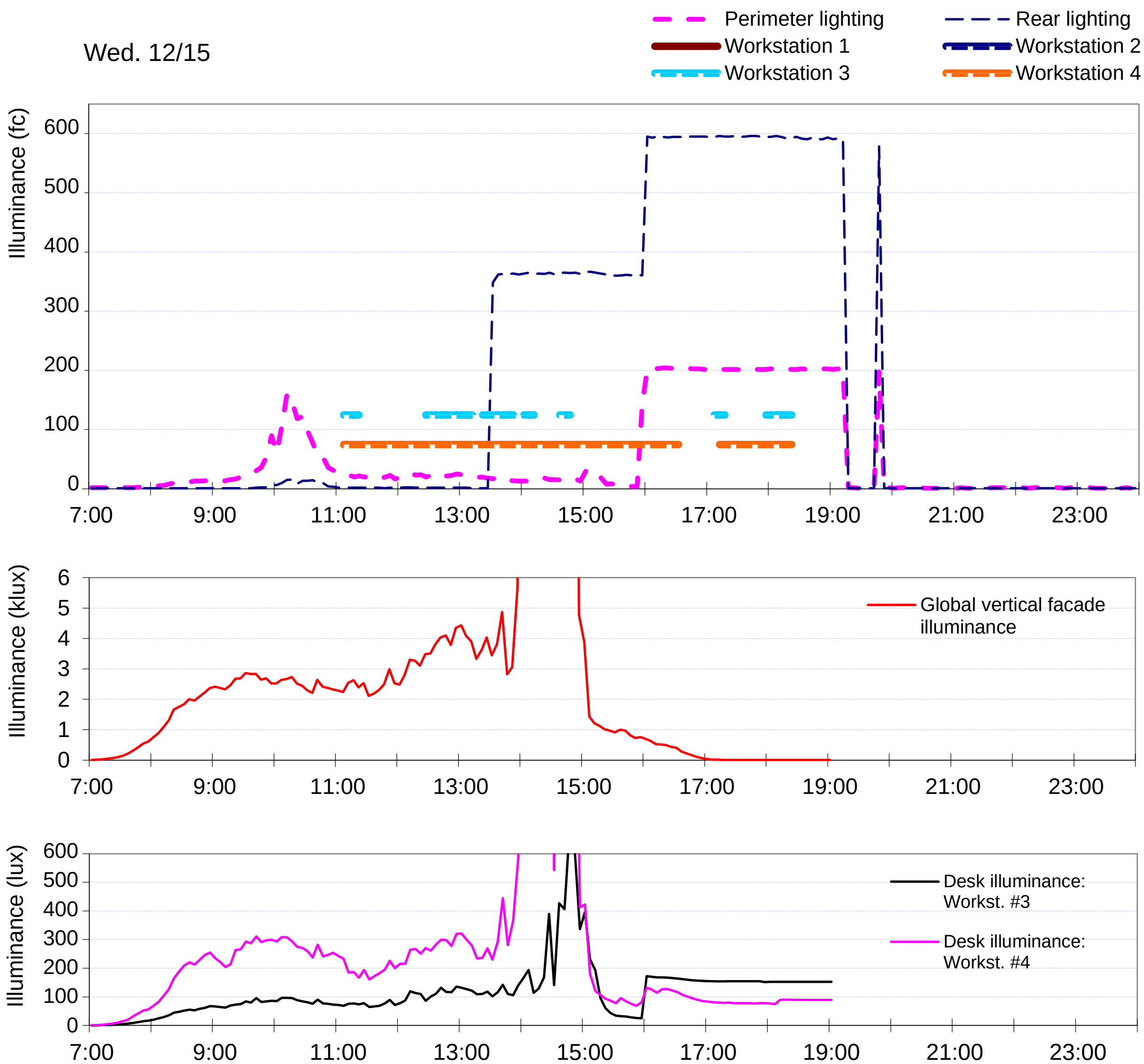
Hourly lighting and occupancy graphs (ctd.)



Hourly lighting and occupancy graphs (ctd.)



Hourly lighting and occupancy graphs (ctd.)



Appendix I: Computer model material properties

The following two tables list properties for materials used in the computer daylight model. Reflectances for diffuse materials were measured on site using a Philips surface reflectance chart. Reflectances of specular surfaces and surfaces which are not uniformly diffuse (e.g. carpet) were estimated based on reflectance values cited in existing literature. Glazing transmittance was obtained from the David Brower Center construction drawing set.

Transparent material properties

Element	Type	Transmittance
Double glazing	Clear double glazing with low-e coating	0.705
Single interior glazing	1/2" clear	0.85

Opaque material properties

Element	Color	Material	Reflectance	Specularity	Roughness
Walls	off-white	gypsum	62%	0.03	0.03
Ceiling	white	gypsum	80%	0.03	0.02
Floor	medium grey-blue	carpet	20%	0	0.2
Concrete columns, interior	grey	concrete	42%	0.03	0.02
Concrete columns, exterior	grey	concrete	38%	0.03	0.02
Desk	light brown	wood	45%	0.015	0
Cubicle partitions	light brown	fabric	30%	0	0.1
Cubicle cabinet closure	med-light brown	fabric	25%	0	0.1
Desk cabinets	black	metal	5%	0.5	0.1
Couch	beige	fabric	25%	0	0.1
Armchair	beige	fabric	15%	0	0.1
Window framing	unpainted	metal	70%	0.3	0.2
Table	off-white	plastic	48%	0	0.05
Exterior siding	dark gray	painted metal	14%	0.03	0.03
Shading, typical	unpainted	metal, dusty	50%	0.3	0.2
Shading, first floor	dark grey	unknown	10%	0	0.08
Concrete, exterior	grey	concrete	34%	0.005	0
Oxford Plaza wall, gray	gray	stucco	34%	0	0.15
Oxford Plaza wall, orange	orange	stucco	20%	0	0.15
Conference room, ext. wall	off-white	stucco	50%	0	0.15
Courtyard paving	salmon	concrete	15%	0.005	0.05
Courtyard tables	dark brown	wood	5%	0	0
Buildings across street	grey	concrete	34%	0.03	0.02
Sidewalk	light grey	concrete	30%	0.03	0.03
Street	dark grey	asphalt	19%	0.005	0.05
Vegetation	dark green	N/A	10%	0.05	0
Tree	dark green	N/A	70%	0	0

Appendix J: Simulated luminance ratios

The following pages contain simulated luminance ratios for workstations #2 and 4 for a case with and without exterior shading. Simulations were conducted for a clear sky at 9:00, 12:00 and 15:00 on June 21st, Sept. 21st, Dec. 21st, and an overcast sky at 12:00 on Dec. 21.st Two types of analyses were conducted:

a) luminance ratio analysis between the task area and the immediate surroundings

b) luminance ratio analyis between the task area and remote surroundings

Luminance ratio limits recommended by IESNA are listed in the table below.

IESNA recommended luminance ratio limits (IESNA, 1999)

IESNA classification	Zone definition (Meyer et al. 1996)	Corresponding cone of vision[1]	Upper limit	Lower limit
Between paper task and adjacent VDT screen	N/A	N/A	3:1	1:3
Between task and adjacent dark surroundings	“Ergorama”	60°	3:1	1:3
Between task and remote (nonadjacent surfaces)	“Panorama”	120°	10:1	1:10

[1] The 60° and 120° cones of vision for the adjacent and remote surroundings prescribed by IESNA are defined based on the Meyer et al. (1996) definition of the ergorama and panorama.

