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Demonstration of Energy Efficient Retrofits for Lighting and Daylighting in New York City Office Buildings

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April 2017

DISCLAIMER

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231. Additional support was provided by the New York State Energy Research and Development Authority (NYSERDA) and The Scherman Foundation.

This report was prepared for:
US Department of Energy
Building Technologies Office
Commercial Buildings Integration Program
Washington DC

and

New York State Energy Research and Development Authority.
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Albany, NY 12203-6399

The R&D team would like to acknowledge the contributions of their colleagues and in-kind partners on this project:

Goldman Sachs

Bank of America

Industry Partners

Acuity Brands Lighting
Crestron
Eaton Lighting Division
Enlighted
Fluxwerx
Focal Point
Lutron Electronics
MechoSystems
OSRAM Sylvania, Inc./ Encelium
Peerless
Philips Lighting
Selux Corp.
Specification Lighting Sales

Lawrence Berkeley National Laboratory
Darryl Dickerhoff
Daniel Fuller
Christoph Gehbauer
Jordan Shackelford
Anothai Thanachareonkit
Ellen Thomas

Building Energy Exchange (BEEx)
Ellen Abramowitz

Sustainable Partnerships
Adam Hinge

Consultants to the Owner
HDLC Architectural Lighting Design
Susan Brady Lighting Design
Vidaris, Inc.

NYSERDA Technical Representative
Energy Resource Solutions

This report and other resources related to this project are available at:
https://facades.lbl.gov/nyclivinglab
http://be-exchange.org/search?q=living+lab

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ABSTRACT

The U.S. Department of Energy's (DOE) Commercial Buildings Integration (CBI) program's mission (and that of the New York State Energy Research & Development Authority (NYSERDA)) is to accelerate the adoption of cost-effective, underutilized building technologies with large energy savings potential. The key question which CBI asks for each high impact technology is: "What can the DOE do to improve the market adoption of this technology?" Answering this relies on an assessment of the most significant barriers, including:

- A lack of product available in the market to meet current needs;
- Owner uncertainty about how the technology will perform in real world settings; and,
- A lack of operational understanding by potential adopters limiting technology acceptance.

Innovative, automated shading and LED lighting controls were identified as key technologies that have the potential to significantly reduce perimeter zone energy use and peak demand in existing commercial buildings. Technological advances in the field of low-cost embedded controls have enabled high-resolution sensing and more optimal control on a per fixture or shade basis. The Lawrence Berkeley National Laboratory (LBNL) partnered with the Building Energy Exchange (BEEx) and a commercial building owner to evaluate leading-edge technologies on a 40,000 ft^2 floor in an occupied, high-rise commercial office building in New York, New York. This "Living Laboratory" was monitored for a year prior to and six months following the installation of four sets of lighting and shading technologies and their performance was compared to a parallel reference floor in the same building.

The Living Laboratory demonstrated that there were many competitive products on the market, that the products were able to meet current needs, and that the various advanced features provided significant added value over and above that of conventional products. Monitored data provided detailed insights into how and why each technology performed the way it did, and what the impacts were on energy-efficiency, peak demand, visual and thermal comfort, indoor environmental quality, and occupant acceptance and satisfaction within the resultant environment.

Key findings

- Retrofit of existing fluorescent fixtures with daylight dimming in the primary 10-ft deep zone and low-resolution occupancy controls (4800-6800 ft^2/zone) with new LED fixtures with high-resolution controls in the 40-ft deep perimeter zone (100-650 ft^2/zone) can yield very significant reductions in lighting energy use (79% in the case of this Living Lab) and peak demand (74%). (Cooling energy use savings due to reduced heat gain from the lights and façade were not monitored.)
- At a mature market cost of \$2/ft^2 installed, advanced control upgrades to LED fixtures would yield a simple payback of 4 years. At a mature market cost of \$1/ft^2 installed, the incremental add of advanced controls would yield a 2 year simple payback.
- In today's emerging market given an installed cost of \$3-10/ft^2 for both LED fixture and advanced controls, the simple payback period was estimated to be 3-12 years.
- The key value proposition for use of these digitally-configurable technologies revolves around not only significantly lower utility bill costs (and therefore lower greenhouse gas emissions) but also potentially improved indoor environmental quality, with respect to

daylighting and access to views, and increased thermal and visual comfort. These software driven solutions also provide owners, facility managers, and tenants with the ability to reconfigure and fine tune workplace conditions more economically over the life of the building with data analytics that can help improve building and business operations.

Lessons learned

- At the time this study was initiated (November 2013), the industry was not yet sufficiently mature to enable widespread adoption of these technologies at the costs demanded by the market. The technologies were not yet standardized in even basic issues such as wire color. The design community was generally confused about the definitions, hierarchy, and methods used to implement the various control algorithms, significantly hindering specification, bid selection, and procurement. Design tools were not yet turnkey and input data on products were not yet available, hindering analysis of energy consumption and payback from various design scenarios for lighting and daylighting systems.
- Qualitative factors drive occupant acceptance and satisfaction with these advanced technologies and ultimately their resultant energy savings and widespread adoption. Perimeter zones are subject to broad variations in solar radiation, daylight, and outdoor temperature, making these areas the most challenging and yet the most highly-valued real estate in the entire building. Automation enables optimization of synergistic energy-related parameters but achieving this optimum balance is not yet turnkey. Increasing sensor and control resolution may provide opportunities for improved, more optimal control but industry has only begun to fully leverage this capability.

Recommendations

- In the near term, to affect widespread adoption of LED lighting in the retrofit market, LBNL recommends one-for-one, drop-in replacement LED fixtures with built-in dimmable, addressable drivers, controls and wireless communications to lower installed cost. For sensing, several options evaluated in this study are available that can significantly reduce costs: factory-installed sensors within the fixture and battery-powered sensors with wireless communications that can be installed in minutes in any location and quickly readjusted throughout the life of the installation. Simpler control options such as area controllers can also reduce costs as well as combined power and communications networks via power over Ethernet. LED lighting with advanced controls is recommended for all commercial buildings throughout the US.
- High-resolution occupancy sensing can provide additional energy savings in some applications (e.g., open plan office areas) but must be implemented with the proper shielding and controls to avoid false triggering and shut-off and also configured to address lighting quality requirements. The benefit of high-resolution sensing for daylight control was not evaluated in this study.
- Automated shading is recommended in commercial building applications where active load management is critical and/or in shared spaces (e.g., open plan offices or atria). Automated shades require fairly sophisticated sensing and control algorithms to optimize for all key parameters, particularly with regards to occupant comfort. Systems with a transparent (easy to understand and user friendly) interface and proactive diagnostics can help to facilitate fine-tuning and adjustment of solar control/ daylight and glare/ view control trade-offs as space usage changes over time.

- User-interface options enable fine tuning of individual control parameters but systems that provide clear diagnostics, troubleshooting, and forecasting tools to support decisionmaking on how best to tune the controls will more likely result in long-term realization of control objectives and satisfaction of occupant requirements.
- Workforce training and education would be of enormous benefit to increase market uptake. Standardization of hardware (e.g., power, communications, control interfaces) would go a long way to reducing the cost of on-site labor.

Actions taken

- Over the course of this project, product offerings have continued to evolve. Industry consortia have emerged to develop standards and protocols for advanced lighting and daylighting control products, addressing the high labor costs for installation seen in this demonstration.
- Specifications, zoning diagrams, sequences of operation, training materials for contractors, and educational materials for lighting designers were developed within this project and disseminated publicly via seminars and the project websites:
  https://facades.lbl.gov/nyclivinglab
  http://be-exchange.org/search?q=living+lab
  These activities translated the lessons learned into actionable guidance for the industry.

EXECUTIVE SUMMARY

Advanced lighting and daylighting solutions have the potential to reduce both lighting and HVAC energy use through judicious admission of daylight through windows and a proportional reduction of electric lighting loads and heat gains associated with these loads. Prior studies have estimated that the technical potential of daylighting in the United States commercial building sector compared to business as usual practice is 1 Quad (10^{15} Btus) with an additional 1.6 Quad savings if solar and thermal loads through windows are actively managed with advanced dynamic façades [Arasteh et al. 2006].

Peak electric demand reductions are of equal importance in some applications. Daylighting was identified as a solution that could potentially offset 160 megawatts of peak electric demand and 340 gigawatt-hours of electricity in the U.S. by the Building Energy Exchange (BEEx) in a report called "Let There Be Daylight" [BEEx, 2012]. Beyond energy efficiency concerns, daylighting addresses fundamental occupant requirements (access to information about the outdoors, view, temporal and spectral variation in light levels), which in turn can affect productivity, performance, health, and sense of well-being within the indoor environment. As we continue to push toward net zero energy and low carbon emission goals, integrated solutions will increasingly deliver the deep savings and holistic benefits owners are seeking from advanced building solutions.

Several innovative technological advances have been made in the past few years that enable lighting and daylighting technologies to deliver deeper benefits at lower cost to the retrofit construction market:

- light-emitting diode (LED) drop-in fixture replacements embed dimmable drivers, layered control strategies, wireless communications, and built-in sensing which when networked as a system enable high resolution control, commissioning and reconfiguration via software, trending, and demand response; and,
- automated shading systems with wireless sensing and communications and innovative control algorithms balance competing control criteria (i.e., daylight and view versus window heat gains, visual and thermal discomfort) and minimize both lighting and HVAC loads, even in complex urban environments.

This study evaluated the in-situ performance of commercially-available, advanced lighting and daylighting technologies with the primary goal of providing critical third-party measured data to potential adopters of the technology in the buildings industry. Four high-resolution, advanced LED lighting control systems and two automated, motorized interior shading systems were procured, installed in four separate areas or quadrants on a 40,000 ft^2 floor in an occupied commercial office building in New York City, then monitored over a six month, solstice-to-solstice period. Performance was compared simultaneously to a parallel reference floor in the same building. The study provides insights into how the products perform in a real world setting and how they impact end users with respect to comfort, environmental quality, and workplace amenity. Lessons learned from the process of procuring and installing the technologies as a retrofit measure in an existing building are delineated. Supporting educational and training resources were developed for use by the buildings community.

Project Description

This monitored study involved a relatively new high-rise commercial office building built to exceed the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 90.1-1999 Standard [ASHRAE, 1999] and occupied in 2009. The building earned a U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) Gold certification. Existing conditions included spectrally-selective, low-emittance (low-e), dual-pane floor-to ceiling glazing, automated roller shades, T5 pendant fluorescent lighting with daylight-responsive controls in the first 15 ft deep daylit zone near the windows, and an underfloor air distribution (UFAD) system.

In this study, a "Living Laboratory" was established on one floor of the building where new LED pendant direct/ indirect lighting and controls and an alternate automated shading system were installed in the 40-ft deep perimeter zone of the 40,000 ft^2 floor. Sensors were installed on the reference and Living Lab test floors to monitor energy and environmental conditions over a twelve-month solstice-to-solstice period prior to and six-month period following the installation of the new technologies. Occupant surveys were issued at the conclusion of the six month test.