June. 21, sunny sky

> 600 cd/m²

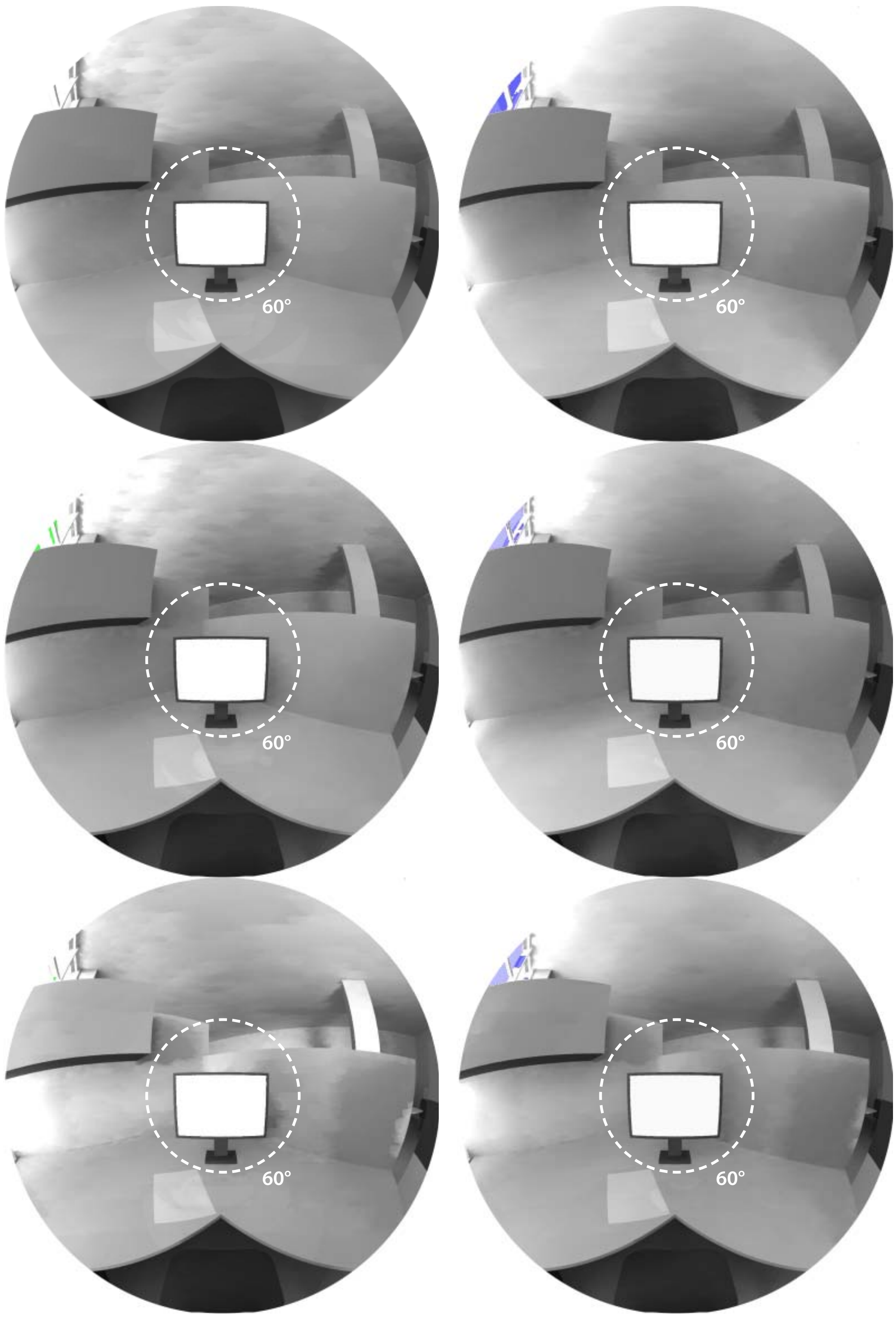
Workstation #2

with exterior shading | **without exterior shading**

9:00

12:00

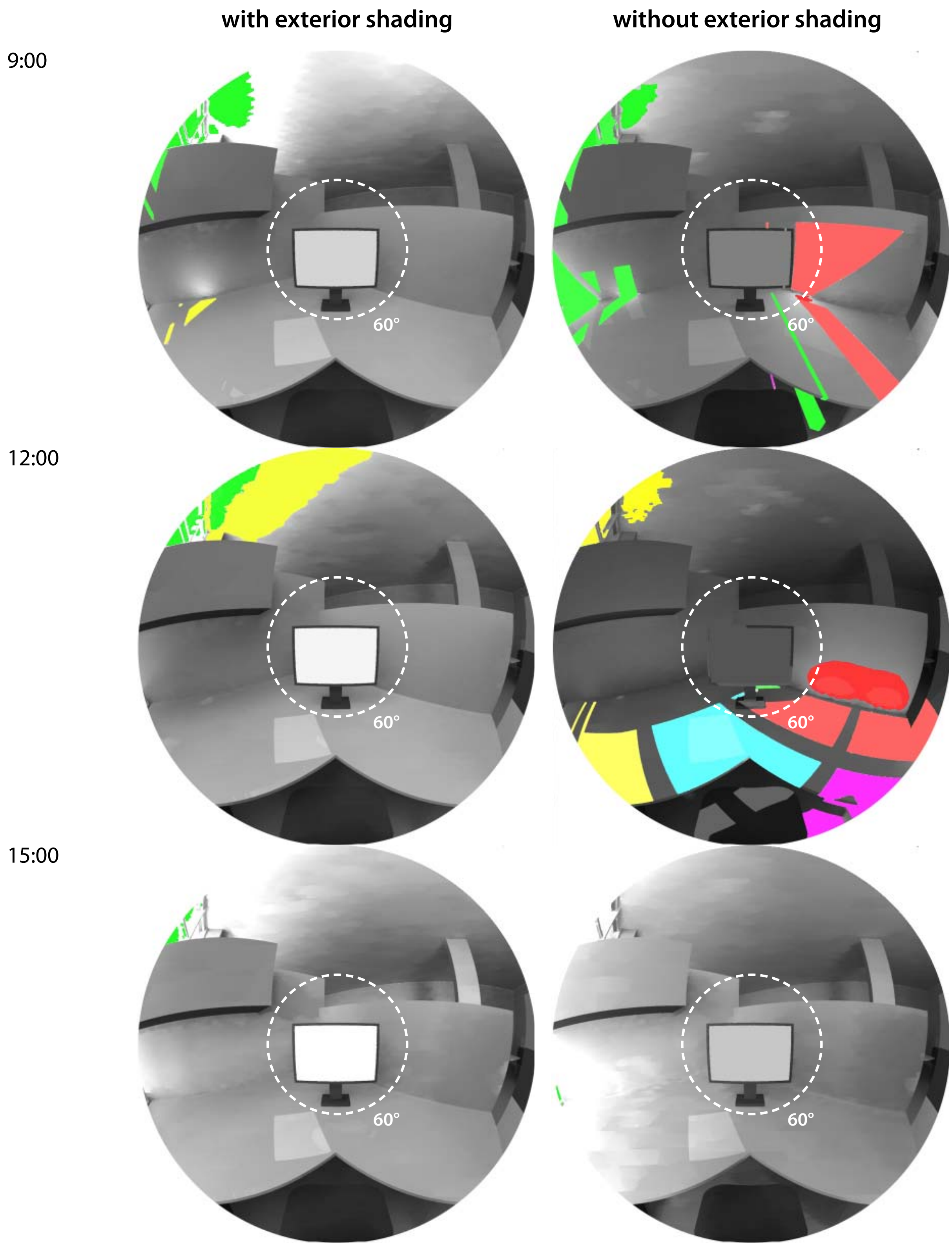
15:00



Sept. 21, sunny sky

> 600 cd/m²

Workstation #2



Dec. 21, sunny sky

> 600 cd/m²

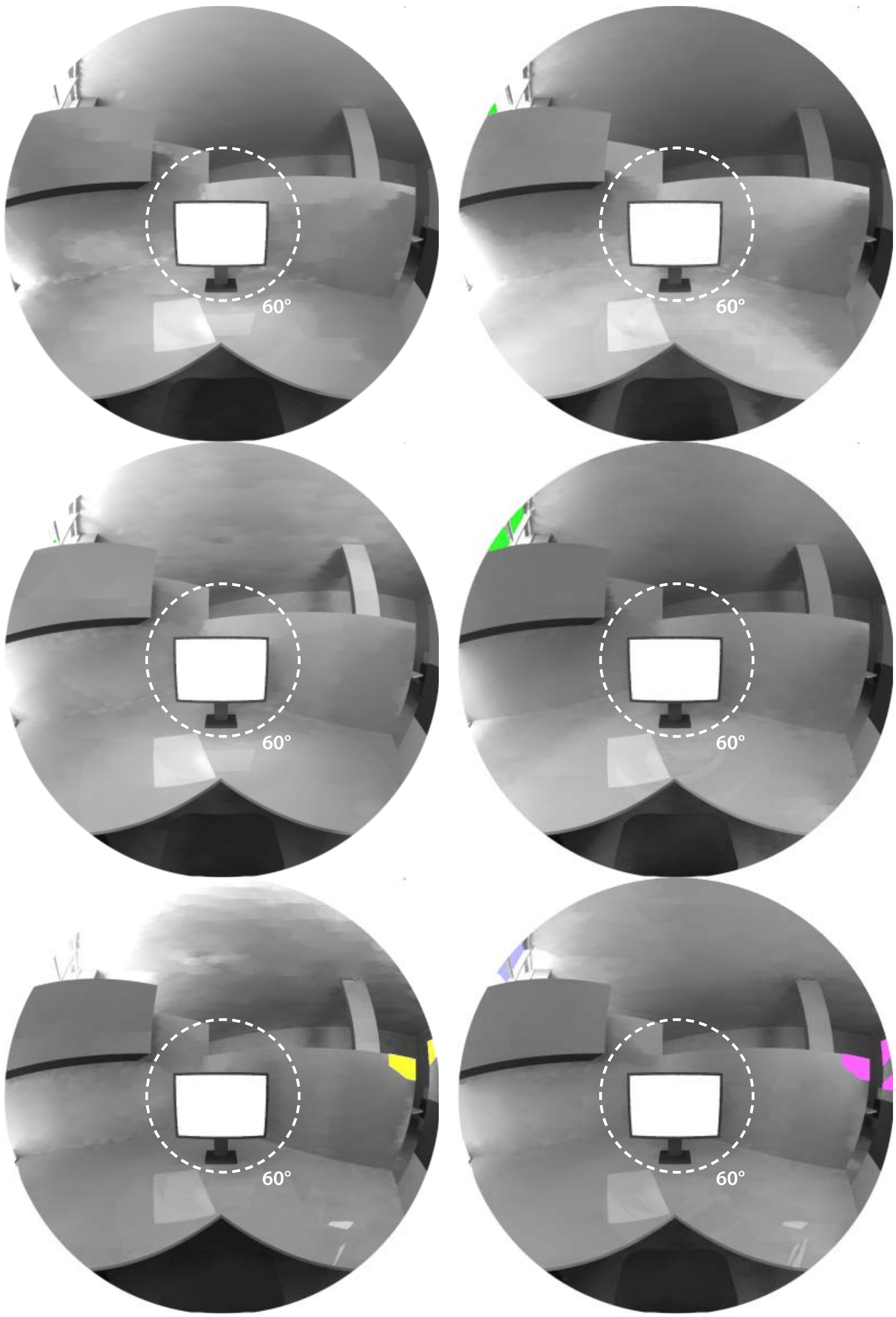
Workstation #2

with exterior shading | **without exterior shading**

9:00

12:00

15:00



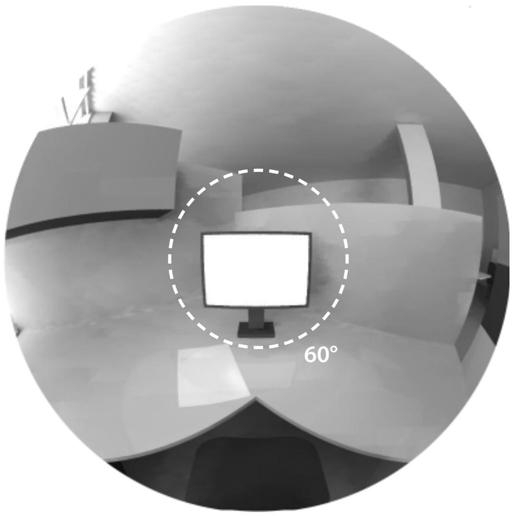
June. 21, overcast sky

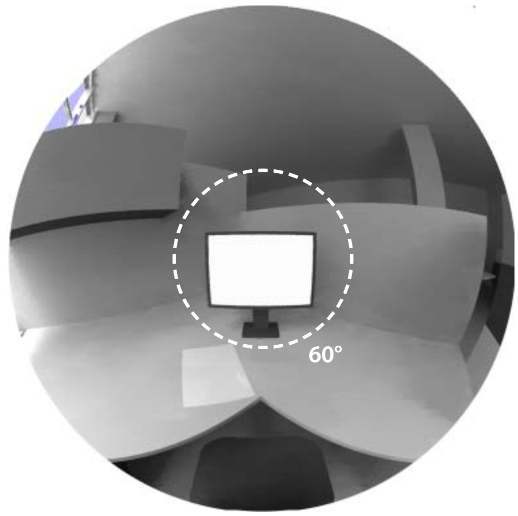
> 600 cd/m²

Workstation #2

with exterior shading | **without exterior shading**

12:00





June. 21, sunny sky

> 2000 cd/m²

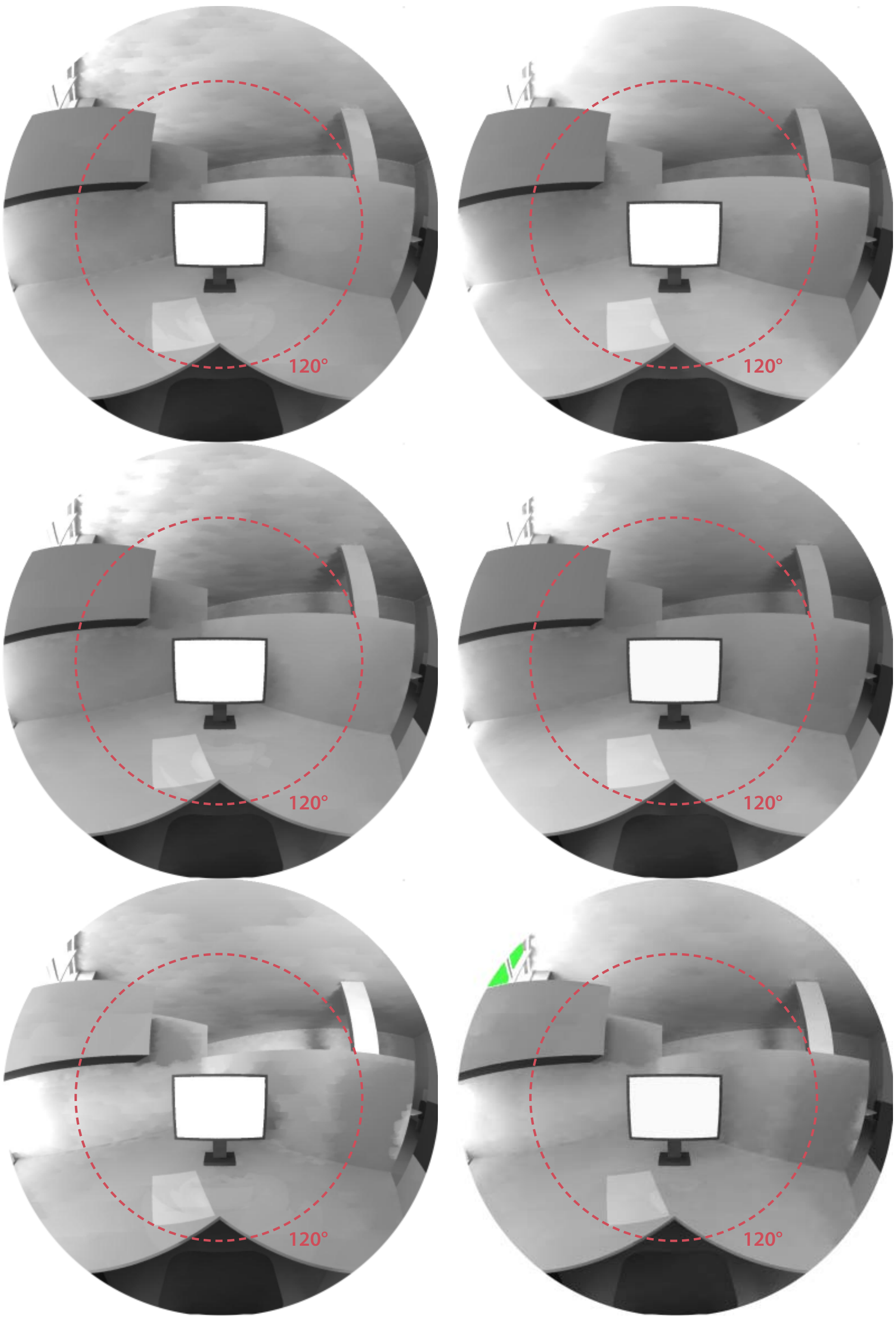
Workstation #2