Analysis focused on the evaluation of the incremental benefit of LED lighting with high-resolution, fixture level controls compared to T5 lighting with low-resolution, quadrant level control. The daylit and thermal environment resulting from two automated shading control systems, one with a more densely woven fabric and a different sequence of operations, was also evaluated. The evaluation occurred in primarily an open plan work environment with 3.5 ft high partitions and heavy computer use.

Findings

Lighting energy and peak demand savings – total floor savings

Total floor level perimeter zone lighting energy savings were 3.35 kWh/ft^2-yr (79%). The reference and test floor perimeter zone lighting energy use was 4.26 and 0.91 kWh/ft^2-yr, respectively. These data were based on monitored circuit and sub-circuit level energy use in the four 40-ft deep perimeter zone quadrants on the test and reference floors. The monitored perimeter zone area was 53% of the total area on a floor.

Electric lighting demand reductions during peak afternoon periods (2-5 PM) were 0.60-0.63 W/ft^2 (64-81%). The hourly reference floor demand was 0.81-0.85 W/ft^2 and the test floor demand (all quadrants in total) was 0.208-0.214 W/ft^2 (Table 1). In areas with time of use utility rate structures, these reductions in peak electric demand occur during the most expensive periods of the year.

Overall, these savings were due to dimming in all 40-ft deep perimeter areas of the floor, not just the "primary" 10-ft deep zone next to the window, implementation of *all* lighting control strategies at a fixture-by-fixture resolution, not just quadrant level basis, and active management of daylight by the automated roller shades (Table 2).

Table 1. Average lighting power density (W/ft2) during peak afternoon periods, March 1 -- June 30, 2016.

Area	Floor	2-3 PM	3-4 PM	4-5 PM
All*	Reference	0.812	0.824	0.848
	Test	0.208	0.211	0.214
	Savings	0.604	0.612	0.634
	% savings	74%	74%	75%

*Total demand is given as the average of all perimeter zones (G1-G4) on the reference or test floors.

Table 2. Substantive differences between reference and test cases

	Reference case	Test case
Light source	T5	LED
Fixture	Direct/ indirect	Independent control of up & down lights
Dimming control	0-15 ft area from window	All fixtures in the 40 ft deep zone
Control resolution	DALI in 0-15 ft from window	Up and downlights in all fixtures were addressable
Scheduling	On: 7AM to 1 AM weekdays, all lights turned on	On: 7AM-7PM up lights at setpoint level, weekdays
Occupancy	Quadrant level control (4580-6860 ft^2/zone)	Sub-quadrant (100-653 ft^2/zone)
Tuning	None, 517 lux	250 lux total from up & downlights
Daylighting	0-15 ft from window	0-40 ft from window
Shading	Automated	Automated

Note: See Sections 3.4 and 3.5 for exact descriptions of set-up.

High resolution lighting control was defined as LED dimming implemented on a fixture-by-fixture basis. Output from the direct (down) and indirect (uplight) LED sources were separately controlled. Scheduling, tuning, occupancy, and daylighting strategies were each executed at independent levels of resolution. Scheduling and setpoint tuning were implemented as a single control zone per quadrant (subzone control was enabled but not used). Occupancy controls subdivided the quadrant into smaller work areas with 100-653 ft^2 resolution. Daylighting control was implemented on a fixture by fixture basis. The photosensor-to-fixture ratio ranged from 1:1 to 1:6, where the readings from one or more photosensors could be used to control the up- or downlights in a single fixture. Daylight was modulated in all reference and test areas by automated roller shades, which were controlled to limit direct sunlight, window heat gains, reduce glare, and allow outdoor views in response to outdoor conditions. Strategies involving systems integration or cost minimization were not implemented (e.g., energy minimization through integrated control of shading, lighting, and HVAC systems; demand response or transactive control strategies; etc.), but all four systems could in the future implement such strategies via server level gateways.

Lighting energy savings – by quadrant

Across the four quadrants facing nominally north, south, east and west, annual lighting energy savings ranged from 2.85-4.19 kWh/ft^2-yr (73% to 87%) compared to existing reference conditions. The existing reference lighting energy use was 3.85-4.81 kWh/ft^2-yr and the test case energy use was 0.62-1.01 kWh/ft^2-yr.

This variation in performance across quadrants was due to differences in window orientation, space geometry, occupancy patterns, implementation of shading and lighting control, as well as other factors. Energy use and peak demand were therefore not compared *between* quadrants because of this non-comparability of conditions.

Such comparisons (e.g., "product A did better than product B as evidenced by LBNL monitored data") would result in confounded, invalid conclusions.

Differences in performance were only analyzed between the reference and test floors within the *same* quadrant where the window orientation and interior conditions were nominally the same. The difference in lighting energy use between the two floors was monitored for a year prior to installation of the new technologies. Results of this analysis are given in Section 3.6.1 and Appendix C.

Lighting energy savings – weekday savings by source and control strategy

Dimming level, power use, and control strategy data per fixture were not available from all manufacturers so incremental savings due to each of the lighting measures/ control strategies were estimated according to methods described in Section 3.6.3a. Percentage savings across the four quadrants compared to the reference case baseline with scheduled controls were as follows:

- Weekday lighting energy savings due to the change in light source from T5 fluorescent lighting to LED lighting were 33-51% compared to the reference T5 lighting system. Both systems had scheduled controls (ON for an 18-hour schedule). Both systems produced the same reference setpoint illuminance level of 517 lux.
- Weekday lighting energy savings due to LEDs and a change from a setpoint illuminance of 517 lux to 153-276 lux was 74-75% compared to the reference T5 lighting system with scheduled controls.
- Weekday lighting energy savings due to LEDs, setpoint tuning, and a change from low-resolution occupancy controls (control per 4580-6860 ft^2 quadrant) to medium- to high-resolution occupancy controls (100-600 ft^2 per controlled area) and fixture-by-fixture daylighting controls was 80-87% compared to the reference T5 lighting system with scheduled controls.

Of the total weekday savings given above, 41-59% was due to the change from T5 to LED fixtures, 27-51% was due to setpoint tuning, and 8-14% was due to occupancy and daylighting. On average, LED source savings made up 51% of the total savings and the advanced controls made up 49% of the savings. Example quadrant-level savings are represented in the waterfall graph shown in Figure 1.

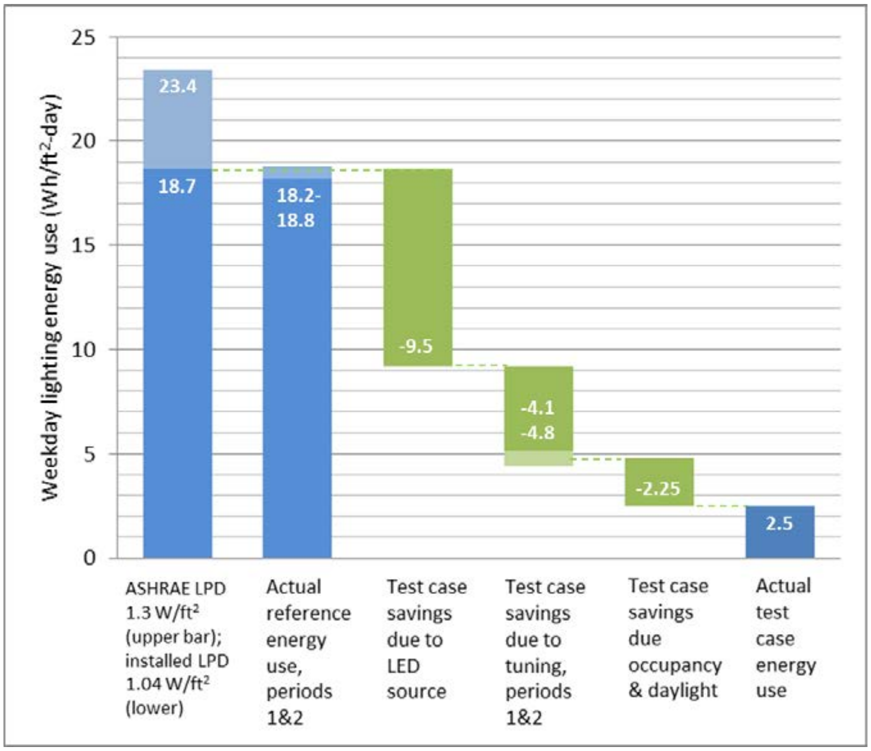


Figure 1. Area G1. Weekday lighting energy savings due to LED source, setpoint tuning, and occupancy and daylighting controls.
Savings relative to the installed reference fluorescent lighting system with 18-hour scheduled controls (18.7 Wh/ft^2-day). Actual monitored weekday reference[1] *(18.2-18.8 Wh/ft^2-day) and test energy use (2.5 Wh/ft^2-day) are shown. ASHRAE 90.1-1999 with 18-hour scheduled controls (23.4 Wh/ft^2-day) is also shown.*

Note that the 40 ft deep open plan perimeter zones were well daylit due to the automated shading, potentially lessening the impact of the reduced setpoint illuminance level that was used in this study on visual performance. If the setpoint illuminance level (269 lux (25 fc)) was increased, savings due to occupancy and daylighting would increase.

Savings due to high-resolution occupancy controls were obtained primarily during the evening hours; lights were turned off when small areas were unoccupied on the test floor whereas lights were turned off on the reference floor at night only if the entire quadrant was unoccupied. Much as we would have liked to isolate energy savings due to differences in resolution of occupancy control, lack of adequate data from the manufacturers and non-comparability between quadrants prevented this analysis.

[1] The actual monitored reference energy use included low-resolution, quadrant level occupancy controls that were atypical of the rest of the building (they were only implemented on the test and reference floors) – the actual monitored energy use on the reference floor was therefore higher or lower than the reference case with the 18-hour schedule. However, the reference case with the 18-hour schedule may better represent actual whole building energy use on all other similar floors.

Savings due to daylighting were modest for two reasons having to do primarily with indoor lighting quality considerations: (1) all uplights remained on (54-108 lux, 5-10 fc output at the task, varying with depth from window) irrespective of occupancy or daylighting between 7 AM to 7 PM in order to maintain a bright ceiling plane across the depth of the open plan perimeter zone. This reduced the daylight dimming potential of the direct/ indirect lighting system. (2) Some control systems were also conservatively commissioned for daylight dimming. One manufacturer explained that their dimming response to daylight was minimal because they wanted to avoid inadequate light levels given that the setpoint illuminance was already very low. Workplane illuminance levels were monitored and these data indicated that for example daylight illuminance levels were greater than 200-300 lux for 25% of the monitored period (weekdays, 7 AM to 7 PM, over 6 months) at 17.2 ft from the west windows – there was clearly sufficient daylight in the open plan work environment with automated shades.

Total energy, demand, and cost savings relative to monitored reference floor

HVAC energy use was not monitored in this study because the quadrants on each floor were not thermally isolated – incremental differences in HVAC energy use could not be measured accurately. HVAC savings due to window heat gain management produced by the automated shades were not estimated.

HVAC energy use reductions due to reduced heat gains from the electric lighting were estimated using the total monitored lighting energy use data from all four 40-ft deep perimeter zones (quadrants) on the reference and test floors. Lighting energy use was converted to instantaneous light heat gains and then to cooling energy use using an 80% or 100% light-to-heat gain (LHG) ratio and cooling system coefficient of performance (COP) ranging from 2-4. With reduced lighting energy use, annual cooling energy use was reduced by 0.67-1.67 kWh/ft^2-yr (across the range of LHG and COP). Peak cooling demand was reduced by 0.12-0.32 W/ft^2.

Combining these HVAC savings with monitored lighting energy use savings, total annual energy use in the 40-ft deep perimeter zones was reduced by 4.02-5.02 kWh/ft^2-yr or 3.65-4.56 MWh/yr (across the range of LHG and COP), if these floor level savings were applied to the 43-story building (Table 32). Total peak electric demand reductions during summer afternoon hours between 2-5 PM were 658-863 kW. If cooling load reductions due to automated shading had been included, these savings would have been greater.

Annual energy cost savings would be $730,000-913,000/yr, assuming a flat rate of $0.20/kWh. If the total installed cost of both the LED fixtures and controls was $3/ft^2, then the simple payback would be 3-4 years. If $10/ft^2, then the simple payback would be 10-12 years (Table 33).

The upgrade from fluorescent to LED fixtures (with nominally the same resultant workplane illuminance) resulted in approximately 51% of the total annual energy use savings. If the installed replacement cost of the LED fixtures was $2/ft^2, then the payback would be 4 years (across the range of LHG and COP). If the installed cost was $6/ft^2, then the payback would be 10-13 years (Table 34). This assumes a reference baseline with the installed lighting power density (LPD) of 1.04 W/ft^2 and an 18-hour weekday schedule of operation.

The upgrade to advanced shading and lighting controls resulted in approximately 49% of the annual energy savings. If the incremental installed cost for advanced shading and lighting controls was $1.00/ft^2, then the payback would be 2 years. If the installed cost was $4/ft^2, then the payback would be 7-9 years.[2] If cooling load reductions due to automated shading were included in the analysis, the payback would be shorter.

Additional long-term, non-energy benefits associated with these systems were not quantified in this analysis. One could argue that improved thermal and visual comfort, better lighting quality (balance between the distribution of daylight and indirect/ direct LED lighting across the room cavity), more optimal façade and lighting load management, greater transparency in facility and business operations given granular data, and facilitated maintenance provide further economic justification toward the use of these technologies in commercial buildings.

Simple payback relative to ASHRAE 90.1-1999

With a less efficient reference condition (i.e., ASHRAE 90.1-1999 installed lighting power density of 1.3 W/ft^2 and an 18-hour weekday schedule of operation) and a total installed cost of both the LED fixtures and controls of $3/ft^2, the simple payback would be 2.0-2.5 years. If the total installed cost was $10/ft^2, then the simple payback would be 7-8 years. Payback estimates do not include cooling load reductions due to automated shading in the analysis.

Occupant comfort, satisfaction, and acceptance of the technologies

Survey participation was low in some quadrants. There were a total of 20 responses on the reference floor (2-8 responses per quadrant) and 58 responses on the test floor (4-30 responses per quadrant) over a monitored area of 21,125 ft^2 per floor. Occupant survey data indicated that the overall level of satisfaction with the lighting systems was neutral (neither agreed nor disagreed that occupants were satisfied with the lighting). Occupants disagreed or were slightly below neutral (toward “disagree”) regarding whether the electric lighting was too dark in the test and reference areas. Overall light levels from both electric light and daylight were slightly above “just right”.

LED fixtures. The luminance distribution produced by the installed pendant LED fixtures was evaluated using the IESNA recommended practice for office lighting (RP-1), which sets limits on ceiling and source luminance and luminance uniformity. Because the original fixture spacing was used for the new fixtures, the resultant solution may not have been ideal. On both the reference and test floors, all fixtures produced luminance conditions that significantly exceeded the limits of the RP-1 guidelines. Results from occupant surveys however countered this finding, indicating neutral to low/ perceptible levels of glare from the fluorescent and LED direct/

[2] In the Living Lab building, total energy savings were due to the upgrade from fluorescent to LED lighting, dimmable lighting controls throughout the test floor, and higher-resolution lighting controls. The retrofit cost represents these changes in fixtures, sensors, and software. There were also changes in energy use due to the new automated shades: the test floor replaced the existing shades with new automated shades in two quadrants and retained the existing shades in the two other quadrants. Therefore, the added cost of the shades on half the test floor is included in the installed cost for this specific demonstration project.

indirect lighting system, which had a neutral to slight effect on difficulty in reading the computer screen.

Occupancy-based controls and indoor lighting quality. There were some comments expressing dissatisfaction with occupancy sensing on the test floor related to turning off the lights erroneously when occupied, particularly during periods of low occupancy at night or on weekends. High-resolution occupancy control was achieved using a variety of methods. In test Areas G2 and G3, a single ceiling-mounted occupancy sensor was used to control a rectangular-shaped work area of approximately 600 ft^2. In test Area G1, a single sensor controlled a 400 ft^2 rectangular area. In test Area G4, each individual fixture had its own occupancy sensor. Complaints regarding erroneous control were likely a result of occupied areas that fell outside of the detectable area of the sensors (e.g., small table areas between the primary desks) and potentially the poor lighting quality that resulted from granular control of the lighting at night. The sensors were shielded to comply with the specification's delineation of occupancy zones, which diagrammatically did not indicate the typical 20% overlap between zones. This lowered the possibility of false triggering from adjacent areas but also led to inadvertent shut off in some areas not seen by the sensors during periods of low occupancy. During the daytime (7 AM to 7 PM), both the constant uplighting and daylight made this inadvertent shut off less noticeable. During the evening, the up- and downlights were on in only the small occupied areas, potentially increasing dissatisfaction with occupancy-based control due to poor lighting quality. These issues pertained to all four test control systems to a greater or lesser degree. Careful attention to shielding, commissioning, and lighting quality is needed to achieve both energy savings and end user acceptance and satisfaction with these controls.

Automated shading. With the automated shading, occupants were also generally neutral (neither agreed nor disagreed) about whether they were satisfied with the reference and test case automated shades. To override the position of the automated shades, occupants telephoned or submitted an electronic request to have the shades adjusted. Sixteen requests were made over a year to override the test shades and none were made to override the reference shades. Glare from the windows was perceived as lower in the west test area with the more densely woven fabric compared to the west reference area, however there were far more comments about glare in the test areas with more densely woven fabric than the same reference areas. There were also comments about illogical shade movement. This may be due in part to the test area shading system being new, whereas the reference shade had been in place for seven years. Both control systems provided options for the facility management team to finetune the controls to better suit occupant preferences.

Thermal comfort. Operationally, the automated shades worked according to their specified sequence of operations with a few exceptions related to test case errors with wireless sensor communications. With respect to thermal comfort, monitored data suggested that both the reference and test area automated shades contributed to a well-controlled thermal environment within 3 ft from the window (occupants sat immediately adjacent to the window), despite low-angle sunlight for the west- and east-facing orientations. The mean radiant temperature, for example, was maintained to within 6°C of the dry-bulb temperature when warm discomfort (PMV>0.5) occurred (7-16 hours over the six-month period), indicating that temperature asymmetry due to direct solar transmission through the shade fabric was not a significant factor in thermal discomfort. Survey data, from all respondents irrespective of proximity to the window, indicated that the internal temperature was within the "just right" range of response.

Visual comfort. With respect to visual comfort, field-of-view luminance data captured during four weekend site visits indicated that for views parallel to the window (the primary angle of view for the majority of occupants in the open plan office area), discomfort glare from the windows was adequately controlled by both the reference and test area automated shades during equinox and solstice conditions. On occasion, views of the sun through the fabric of the lowered shade caused glare. Neither the more open nor more densely woven fabrics were able to reduce this direct source glare to within acceptable levels. Field-of-view luminance data were also captured for views perpendicular to the window, which is a more difficult condition to satisfy because occupants have direct views of the sun and sky. The automatic control system, however, was not commissioned for this angle of view. Glare occurred for this view angle because the shade was raised even though sky conditions were too bright or direct sunlight through the shade caused glare – adjustments to the shade control system could be made to address these issues if the primary (worst case) view angle was changed.

Daylight quality and views. Total illuminance levels were used as a proxy metric for evaluating indoor environmental quality (daylight illuminance data were not available). If illuminance levels are excessively high near the window, then one can infer that visual and thermal discomfort and window heat gains are likely to be correspondingly high. Monitored illuminance exceeded the 2000 lux limit by no more than 21 hours (1%) over the six-month period between 7 AM and 7 PM. One could argue that the automated shades contributed to a well-controlled daylit environment that met qualitative measures for comfort and adequate daylighting. Access to outdoor view was not systematically compared: the test shading system did not provide server data on shade position. Based on limited data for the test area shade and site observations by occupants and staff, the reference shading system tended to raise the shade more frequently. There were comments from the occupant surveys that indicated a desire to raise the shades more frequently in the test area for unobstructed access to outdoor views.

Lessons Learned

***Reduce cost by reducing on-site labor*.** Although the installation was more complex than a typical installation given the subdivision of the Living Lab floor into four quadrants and use of different technologies in each quadrant, the bid and procurement process did yield some significant lessons about ways for an owner to reduce cost. These ranged from understanding how on-site labor should be scheduled, how equipment should be staged, definition of how zoning should occur per control strategy, and how to handle emergency fixtures. Many of these lessons learned are detailed in Section 5.

Labor in Manhattan is costly and moving occupants out of the space to retrofit the technology may not be an option for some owners or tenants, so whenever possible, incorporating dimming elements (drivers or dimmable ballasts), controllers, or any other required equipment into the fixture housing at the factory can reduce installation costs at the job site. If this is not possible, technological advances and standardization by the lighting controls industry can help to bring down costs. For example, it is important to use products that adhere to industry-standard wire colors – products that don't can lead to considerable added labor cost and unnecessary troubleshooting on the job site. For sensing, several options are available that significantly reduce on-site labor costs: factory-installed sensors within replacement LED fixtures or battery-powered sensors with wireless communications that can be installed in minutes in any location and quickly readjusted throughout the life of the installation. Simpler control options such as area controllers can also reduce costs as well as combined power and communications networks via power over Ethernet.

Define project objectives clearly. There was significant diversity in product offerings, making it difficult to determine the best, most cost-effective implementation for a site. The decision to incorporate sensors in each fixture, for example, is dependent on space use and rate of churn/ reconfiguration of the space within the building. The cost of retrofitting a permanent conference room with occupancy and daylighting controls may be lowest with a single sensor for the entire room rather than a sensor in every fixture. The cost of using hard-wired photosensors and occupancy sensors in a space that is reconfigured every six months could be substantially reduced if sensors are factory installed in the initial installation.