with exterior shading | **without exterior shading**

9:00

12:00

15:00



Sept. 21, sunny sky

> 2000 cd/m²

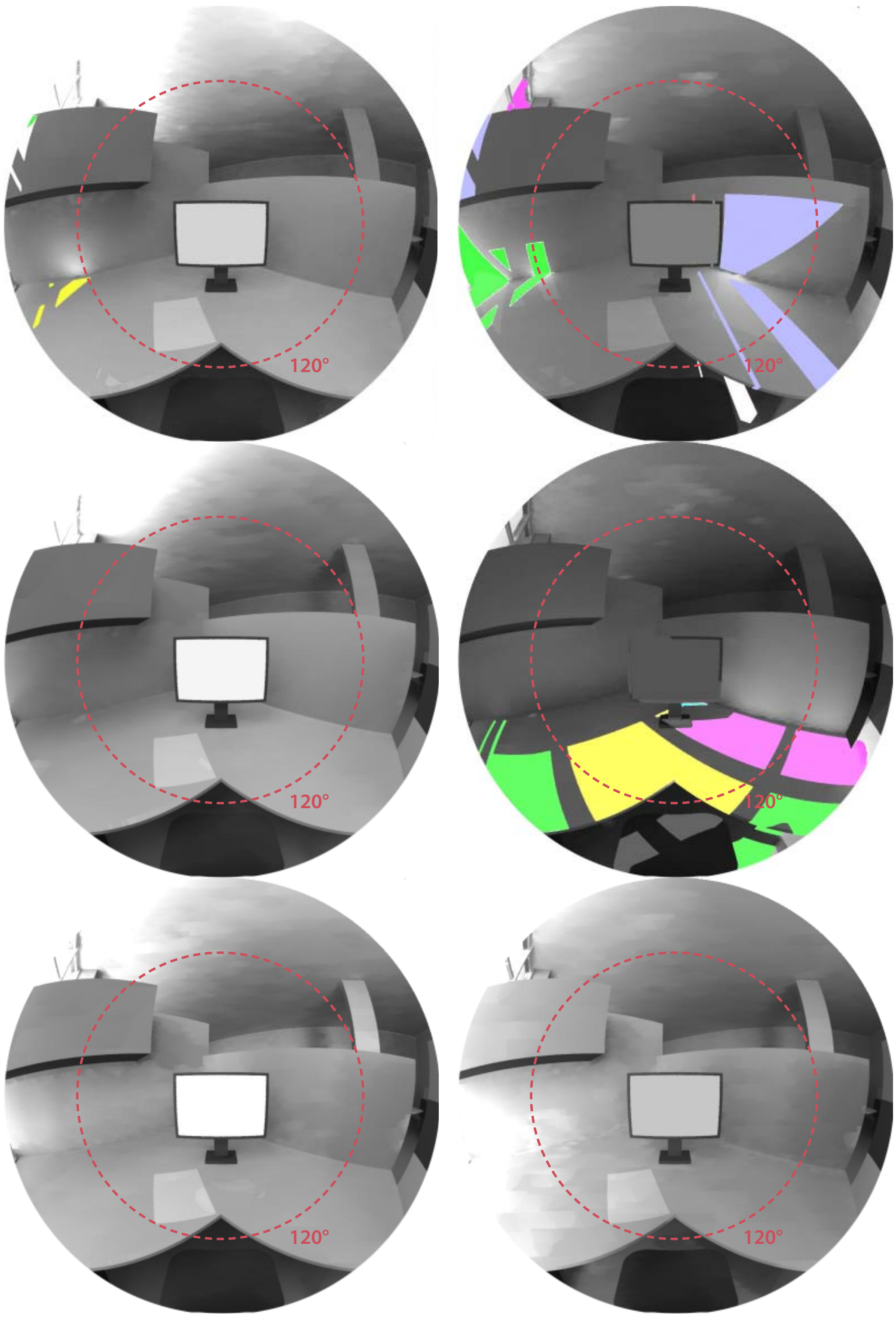
Workstation #2

with exterior shading | **without exterior shading**

9:00

12:00

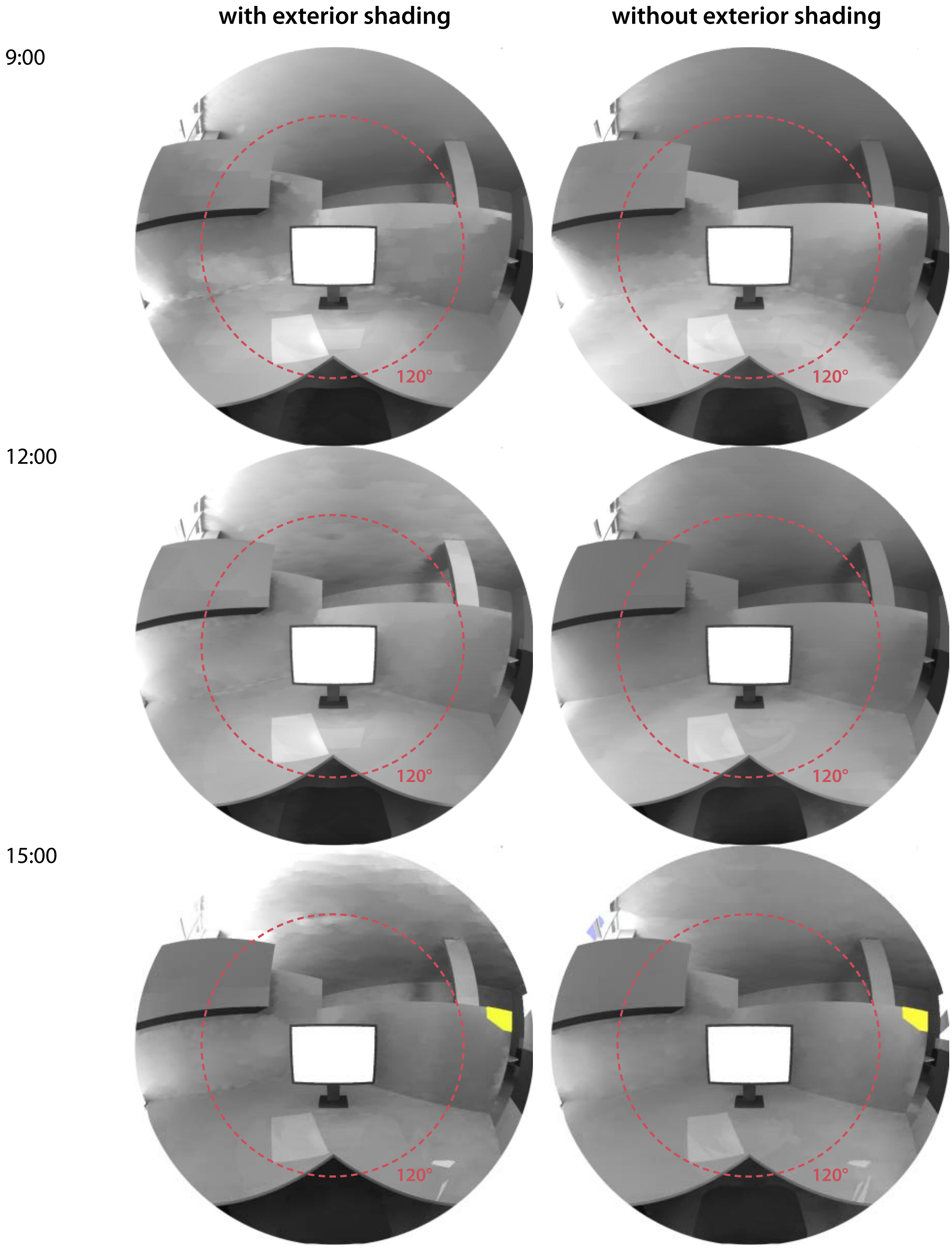
15:00



Dec. 21, sunny sky

> 2000 cd/m^2

Workstation #2



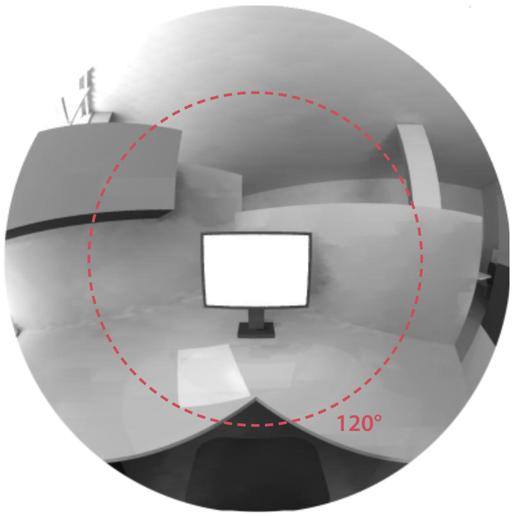