To aid in the sorting out of product offerings and their various features, a specification was developed to aid in the procurement of advanced lighting controls and made publicly available. Example zoning diagrams were provided to illustrate how the control strategies could be implemented in typical perimeter zones. Since the installation involves many players, a list indicating roles and responsibilities of each team member was also developed to help with project task coordination. All of these materials and more were incorporated into educational and training modules that were then disseminated to the local New York City community and world-wide at conferences and via the web:
https://facades.lbl.gov/nyclivinglab
http://be-exchange.org/search?q=living+lab

Because this was an installation in a "class-A" office building, there were many discussions amongst the project team and with the LL building owner on how to meet their expectations for an aesthetically acceptable, high quality indoor environment. Use of dimmable direct/ indirect lighting systems with high resolution controls and automated shading provided a multitude of options to fine tune the daylit environment both spatially and temporally. The value proposition for this degree of control must be discussed with the owner and evaluated on a case-by-case basis. For some owners and/or space types, the bottom line or simple payback is the sole factor in decisionmaking. In these cases, simpler drop-in recessed fixtures with built-in controls and networked communications may be the solution. For other owners, provision of a comfortable, well daylit workplace with amenities to fine tune task illuminance levels to work group preferences or adjust controls to allow for greater access to view may be key to attracting and keeping talent. Still other owners have set sustainability standards to meet a specific level of performance that must be confirmed with metered data after occupancy. For these cases, the economic case may incorporate other non-energy benefits for decisionmaking.

Make operations transparent. Tracking actual performance has also become important as energy use disclosure laws are adopted (as in the case of New York City). The systems evaluated in this study have the potential to log operations and energy use because time step data from the distributed lighting and shading control systems are stored on a central server. Being able to disaggregate end use data from whole building energy use data can help facility managers pinpoint sources of inefficiency and waste.

Access to these data also enables facility managers to run diagnostics to troubleshoot and finetune operations when problems arise. Based on discussions with the facility managers, the end user interfaces to these control systems have room for improvement in terms of ease of use and transparency of the definitions/ functions behind the various control options and reported data. The facility managers were able to switch lights on and off or raise and lower shades when requested by occupants. On some systems, facility managers demonstrated deeper familiarity with the range of options provided by the user interface. For many issues, the facility managers relied on the manufacturers to troubleshoot problems in the field (potentially because of the complexity and short term duration of the Living Lab test itself).

Communicate control objectives clearly to the end users. With automated shading, it is important that facility managers and/or the owner understand and be able to communicate to occupants the objectives and intent behind automated shading. Most occupants figure out the basic logic behind shade control after experiencing automation over time but some of the more subtle aspects of control (e.g., dampening of movement to avoid occupant distraction, control of window heat gains) can be counterintuitive, causing confusion and questioning of control logic.

Occupants (and facility managers) may also not understand that settings for control that improve comfort by lowering the shade can be to the detriment of amenity and daylight quality which requires raising the shade. If increased daylight and views are desired, other toggles could be finetuned – the shade could be allowed to be adjusted more frequently to achieve a more optimal response to real time sun and sky conditions (which could then increase visual distraction if movement is too frequent or abrupt), or occupants could be provided with options to adjust their view angle to the window (adjustable mounts for computer monitors, provision of flexible work areas) to avoid occasional glare.

Both manufacturers' user interfaces enabled settings on the control systems to be adjusted fairly easily. Both had diagnostic features for troubleshooting problems with historical data (e.g., shade position, sensor data, control mode). Facility managers should be cognizant that there is significant variability in occupant's perception of daylight discomfort glare related to view position, task, age, etc. Distance from the window wall also affects the degree of visual and thermal discomfort. In shared spaces, achieving control that is satisfactory to all occupants can be challenging even with manually-operated shades. Self-learning controls have been investigated but not yet been implemented in large multi-occupant spaces.

Recommendations

Retrofitting commercial buildings with advanced lighting controls and LEDs is recommended. Lighting and shading control retrofits of occupied spaces offer significant potential for energy savings and improvements in the quality of indoor environments, but are complex and require a similar level of care typically provided for major tenant improvements. Retrofitting existing fluorescent systems to LED technology provides about half of the available savings, while lighting controls 1) provide significant additional savings at minimal cost increases, 2) enables non-energy benefits related to indoor environmental quality and comfort to be realized, and 3) places the facility in a strong position to benefit from anticipated advancements in data analytics as a driver of building operations.

Over the past few years, there have been significant changes in the lighting controls industry. ASHRAE 90.1-2013 as well as California Title 24-2013 now mandate the automatic control of fixtures in “primary” as well as “secondary” daylight zones in most interior spaces. Fixtures in each zone must be able to dim to different levels (based on their relative distance to the window wall), necessitating the use of significantly more advanced control equipment. California Title 24-2013 now requires that most spaces greater than 10,000 ft^2 be “demand response capable”.

There has also been a paradigm shift in recent years to think about controls as “data points”, and to incorporate digital protocols throughout as much of the system architecture as possible. This and the miniaturization of embedded controls components is driving costs for sensors and controls low enough to make it viable to factory install these elements on a per-fixture basis, which in turn makes retrofit applications in existing buildings more viable. In the long term, energy efficiency standards will drive the market to adopt these solutions more broadly. In the near term, high-resolution, multi-strategy lighting control applications are likely to be most cost effective in large scale commercial and institutional deployments where the cost of proper design, specification, and staging of the retrofit work can be absorbed within the project. If an experienced lighting designer (ideally familiar with the latest product offerings) is brought on board at the outset, applications can be cost effective for smaller scale commercial building deployments.

Retrofit of advanced LED lighting with high spatial resolution is recommended. Retrofitting existing fluorescent lighting systems that are due for replacement with LED fixtures is an obvious unequivocal choice for all commercial buildings – significant energy savings can be attained with this simple increase in light source efficacy. Some argue that the added cost of implementing dimming control is unjustifiable, but LED fixtures are almost exclusively manufactured and sold with dimmable drivers so there’s no cost add for this feature. Energy-efficiency codes (e.g., ASHRAE 90.1-2013) that are applicable to tenant fit-outs and renovations also mandate multilevel control (i.e., setpoint tuning via stepped or dimming control), which with LED fixtures must be implemented through dimming control.

The issue then is justification for the added cost of implementing the various advanced lighting control strategies (scheduling, setpoint tuning, daylight harvesting, occupancy sensing, personal control (which was not evaluated in this study), and demand response/ load shedding (which was also not evaluated in this study)) at a higher spatial resolution for retrofit applications. Higher spatial resolution at the fixture level necessitates a higher granularity of embedded microcontrollers with network communications capability. This concept was introduced over a decade ago with the introduction of digitally addressable ballasts and offers significant benefits in terms of reconfigurability. Higher granularity with respect to occupancy sensors (but not necessarily photosensors, depending on the algorithm for control) could lead to greater energy savings and/or control reliability but this was not proven in this study. Industry has and continues to develop technological advancements to reduce both the hardware and software cost of implementing advanced lighting controls. The findings from this study indicate that there are multiple commercially-available options on the market, each offering unique innovative features, that they perform satisfactorily, and can deliver significant energy and peak demand savings within a satisfactory simple payback period.

Education and training of the workforce are essential for broadening market adoption of this technology. The added cost and complexity of advanced controls should be weighed carefully against the associated energy and non-energy benefits for each application. Standardization across the industry (on wire colors for example) would greatly reduce workforce training requirements. As noted above, this project developed design/ specification/ workflow materials and has made the materials publicly available. In a follow-up activity to this study, lessons learned from implementing these technologies in this Living Lab demonstration were transferred to workforce training seminars and materials.

Increased sensor density and/or enabling sharing of sensor data is recommended as buildings move toward integrated, networked systems. Regarding the value proposition of high-resolution occupancy sensing, one could argue that this feature goes well beyond simply turning lights on and off in smaller areas to save energy. Data from high-resolution occupancy sensing has potential benefits for other end use management control strategies such as demand side ventilation, plug load control, and window heat gain management strategies. This exciting, emerging capability is likely to gain traction as individual controllable end uses throughout buildings become networked and integrated with advanced control systems. On the other hand, increased sensor density may not be needed for some space types (private offices, classrooms, conference rooms, break rooms, restrooms, etc.), so it may be cheaper to install a single area-wide sensor instead of installing a sensor in every fixture if the space layout and use are unlikely to change over the life of the installation.

With daylighting, digitally addressable ballasts for fluorescent lighting have long provided the capability to implement high resolution control at the individual fixture level. The value proposition of adding photosensors to each fixture could be made potentially based on reduced labor cost over the life of the installation if frequent churn/ changes in space use are anticipated. Increased control reliability given increased density of sensing could not be evaluated in this study. Note that the savings due to daylight harvesting are greater with the use of automated shades. The shades are automatically raised in the absence of discomfort, whereas in typical buildings, manually-operated shades are often not adjusted by occupants to the detriment of daylighting. These and other synergies between end uses can be leveraged with coordinated sensing and controls.

Take advantage of "guaranteed" load reductions provided by automated systems. The case for automated shading involves a complex combination of energy-efficiency and non-energy benefits and also should be evaluated carefully per application. Automated shading can "guarantee" that cooling loads due to solar heat gains are controlled to within specified limits, enabling reliable reductions in HVAC energy use and peak loads, and potentially downsizing of capacity (in the event of HVAC upgrades), if such control objectives are included in the sequence of operations. In the Living Lab (LL) building, the automatic system could only be overridden upon request (i.e., occupant calls the facility manager). This feature could be important for retrofit applications where tight control of cooling loads is important to maintain comfort conditions (e.g., in old buildings where HVAC capacity is insufficient to meet the load or in buildings where low-energy cooling strategies such as nighttime ventilation are being used).

Consider use of automated shades to maximize use of prime real estate near the windows. In existing buildings with high density occupancy, it may be necessary to seat occupants right next to the window in order to maximize use of prime real estate (particularly in urban areas such as

Manhattan). In terms of thermal comfort, the monitored data demonstrated that the thermal environment was well controlled within a few feet from the window: the value proposition for automated roller shades (with the appropriate fabric) based on thermal comfort may be a compelling argument. For spaces such as the LL building with large-area windows and floor-to-ceiling glass, automated shading also preserves the architectural and daylighting intent of the building design.

***Develop simulation tools that facilitate evaluation of daylighting and shading systems*.** Quantifying the benefits of automated shading for informed decisionmaking requires simulation tools with which designers and specifiers have confidence. There has been considerable ground work to develop the simulation engines (i.e., Radiance, EnergyPlus, Window, Optics) and supporting product-specific data needed by industry to evaluate and compare the thermal impacts of shading systems (automation notwithstanding). Considerably more effort is needed to develop tools to evaluate the return on investment related to the daylighting, visual comfort, and thermal comfort impacts of automated shading systems – the solar-optical input data for thermal evaluations of shades for example are inadequate for daylighting applications.

With respect to the selection of fabric, it must be noted that the openness factor is not the sole parameter that determines whether the fabric is able to control glare from direct sunlight. The thread color, opaqueness of the thread, and weave are also contributing factors. Quality and consistency of fabric manufacturing was also a concern raised by the manufacturer. It will be important that industry adequately characterizes the angle-dependent solar-optical properties of shade fabrics with all its variability to ensure that performance goals are met after the final installation.

Separately, robust, validated models for evaluating visual discomfort due to daylight are needed as well as thermal comfort models that account for direct solar irradiance on occupants. With more accurate tools and better models, both cost-benefit justification and proper specification of automated shading for building applications can be achieved with greater confidence in the outcome.

1. INTRODUCTION

1.1. Problem Statement

Daylighting is, or should be, a key design element in most high performance commercial buildings. Properly designed and operated, a well daylit building can provide many benefits to owners and occupants. It can reduce annual electricity use for lighting and cooling, reduce peak electric demand, provide thermal and visual comfort, and enhance appearance and amenity. The views associated with daylight, visual variability of daylight, the spectral content, the directional nature of daylight all contribute in ways not yet fully understood to its perceived desirability. Recent studies suggest there may be health and productivity benefits as well, although these findings are difficult to demonstrate and quantify. But the “market” interest in daylighting is clear, and is evidenced in numerous ways, from explicit mention of “natural light” in advertisements for leasing space, to credits in LEED ratings for daylighting of buildings.

All buildings with windows or skylights can be said to be “daylit” but only those with lighting controls and window management systems can effectively save energy. Daylighting is intrinsically a dynamic effect in buildings, which likely accounts for some of its perceived value, but the corollary is that successful daylighting solutions require controls that can effectively manage these dynamic impacts. The problems become more challenging in urban environments where real estate values and preexisting construction dictate floor plate dimensions and obstructions may limit access to the sky and sun.

But despite the potentials, the documented and measured energy impact of daylighting is small. There are many interrelated reasons for this, and these implicitly define the challenges to move daylighting strategies from the realm of “potentials” to “realities”:

- Successful daylighting strategies involve a level of systems integration between design team members that is often difficult to achieve.
- The costs of critical components (e.g., sensors and controls) are higher than can be readily justified in most projects in terms of energy and demand paybacks.
- Daylighting systems require calibration after installation, a process that is often complex and expensive.
- Because daylighting solutions must respond to a variety of time-varying external conditions and to changing interior functional task needs, the systems must be flexible, responsive and adaptive.
- The operation of daylighting systems involves dynamic changes to the interior luminous environment that are noticeable to occupants and may at times be considered disturbing.
- Solar gain and cooling loads associated with daylight systems must be properly controlled at the glazing system. Failure to manage cooling loads from glazing can lead to a net increase in energy use or higher peak demand.
- A dynamically controlled shading system and variable output light fixture introduce changes in interior spaces that are often confusing to occupants and lead to overrides of the control systems, thus defeating the daylighting strategy.
- Thermal comfort as well as visual comfort must be provided in a daylighted space.
- Solutions that “work” in one location or orientation may not work on another.

Despite these real obstacles, there are enough measured examples in existing buildings to demonstrate that daylighting "can" work although it has yet to become a "mainstream" energy efficiency strategy. Daylighting has been recognized as a potential energy and load control strategy since the 1970s. The rebirth of interest in the topic led LBNL to organize two International Daylighting Conferences in the early 1980s to capture the state of practice and R&D. LBNL has kept an active R&D program underway since the 1970s helping to create technologies (e.g. electronic ballasts, low-emittance windows), tools (e.g. DOE-2, Radiance) and demonstration projects (e.g., The New York Times Headquarters, San Francisco Federal Building testbed) to establish energy savings potentials. These R&D projects, supported primarily by the US Department of Energy (DOE) with cost shared support from the California Energy Commission (CEC), General Services Administration (GSA), New York State Energy Research and Development Authority, utilities and other public/private partners, are well documented and the impact on practice is measurable although slow.

Recently, there have been significant technological advances in both the lighting and fenestration industries that address these market and technical barriers:

- There has been an enormous investment in light-emitting diodes (LED) and these sources are now becoming mainstream with the easier dimmability, proper color temperature, reduced flicker, and lower cost needed to be competitive with fluorescent light sources;
- Lighting manufacturers have been developing low-cost, drop-in lamp and ballast or driver retrofit options that enable dimmable control on a per fixture/ high-resolution basis using wireless communications, which is particularly economical for retrofit applications;
- Lighting manufacturers have also been developing drop-in fixture replacement options with built in high-efficiency light sources, occupancy and photosensors, digitally addressable or analog dimmable ballasts, and wireless communications;
- With wireless communications and improved software, the capabilities of configuring, commissioning, running diagnostics, trending, and reconfiguring controls over the life of the building have significantly improved, lowering initial capital costs, improving reliability over the life of the installation, and decreasing costs for buildings with high churn rates;
- Control systems for automated shading have evolved significantly over the past five years due primarily to advances in sensors and control algorithms that can lower cost and increase user acceptance and comfort, broadening the economic justification for their inclusion on high performance building projects (demand response, integration with whole building controls, integration with demand and supply side controls to minimize energy costs).

The U.S. Department of Energy's Commercial Buildings Integration (CBI) program's mission is to identify underutilized building technologies with large energy savings potentials and provide the market with resources needed to accelerate their adoption. The key question which CBI asks for each high impact technology is: "What can the DOE do to improve the market adoption of this technology?" Answering this relies on an assessment of the most significant barriers, including:

- A lack of product available in the market to meet current needs,
- Owner uncertainty about how the technology will perform in real world settings, and

- A lack of operational understanding by potential adopters limiting technology acceptance.

Addressing these barriers directs the Department of Energy towards activities that have the greatest likelihood of significantly impacting the markets for the chosen technologies. In this case, demonstration projects can help pull emerging solutions into the market and accelerate adoption of innovative technologies by reducing the risk perceived by slow adopters in the buildings industry. The model of demonstrating new technologies in real-world, occupied buildings can provide the necessary third-party data needed by owners to understand both the long term financial and occupant impacts of their procurement decisions.

1.2. Opportunity

The objective of this study is to demonstrate that it is possible to design, specify, install and make operable packages of cost effective, energy efficient retrofits for lighting and daylighting in office buildings. New York City (NYC) contains the largest concentration of office buildings in the U.S. and has stringent energy codes and policies to support efficiency efforts. Advanced, innovative lighting and daylighting solutions are applicable in virtually all commercial buildings. New York City alone has over one billion square feet of floor space, much of which must be retrofit in the next 15 years. The Building Energy Efficiency Exchange (BEEx) proposed energy-efficiency measures as an alternate, potentially more cost-effective method of improving grid reliability compared to nuclear power generation. Daylighting was identified as an energy efficiency solution that could potentially offset 160 megawatts of peak electric demand and 340 gigawatts-hours of electricity by the Building Energy Exchange report called “Let There Be Daylight” [BEEx, 2012].

This study concept targeted 50%+ lighting and daylighting energy savings with other associated energy savings. By using a “Living Laboratory” approach, where new technologies are installed and evaluated in occupied spaces, we explored design process and procurement challenges as well as technology integration challenges, thus increasing the likelihood that the solutions can be implemented at scale.

Two owners agreed to implement a “Living Laboratory” in their buildings to fully explore a range of advanced efficiency performance options, and then use the lessons learned from the Lab for follow-on retrofit action in their overall building. Each owner also occupies commercial floor space in many other locations. By virtue of their building size and presence, they can influence both suppliers of technology as well as peers in the real estate industry.

The owners committed to sharing information gained from this study widely outside their organizations. The study engaged expert lighting designers to specify, observe, synthesize, and reduce the lessons learned into actionable information for the lighting community. To affect widespread market transfer, a partnership was formed between LBNL and the Building Energy Exchange (BEEx), a local non-governmental organization (NGO) committed to working with New York City to implement a new law to retrofit the lighting of almost one billion square feet of floor space by 2025.

The study aims to produce a number of significant outcomes, with a key goal of targeting replicability and extensibility of the study to all US commercial office buildings.

- High visibility Living Lab in a large office building – becomes an exemplar for others;
- Size and scope of the project can help drive down the installed cost of dimmable addressable lighting systems and associated daylight controls;
- Documentation and developed examples (e.g., Request for Information (RFI) and project plans + timeframes) of successful processes, issues, lessons learned, and tools to ensure specification, installation, commissioning and operations meet performance goals, and identify opportunities for workforce training;
- Shift industry to expectations that aggressive energy performance goals can be routinely met;
- Build industry confidence in the performance of "advanced building controls"; and,
- Use New York City legislative package and local NGO collaboration to build replication models in buildings in other cities and states. The study also leverages the partnerships and activities of DOE's Better Building Alliance (BBA), Better Buildings Challenge (BBC), and the State and Local Energy Efficiency Action Network.

2. TECHNOLOGICAL INNOVATIONS

The concept of systems integration at the perimeter zone is one that has been researched and advocated by LBNL over the past 30+ years. The concept has evolved from achieving an optimal balance between solar heat gains and daylight on an annual basis through proper window design and use of daylighting controls [Johnson et al., 1983] to sentient fenestration and lighting systems that operate optimally in real time in concert with supply side resources at microgrid and utility grid levels to achieve zero net energy performance and resiliency goals [Lee et al. 2015].

Technologies and industry at large are quickly advancing to levels where such ambitious goals can be enabled at the perimeter zone of buildings using commercialized technologies now available on the market, but are not yet achieved on a routine basis. To lay the foundation for this broader strategic vision, this study evaluated the ability of commercially-available systems working in parallel to fulfill independent but interrelated perimeter zone level performance objectives on a cost-effective, routine basis:

- dimmable LED lighting systems with high-resolution, per fixture control capabilities designed to provide specified levels of lighting quality and sufficiency that supplement daylight when occupied and that minimize lighting energy use when work areas are vacant; and,
- automated motorized shading systems with sufficient intelligence to balance solar heat gain, daylight, comfort, and view tradeoffs and therefore satisfy a group of occupants with diverse levels of sensitivity and tolerance to indoor environmental conditions.
- (Note that HVAC controls will independently reduce energy use as a result of the reduction in lighting and window loads and could leverage sensor data from the two systems to further increase savings (e.g., occupancy data for demand side ventilation strategies) – this system however was not evaluated in the scope of this study.)

For both technologies, we eschewed autonomous, stand-alone component solutions that lacked centralized data management and the networking and communications infrastructure needed to achieve whole building systems integration, performance benchmarking and automated fault diagnostics, and demand response, all of which add to the life cycle value proposition of the technological solution. Integration for demand response and building-to-grid optimization is enabled via tailored current server-based systems and gateway solutions between systems -- this performance assessment focused on the impacts of local, zonal controls as the basic building blocks toward full systems integration.

By necessity, technological solutions were selected to fit the requirements of the client and demonstration site. By far and away, occupant comfort, satisfaction and sense of well-being and amenity were the most important underlying constraints for both the hardware solutions and control configurations that were selected for the Living Lab. As a result, the technological demands and resultant solutions were sophisticated, pushing the upper boundaries of the various capabilities provided by the control systems (particularly with the use of direct-indirect light fixtures). If the commercial systems met the demands of this client, they would likely succeed in fulfilling the requirements of simpler control sequences.

This study also argues that until the basic building blocks are made cost effective for the purchaser, the broader vision of whole building, campus, city, and grid systems integration cannot be fully realized. Therefore, current product offerings were evaluated with a focus on cost effectiveness for retrofit applications in commercial office buildings since a very large percentage of the construction market is existing buildings.