June. 21, overcast sky

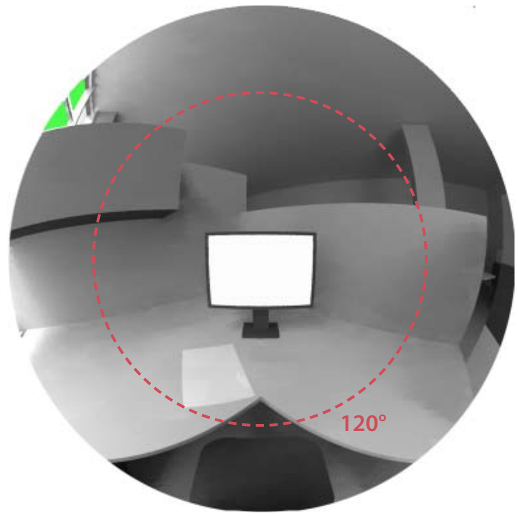
Workstation #2

> 2000 cd/m²

with exterior shading **without exterior shading**

12:00





June. 21, sunny sky

Workstation #4

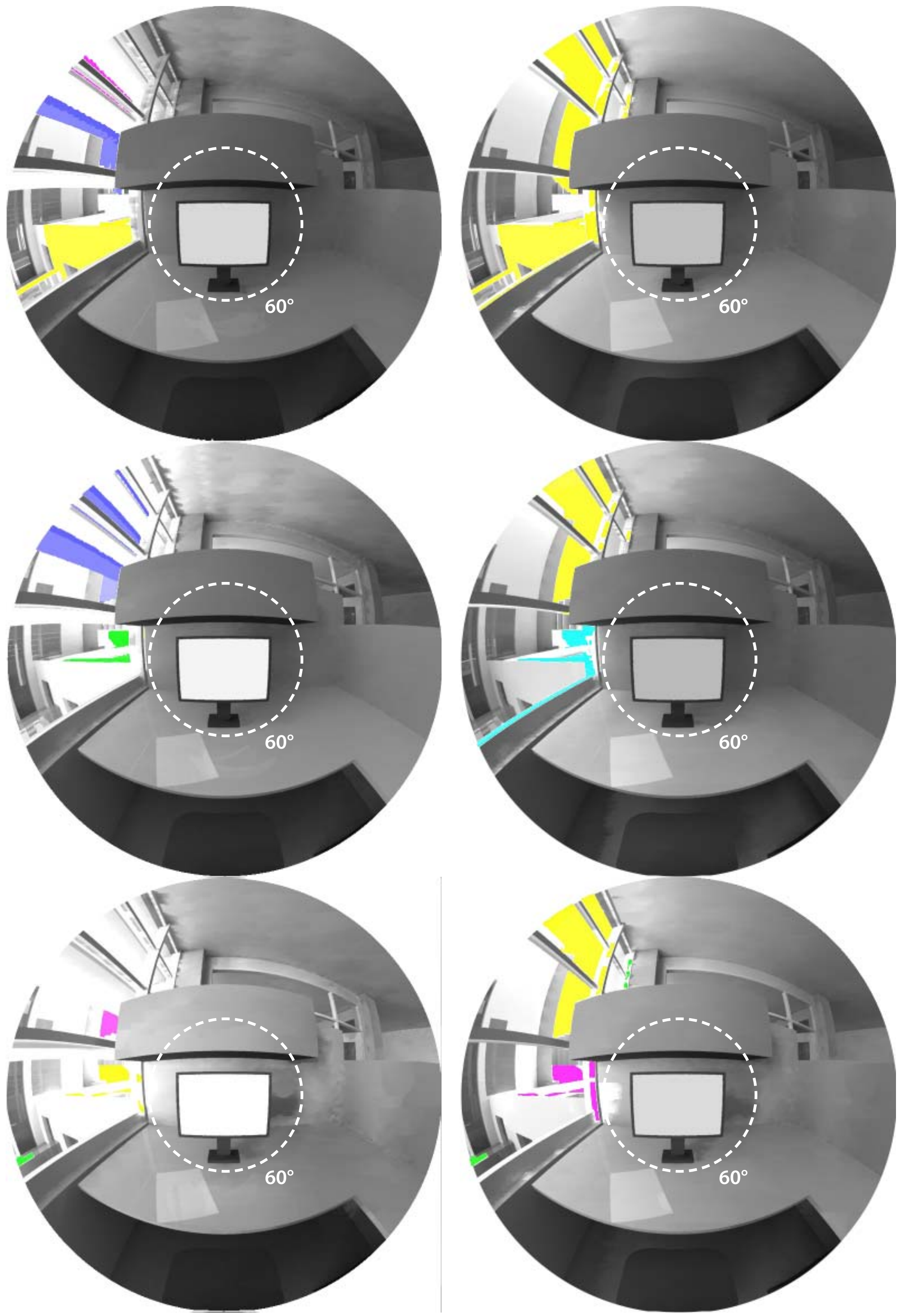
> 600 cd/m²

with exterior shading | **without exterior shading**

9:00

12:00

15:00

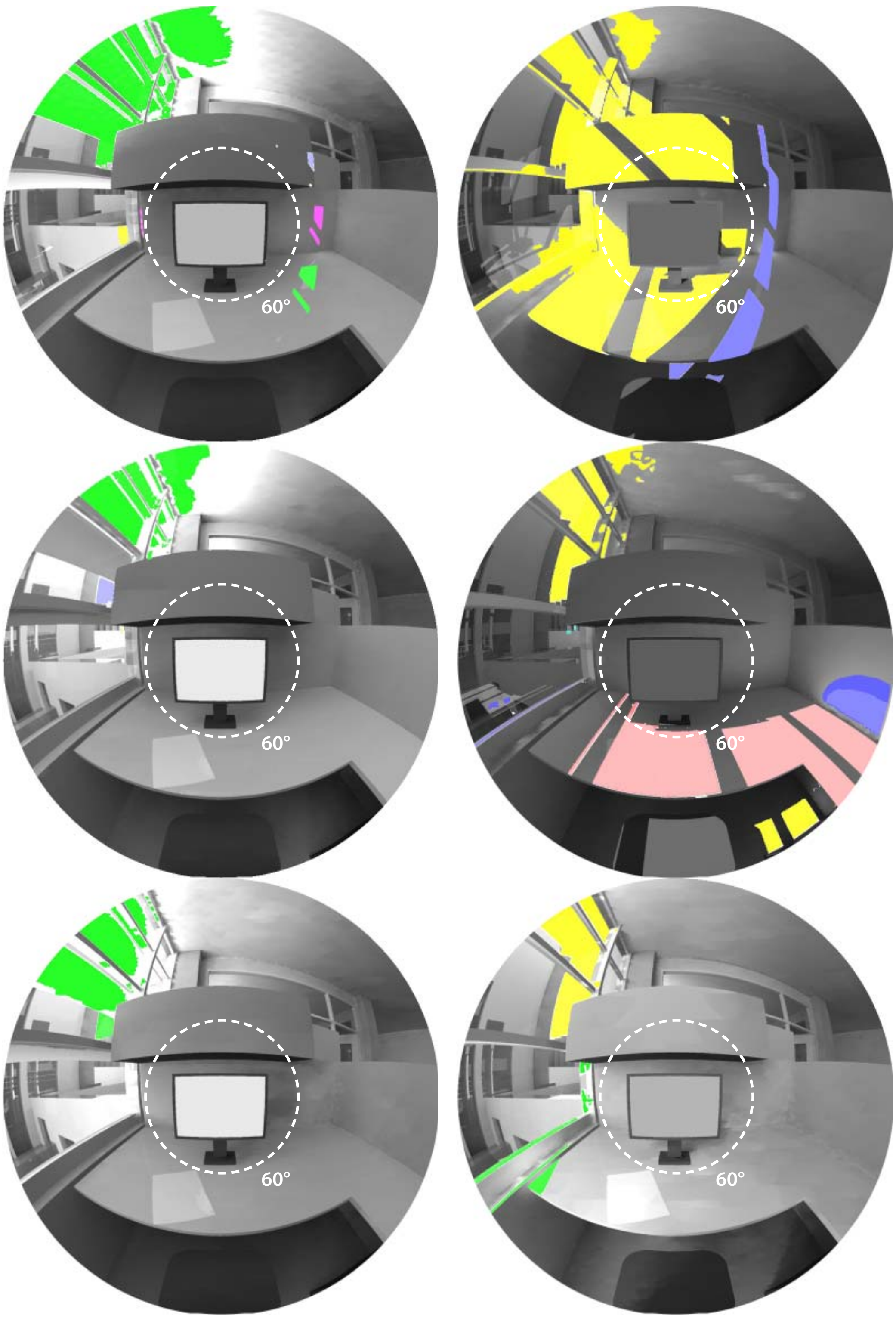