The evaluation included observations of market factors to determine whether there were sufficient advances in the technology to lower the cost of implementation and facilitate sustained, reliable performance, thereby enabling widespread adoption. These technologies have advanced substantially over the past decade and incorporate sophisticated algorithms and capabilities under the hood that are not self-evident. To avoid the perception of required intervention by a National Laboratory to make things work, the approach in this study was hands-off and observational in nature, allowing the project team to gather practical insights and lessons learned from the real world. No technical expertise was assumed of the owner or the facility managers or of the building's engineering team. The project had no single institutional champion to make the project happen, reflecting typical institutional real estate management practice in the U.S.

2.1. Advanced Lighting Controls

There are many lighting control products currently available in the market. They can generally be broken down into four categories: 1) standalone fixture-integrated controls, 2) room-based controls, 3) "autonomous" systems using fixture-integrated controls where fixtures communicate via radio frequency (RF) signals, and 4) advanced lighting control systems with both distributed (fixture, room, or zonal) and centralized (building-level) control.

As discussed above, the fourth category was evaluated in the Living Lab study and is defined as follows:

System components – Advanced lighting control systems are networked, addressable, dimmable systems that use software in conjunction with intelligent controllers, fluorescent ballasts and/or LED drivers to simultaneously implement multiple lighting control strategies for a space or group of spaces. The system incorporates a graphic user interface for commissioning, programming, zoning and troubleshooting, as well as for energy use display and recording. Advanced lighting control systems almost always have a server that enables set-up of these functions, provides supervisory control in some situations, and can archive data.

Networking – A control system is networked if all of the light fixtures and associated control devices communicate with each other (including sensors, switches, etc.). Connection to the network may be hard-wired or wireless. Note that new "autonomous" systems are also networked but can't capture data after installation and configuration. However, they are not provided with a graphic user interface and typically no interaction with the system occurs after the initial setup.

Addressability/granularity – In an "addressable" system, each light fixture controller (or ballast or driver) as well as each control device (switch, dimmer, sensor, etc.) has a unique identifier (address). Note that with most systems available today, it is possible to control more than one light fixture with a single "controller". This normally has the effect of reducing the overall system cost, but also its flexibility of usage. Any system can be installed with maximum granularity – meaning that every single light fixture has its own uniquely addressed ballast, driver or controller.

Control strategies – An advanced lighting control system is capable of implementing multiple control strategies such as scheduling, daylight harvesting, facility-wide tuning, occupancy control, personal control, and demand response or load shedding.

Intent of integration

One of the main benefits of using an advanced lighting control system is that it can control, display, record and store every aspect and function of the lighting system. This capability can have an impact on internal as well as external equipment and functions:

Internal – The internal control system relays information back and forth to light fixtures, occupancy sensors, photosensors, switches, dimmers, touch panels, etc. All functions of the system can be accessed by trained personnel from the central server, handheld devices, or remotely off site if so desired, regardless of whether or not other user-friendly interfaces are utilized (such as local switches or dimmers).

External – Such a system may also be connected to external equipment. For example, an Automated Demand Response signal may be accessed by the lighting control system to dim or turn off lighting loads during periods of peak demand. Another possibility is connecting the lighting control system to other building management systems that may aggregate reporting of energy usage, or even control the lights. For example, a building management system (BMS) may command the lighting control system to turn lights on to full output during an emergency situation, while the BMS also activates alarms or other notifications about the emergency condition.

Claims

For the more innovative products, improved performance and cost-effectiveness are expected to result from:

- Greater efficiency of LED sources and fixtures
- Reduced installation cost of drop-in fixtures with factory-installed wireless controls compared to site-installed LED/ driver/ control retrofit kits for existing fixtures
- Minimal to no incremental cost for dimming with LED sources compared to dimmable fluorescent ballasts
- Reduced minimum power draw of LED drivers compared to fluorescent ballasts when lights are dimmed to minimum level
- Reduction of false-negative and/or false-positive signals from auto-commissioned occupancy sensors
- Reduction in over- and under-dimming due to daylight given automated commissioning tools
- Reduction in churn costs since fixture zones can be reconfigured using software, given that each fixture has a unique address
- Improved lighting quality and end user acceptance because light levels can be tuned and actively controlled to meet the requirements of individuals and/or work groups
- Increased transparency into the real-time operations of the control systems through automatic display and plotting of real-time historical data from the graphical user interface.

2.2. Automated Shading Controls

Similar to lighting, there are a wide variety of automated shading and window control products in the market. The control systems operate all manner of fenestration systems: indoor, between-pane, and outdoor shades, switchable electrochromic windows, operable windows and skylights, ventilation openings, daylight-redirecting systems, and non-coplanar shading elements such as retractable awnings. Systems are scaled to the application – some involve a simple remote control or wall-mounted switch that allows manual control of the shade. Others have embedded controllers that execute autonomous control, are configured upon installation, then left to operate as required. Advanced systems offer broader capabilities and were evaluated in conjunction with indoor motorized roller shade systems in the Living Lab study.

System components – Advanced shading control systems are networked, addressable systems that implement control strategies for a space or group of spaces using distributed embedded controllers and supervisory control from a central computer. The system incorporates a graphic user interface for commissioning, programming, zoning and troubleshooting, as well as for energy use display and recording. Advanced shading control systems have a central server that controls these functions and archives data.

Networking – A control system is networked if all of the motorized shades and associated control devices communicate with each other (including sensors, switches, etc.). Connection to the network may be hard-wired or wireless.

Addressability/granularity – In an "addressable" system, each motor controller as well as each control device (switch, sensor, etc.) has a unique identifier (address). To save on the cost of motorization, there can be multiple shade "bands" served by a single motor but this reduces flexibility when it comes time to reconfigure spaces. Several motors can be grouped using software into a single zone of control so that when automated, the shades are set to the same height across a prescribed width of a façade. This configuration could also be set up to allow individual motors within the group to be overridden with a manual switch.

Control strategies – An advanced shading control system is capable of implementing multiple control strategies such as scheduling, direct sun control, glare control, daylighting, personal control, and demand response or load shedding. The sensor and control algorithms are what distinguish the performance of one system from another. Shading has direct observable impacts on occupants so if the automated system does not operate in a manner that is perceived as somewhat logical by the occupants or does not alleviate discomfort, the system is likely to be decommissioned.

There has been considerable work to achieve reliable control of direct sun over the years. The key challenge is to determine if and when the sun is not sufficiently obscured by cloud cover and when the conditions are deemed to be sunny, then to determine if local obstructions (e.g., trees, other buildings near and far, adjacent building wings, mountains) shade a particular window from direct sun. Some systems ignore urban obstructions, leading to frustration when the shades are lowered even though the window is shaded by a nearby building. Others combine virtual models with sensor data to achieve more accurate control of each motor group.

Glare control has been and will continue to be a significant challenge due to a number of factors: a) the degree of discomfort experienced by occupants varies significantly with location in the room, view position, type of task being performed, and sensitivity to glare, and b) glare discomfort from windows and daylight is difficult to predict and measure. Personnel with low glare tolerance working on a computer near the window may cause the shade to be lowered far more often than if personnel with greater glare tolerance were seated near the window. In an open plan office space, the challenge is how to meet the competing demands of a diverse group of occupants. If the glare mode is too conservative, the shades will be lowered more often, limiting access to daylight and unobstructed views to the outdoors.

Intent of integration

The purpose of internal and external integration is the same as that of lighting control systems.

Claims

For the more innovative products, improved performance and cost-effectiveness are expected to result from:

- Improved sensors and control algorithms, leading to greater occupant comfort, satisfaction, and acceptance of the technology
- Alternate approaches to controls that can be implemented and maintained over the life of the installation at lower cost.

2.3. Summary of Technologies Tested

The following list summarizes the technologies that were evaluated in this field study:

Application

- Commercial office building, ASHRAE 90.1-1999 compliant, LEED Gold
- Open plan office environment
- Daytime occupancy

Advanced Lighting Controls

- LED source
- Five types of pendant direct/ indirect lighting fixtures
- Addressable, dimmable drivers for each light source in each fixture
- 0-10 V, DALI, and proprietary protocols for communications
- Factory- and site-installed controls, wired and wireless networking
- Scheduling and setpoint tuning
- High-resolution occupancy controls (1 sensor per fixture or 1 per group of fixtures)
- Daylight dimming (1 photosensor per fixture or 1 per area with flexible control architecture)
- Self-commissioning software for daylight dimming
- Server with full capabilities including data archiving
- BMS integration via BACNet or BACNet-IP gateways

Advanced Shading Controls

- Automated, motorized roller shades with proprietary communications
- Roof and window sensors plus urban shadow model: Direct sun, glare, daylight, and view controls; raises shade if window is shaded by outdoor obstructions
- Window mounted sensor only plus controls
- Roller shade fabrics with 1% and 3% openness factors
- Server with full capabilities including data archiving
- BMS integration via BACNet gateway

3. M&V EVALUATION PLAN

3.1. M&V Objectives

The overall monitoring and verification (M&V) objectives of this study were to:

- Identify commercially-available products that meet current needs,
- Reduce owner uncertainty about how these technologies will perform in real world settings, and
- Improve operational understanding by potential adopters so as to broaden technology acceptance.

The technical objective of this study was to determine based on monitored data and occupant surveys whether the advanced lighting and shading technologies performed as claimed (see

Section 2). Strong positive evidence would suggest that these technologies are suitable for further deployment in other similar facilities.

Market-related objectives were to observe, synthesize, and reduce the lessons learned from the design, procurement, installation, commissioning, and operation phases of this project into actionable information for the daylighting and lighting community.

3.2. Demonstration Site

This project initially involved demonstrations in two large commercial office buildings located in Manhattan, New York. Both were relatively new high-rise commercial office buildings occupied in 2008 and 2009. Demonstration in one of the buildings (the “BA” building), however, did not progress beyond the bid phase due to changes in the real estate management structure within the company. Lessons learned from working with this owner from the design through bid phases are included in this report. Monitored results and lessons learned from the fully executed demonstration in the second building, called the “LL” building hereafter, are also included in this report.

The “LL” demonstration building located at 200 West Street is a 2.14 Mft^2, 43-story commercial office building located in New York, New York. The building was designed to meet the ASHRAE/IESNA Standard 90.1-1999 using the Energy Cost Budget Method, but incorporated a number of additional energy-efficiency measures to earn points under the LEED 2.1 Energy & Atmosphere section (credit EA-c1 “Optimize Energy Efficiency”). As a result, the building received LEED Gold certification when it was occupied in 2009.

The demonstration involved two floors located on the mid-height, relatively unobstructed floors of the building: the reference floor and the “Living Lab” test floor. The test floor was subdivided into four areas (G1-G4) and four different combinations of advanced shading and lighting technologies (described in Sections 3.4 and 3.5) were evaluated in each of these areas. The reference floor was subdivided into the same four areas as the test floor. Monitored performance in each of the four test areas was compared to each corresponding reference area.

The façade of the building is a flush-skin, curtainwall façade with floor-to-ceiling, dual-pane, spectrally selective, low-emittance windows (Figure 2). The facades face primarily east and west, with the west façade facing the river. The east façade is oriented about 19° south of due east. The west façade consists of a single broad curved arc. The sill and head height of the window were 0.5 ft and 10.5 ft, respectively. The ceiling height was 9.5 ft. The window to exterior wall area ratio (WWR) was 0.62-0.70. The windows had a whole window solar heat gain coefficient (SHGC) of 0.35-0.36, a visible transmittance of 0.65. The U-value was 0.29 $Btu/h\text{-}ft^2\text{-}°F$. The window was flush with the exterior face of the façade. On the interior, there were 4 ft deep square columns at 20 ft on center at the façade. The existing window shades are described in detail in Section 3.5.

Floors were conditioned using an underfloor air distribution system that supplied cooling, heating and conditioned outside air through swirl diffusers in the floor. Additional perimeter linear diffusers in the ceiling adjacent to the window provided localized heating and cooling at the window wall. Outside air, supply air temperature, and demand control ventilation were controlled on a floor-by-floor basis. The central refrigeration plant had ice storage cooling to reduce on-peak cooling demand. Offices were conditioned to a 72°F setpoint during the winter and 74°F during the summer with 20 CFM per person. Small personal fans were noted on less than a handful of the workstation desks on the two floors. No space heaters were detected.

The layout on each of the two floors was typical of most floors in the building. Each floor was 39,980 ft^2 in total gross floor area. The façade and interior were designed to allow maximum access to daylight and views. Open plan workstations were situated at the perimeter and private offices were situated at the core. The depth of the open plan office zone was about 40 ft from the east or west windows to the core or face of the interior private offices.

In general, the open plan workstations consisted of rows of 5.25 ft by 30 ft long desks positioned perpendicular to the window at 20 ft on center. Occupants sat on either side of the desk facing each other with a continuous 3.5 ft high partition separating the two sides of the desk. The primary view orientation for occupants in the open plan area was parallel to the window.

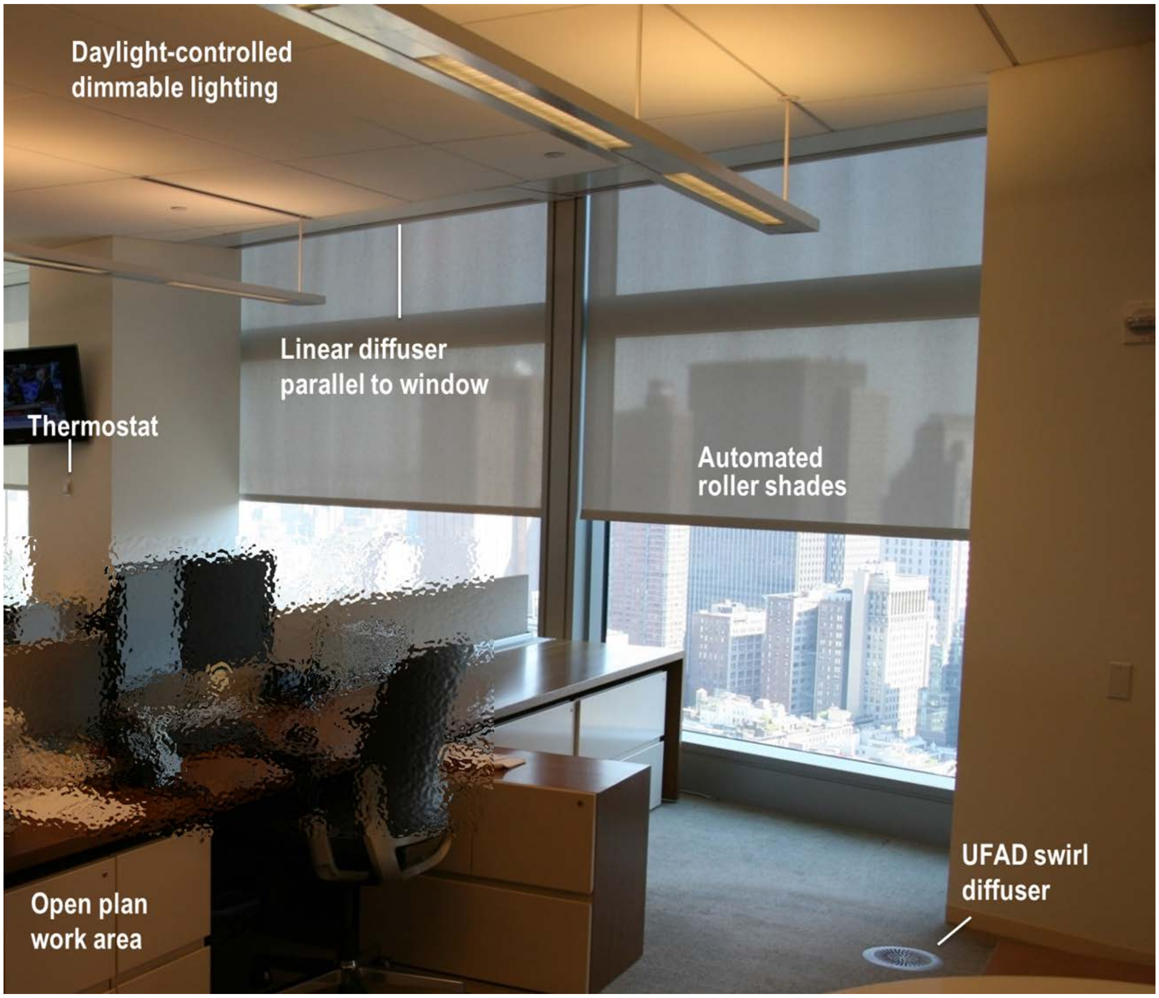


Figure 2. Photograph showing the lighting and window conditions in the open plan area on the reference floor.

Computer monitors partially blocked views parallel to the window if occupants were seated. Views toward the window in the open plan area were unobstructed. The interior private offices had floor-to-ceiling glass fronts enabling unobstructed views to the windows.

The floor plan deviated from this open plan layout in two instances: 1) on the reference floor in Area G4, a large 30x30 ft conference room with glass walls was situated near the windows in the northeast corner of the floor, and 2) on the test floor in Area G1, seven private offices with glass rear walls formed a continuous 140 ft row along the west window wall along the south end of the floor. The interior itself had surface reflectances that were light colored: approximately 0.80, 0.60, and 0.20 for ceiling, walls and floors.

The existing lighting is described in detail in Section 3.4. Equipment use (computers, monitors, phones, printers, etc.) on the floors were fairly typical of office buildings. Each occupant had two to three side-by-side, flat screen computer monitors, the vast majority of which had a matte, anti-glare coating on the screen. On about 10% of these monitors, a privacy, low reflectance film had been placed over the face of the monitor. No task lights were evident on the desks of any of the workstations.

Private offices and open plan workstations had assigned seating. Occupants were permitted to work on location or telecommute from home. On the floors being investigated, business occurred during a typical eight hour day.

3.3. Technology Specification and Deployment

Technologies for the Living Lab were selected through a staged process involving an initial Request for Information (RFI), a second round review through interactive discussions with a subset of the initial respondents, then a final bid phase involving cost estimates of materials and installation. Staging of the installation occurred through discussions and coordination with electrical contractors. Lessons learned from the implementation phase are given in Section 5.

As a Living Lab, the test floor was subdivided into four quadrants (named G1 through G4) so that multiple technologies could be evaluated simultaneously within the monitoring period. Because the window orientation differed for each of the four quadrants, comparisons between technologies (e.g., comparisons in performance between test Area G1 and G2) could not be performed. The test area technologies in each quadrant could only be compared to the reference floor quadrant, which had similar space geometry and window orientation.

Each of the quadrants had unique lighting and shading equipment installed, each representing a different tactic for achieving high resolution advanced control, energy-efficiency, and life-cycle cost effectiveness. Multiple technologies were also installed in the private offices, primarily to evaluate lighting quality from different LED fixtures and to evaluate occupancy sensors and manual controls in individually-occupied spaces. Technologies in the interior private offices were not evaluated in this study.

3.4. Description of Lighting Systems

3.4.1. Reference floor lighting system

The overhead lighting system throughout the building consisted of pendant direct/ indirect linear T5 fluorescent fixtures with an installed lighting power density of 1.04 W/ft^2. The system was designed to provide an illuminance of 538 lux (50 fc) at the workplane. In the open plan areas, six 5 ft fixtures were placed end to end to form a 30 ft continuous row that was either parallel or perpendicular to the window wall. In the case where the fixtures were perpendicular to the window, the two fixtures (on the end of the 30 ft row) nearest the window on the south, east, and west facades were installed with dimming ballasts (design minimum 10% light output, 18% input power). The four remaining fixtures further from the window were non-dimming. For the fixtures parallel to the window wall, the single fixture row nearest the window on the north was dimmable. The 30 ft rows of fixtures were spaced 10 ft on center and mounted 18.5-inches below the ceiling. See Table 3 for details on the installed equipment.

The lighting system was automated to turn on based on a schedule defined by the individual business units and by the night cleaning crew. If lighting was required after hours, occupants were asked to call and specify the time period for the lights to be turned on. On the reference floor, the lights were scheduled to be turned on from 7 AM to 1 AM or 1:30 AM. On the test floor during the pre-retrofit period, the lights were scheduled to be turned on from 6:30 AM to 1:30 AM.

In 2010 (prior to this study), occupancy sensors were installed on the reference floor. The floor was subdivided into four business units. When a business unit was entirely vacant, the occupancy sensors triggered the lights to be turned off after a 15-min delay.

When occupied, daylight dimming of the two fixtures nearest the window occurred based on input from the photosensor (50 fc setpoint). Since a single ballast served one fixture, both the up- and downlights were dimmed simultaneously.

In the conference room near the window on the reference floor in the G4 area, lights were controlled by the occupant using a wall-mounted keypad or based on occupancy. When vacant for more than 15 minutes, lights were shut off. Daylight dimming was disabled in this space.

When occupied, the emergency lighting was controlled in the same way as all the other fixtures. When unoccupied, the emergency lighting was turned off.

Table 3. Existing installed lighting equipment on the reference floor.

Component	Manufacturer	Description
Fixture	Neoray Panelit 52 DIP	7.25-in wide by 1.75-in high by 5-ft long direct/ indirect, pendant mounted fixture with 2.875-in wide lateral semi-specular aluminum baffle; (6) fixtures placed end to end in open plan area to form one continuous row
Lamps	Sylvania FP28T5/ 830/ ECO	(2) 4-ft long, 28 W, T5 fluorescent lamps, two lamps side-by-side in cross section
Ballast1	Universal B228 PNUV85-D	Non-dimming electronic ballast, 53 input watts each, 0.85 ballast factor, 1 ballast per fixture or,
Ballast2	Lutron EC5t528J2772-C85	Dimming electronic ballast, 55 input watts each, 0.85 ballast factor, 1 ballast per fixture
Occupancy sensor in open plan areas -- reference floor	Acuity CM PDT 10	Dual technology occupancy sensor (passive infrared (PIR) and ultrasonic), 360° 2000 ft^2 coverage, 28 ft range; 1 sensor installed every 20-30 ft in four separately controlled areas on the reference floor
Occupancy sensor in open plan areas -- test floor	Lutron PIR, LRF2-OCRB	Pre-retrofit condition: Wireless ceiling mount PIR occupancy/ vacancy sensor with 434 MHz RF communications, 360° coverage, 324-676 ft^2
Photosensor	Lutron EcoSystem Daylight Sensor C-SR-M1-WH	Measures daylight illuminance with photopic response; ceiling mounted, located near and aimed at the window.
Wall mounted keypad	Lutron EcoSystem 1-button wall control (CC-1BRL-WH)	Manual switch that turns lights on or off; raise/ lower light levels with rocker switch; overrides occupancy sensor
Network	Lutron EcoSystem	EcoSystem dimming power module (C5-BMJ-16Z), EcoSystem Bus, and Bus Supply: Networks and controls sensors, keypads, and ballasts; programmable using a hand held IR interface.
Controls	Lutron Grafik Eye 3000/ 4000	

3.4.2. Test floor lighting systems

3.4.2a – Pre-retrofit condition

The overhead lighting system hardware and controls were identical to the reference floor with the exception that a) a different manufacturer provided occupancy-based controls on the test floor but with the same functionality as the reference floor, and b) the Area G1 lighting in the seven private offices at the window wall also had an occupancy sensor and a wall-mounted dimmer and on-off switch to control the lights. When occupied, daylight dimming continued to occur in these private offices. A comparison of pre-retrofit energy use between the reference and test floors is given in Section 3.6.2.