Sept. 21, sunny sky

> 600 cd/m^2

Workstation #4

	with exterior shading	without exterior shading
9:00		
12:00		
15:00		



Dec. 21, sunny sky

Workstation #4

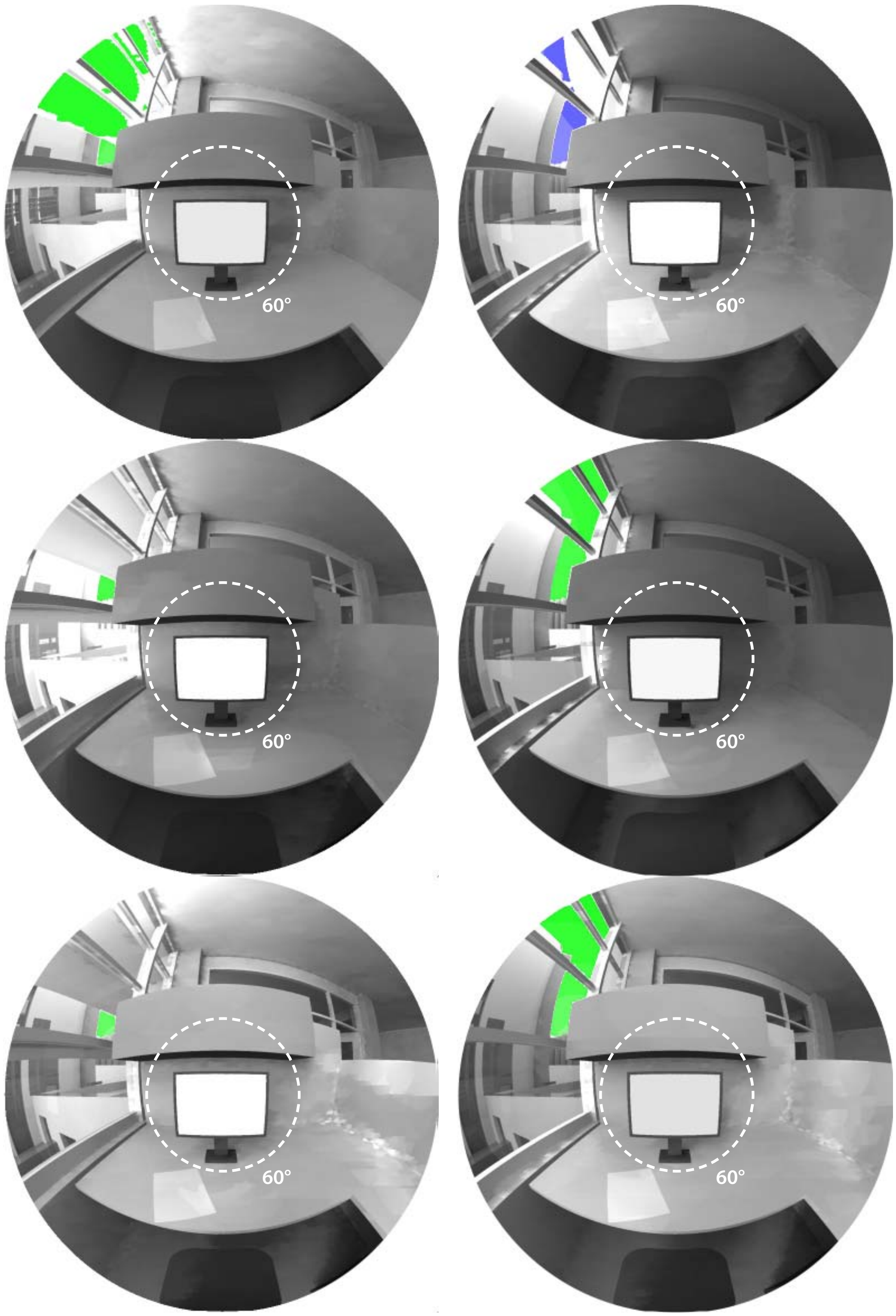
> 600 cd/m²

with exterior shading | **without exterior shading**

9:00

12:00

15:00



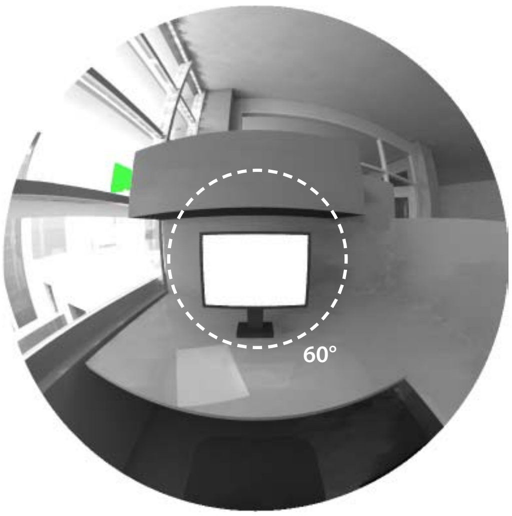
June. 21, overcast sky

> 600 cd/m²

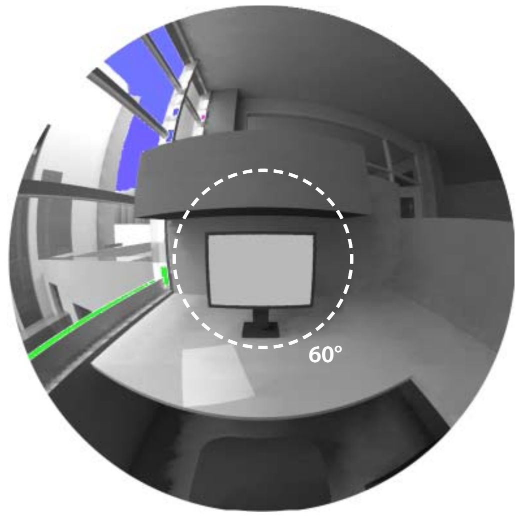
Workstation #4

12:00

with exterior shading



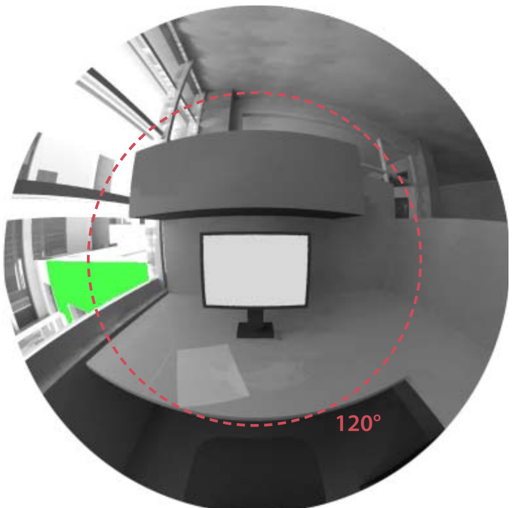
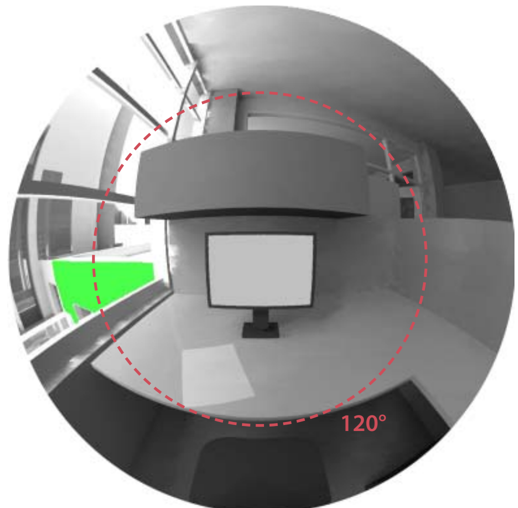
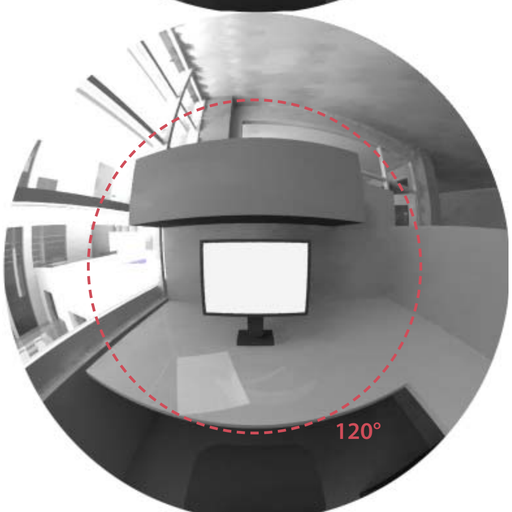
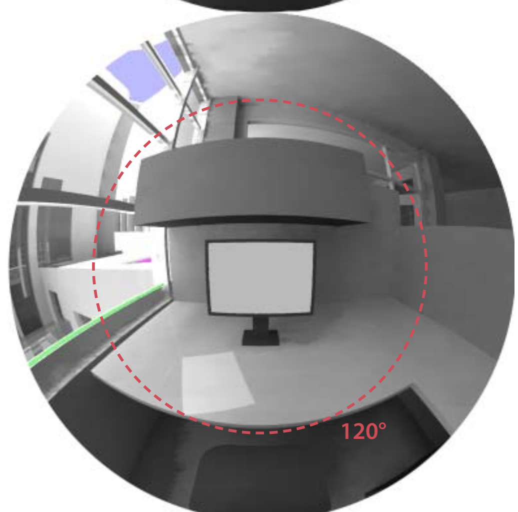
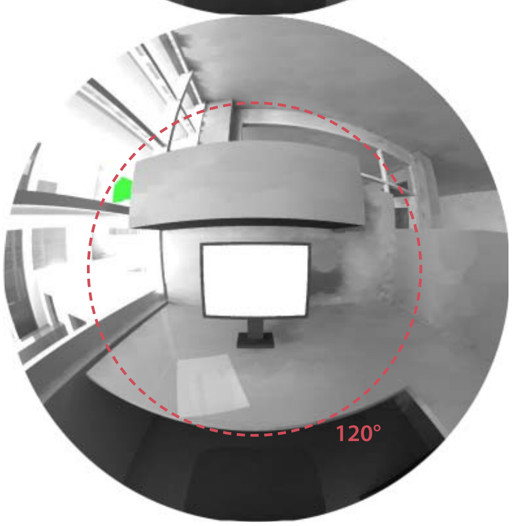
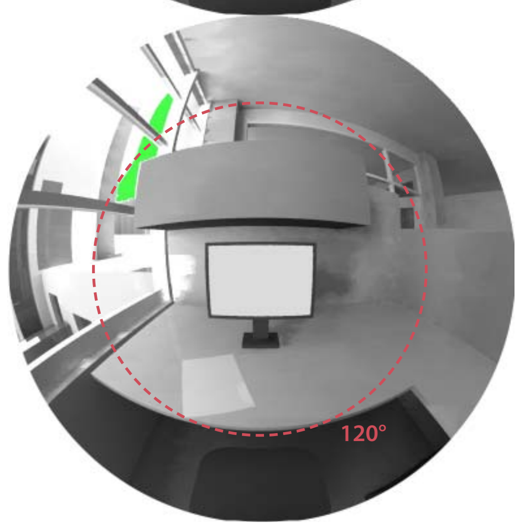
without exterior shading



June. 21, sunny sky

> 2000 cd/m²

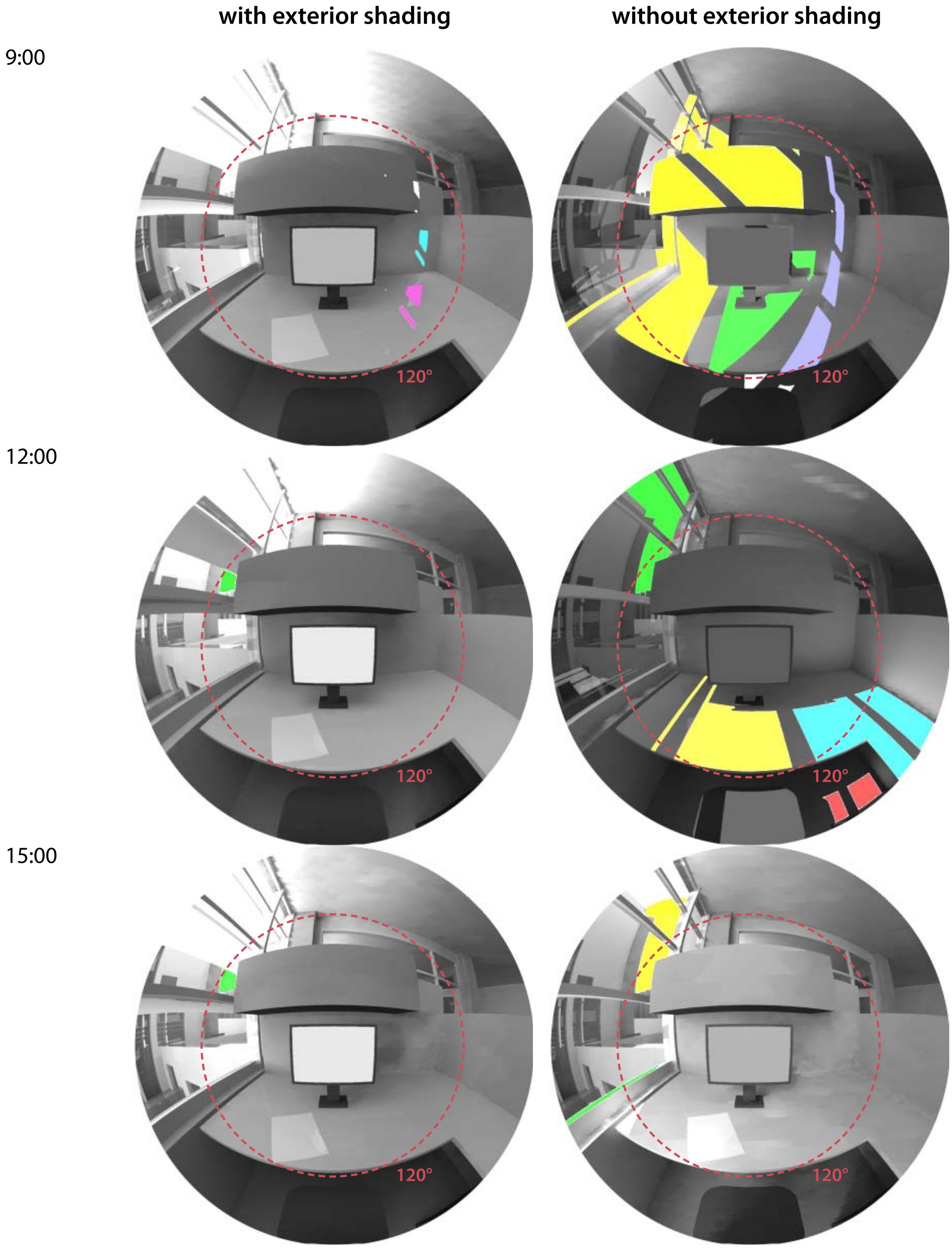
Workstation #4

	with exterior shading	without exterior shading
9:00		
12:00		
15:00		

Sept. 21, sunny sky

> 2000 cd/m²

Workstation #4



Dec. 21, sunny sky

> 2000 cd/m²

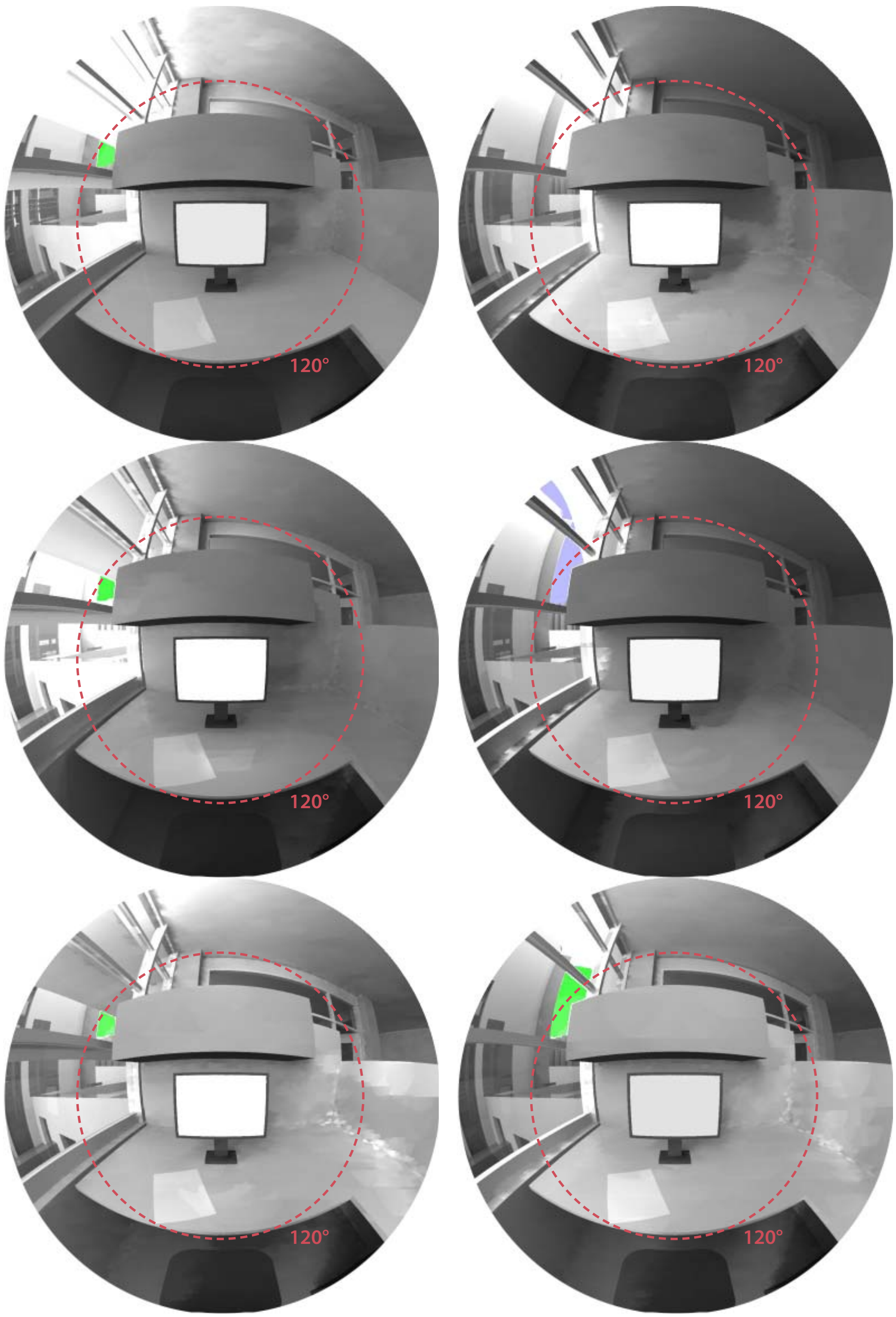
Workstation #4

with exterior shading | **without exterior shading**

9:00

12:00

15:00



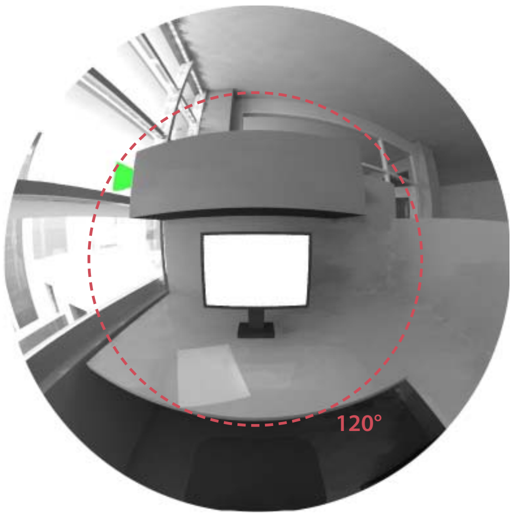
June. 21, overcast sky

> 2000 cd/m²

Workstation #4

12:00

with exterior shading



without exterior shading