3.4.2b – Post-retrofit condition

The lighting system, zones, and control sequences for the test floor were defined by the lighting designer in collaboration with the owner. Detailed descriptions of the final implementation in each of the four quadrants are given in the following sections. Dimensions and fixture and source properties are summarized in Table 4. The fixture layout and zoning diagrams are given in Figures 3-4. The control sequence is given in Appendix B. Figure 5 shows an image of all fixtures used on the reference and test floors.

Note about input power – As indicated in Table 4, the new LED fixtures had input power that varied between 6-19 W per linear foot. This wide discrepancy in input power was due to the lighting designer selecting the highest light output offered by each vendor for the specified fixture types, allowing the owner to visualize the differences in task visibility, space appearance, and lighting quality for different combinations of up- and downlight output levels. The lighting designer's expectation was that each control system would use area-wide tuning to achieve target setpoints for horizontal task illuminance as well as reasonably uniform ceiling luminance.

Setpoint illuminance – When the systems were initially commissioned, Areas G1-G3 were tuned to a setpoint illuminance level of 215 lux (20 fc) and Area G4 was tuned to 538 lux (50 fc). Later (February 2016), given feedback from the occupants, the owner requested that all vendors adjust their setpoint level to 269 lux (25 fc) in all areas on the test floor.

Table 4. New installed lighting equipment.

Area	Reference	G1	G2	G3	G4
Fixture type	LFL	FA	FB	FC	FD
Total no.	varies	49	56	56	48
EM No.	varies	12	10	12	12
Vendor	Neoray Panelit 52 DIP	Neoray S23	Fluxwerx Profile	Selux M36	Philips MicroSquare
Size	7.25"x1.75"x5'	4"x5"x5'	3.25"x3.1"x4'	9"x1.57"x5'	2"x3.75"x5'
CRI	85	85	85	80	80
Lumens/W	89	70 (5 ft)	92.5 (4 ft)	107 (4 ft)	71 (4 ft)
Indirect/ Direct	60%-40%	50%-50%	40%-60%	74%-26%	50%-50%
Lamp	(2) T5	LED	LED	LED	LED
CCT	3000K	3500K	3500K	3500K	3500K
Rated input power: W/fixture	55	95	24 (4 ft)	63	97
W/lft (up+down)	11	19	6	12.6	19.4
Ballast or driver	Universal/ Lutron Ecosystem	0-10 V	Lutron Ecosystem	Lutron Ecosystem	Philips SR Xitanium (DALI)
Up/ down separately controlled?	No	Yes	No	Yes	Yes
Ballast or driver install	Factory-installed	Factory-installed driver; controller in the plenum	Plenum	Factory	Factory
Control system	Lutron Grafik Eye	Encelium	Crestron	Lutron Quantum 3.0	Enlighted

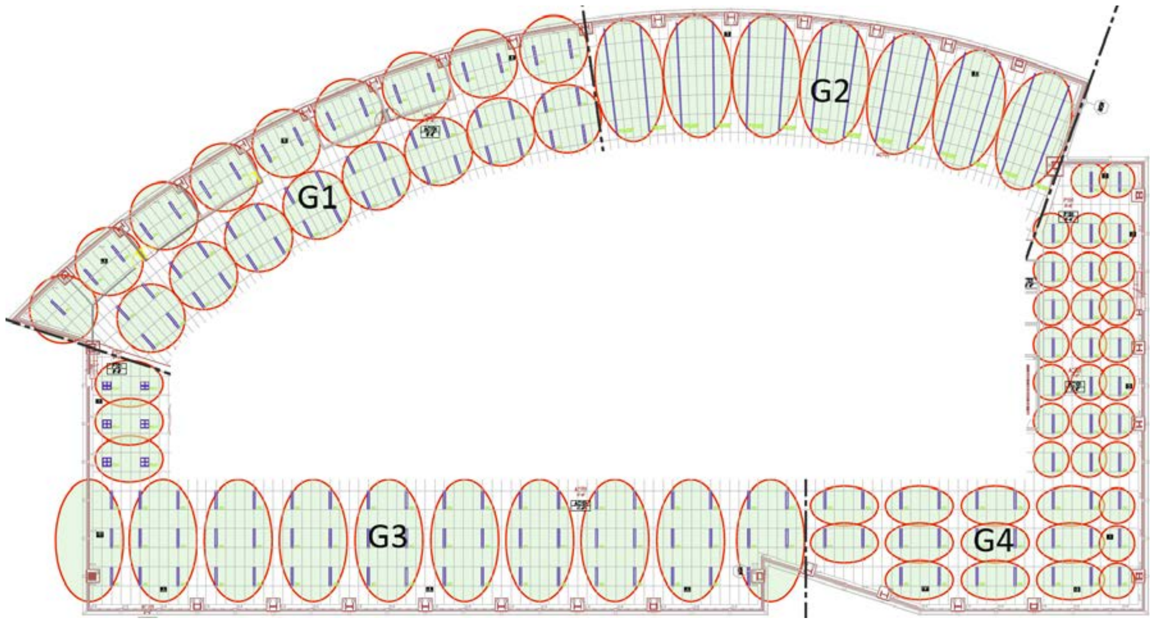


Figure 3. Specified occupancy zones on the test floor.
All manufacturers were successful in configuring the zones as depicted. The curved façade faces west, the lower façade faces east. The core zone (elevators, utility closets, etc.) is the white area in the middle of the floor plan.

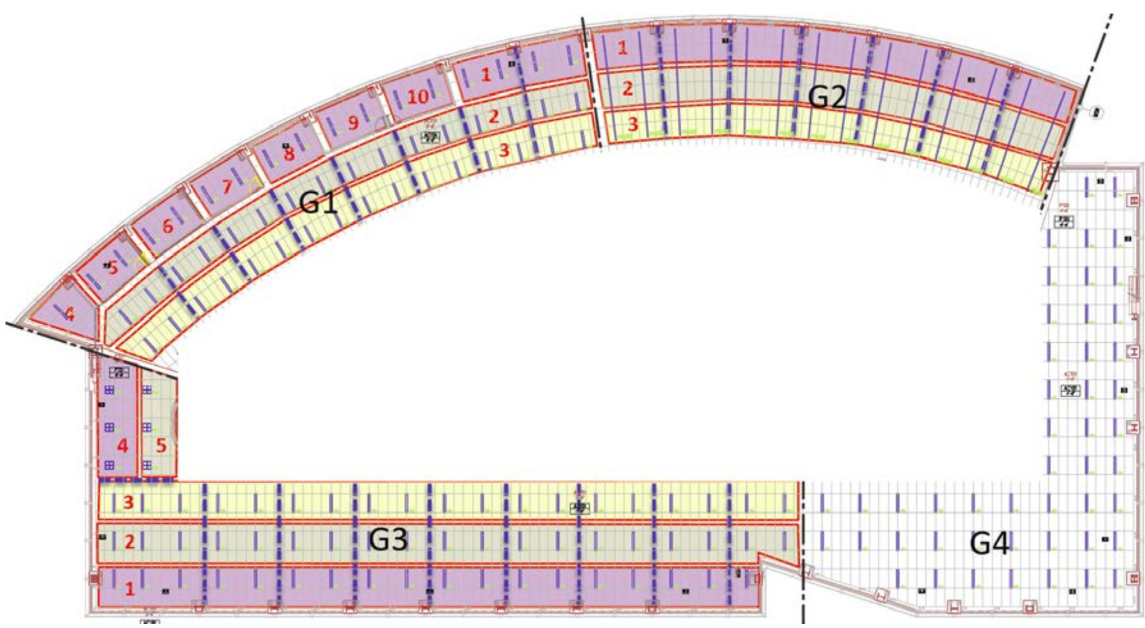


Figure 4. Specified daylight zones, denoted by numbers in red, on the test floor.
Area G2 and the open plan area east of the private offices in Area G1 were not implemented with daylighting in the final installation. Each individual fixture in G4 was implemented with daylighting controls.

G1 – Type FA   G2 – Type FB   G3 – Type FC   G4 – Type FD

Reference   G3 FC-1

Figure 5. Photographs of light fixtures.
These fixtures were installed on the test floor (above), on the reference floor (lower, left). There were also six non-linear fixtures used on the south end of the test floor Area G3 (lower, right).

3.4.2c – Area G1 (southwest quadrant)

Fixtures – In the open plan area and seven private offices near the window, the existing lighting was replaced with new individually-mounted 5 ft long pendant LED fixtures with a 50%-50% ratio of uplight to downlight (TYPE FA). Each fixture was spaced 5 ft apart end to end (so instead of six fixtures for a total length of 30 ft as in the reference case, there were only three fixtures for the same length). Fixture rows were maintained at the original spacing of 10 ft on center and mounted 18-inches below the ceiling. There were a total of 49 fixtures, 12 of which were emergency fixtures. The fixture was a slim rectangular box with a diffusing lens on the downlight and no diffuser on the uplight (see Appendix A).

Fixture controllers – All fixtures were dimmable. Separate 0-10 V drivers were installed so that the uplight could be controlled separately from the downlight in each fixture. Since the fixture housing was too small to accommodate the controllers, two plenum rated circuit controllers were remotely installed in the plenum to switch and dim the uplight and downlight separately. Line-voltage power wires as well as low-voltage control wires (for the 0-10 V signal) ran from the remote junction boxes in the ceiling to the pendant mounted fixtures. The controllers were connected via wireless communications to the gateway. Emergency (EM) power feeds were routed to fixtures closest to original EM fixture locations to provide emergency egress lighting similar to the original design.

Sensors and switches – 10 wireless multi-sensors (passive infrared occupancy sensor and photosensors, Encelium EN-SCPPH-1500-ZB) and two wireless wall dimmers were installed in the open office area. One wireless multi-sensor and one wireless wall dimmer switch were installed in each of the seven private offices near the windows.

Control system panel and gateways – A new control system panel was installed in the electrical closet. Two wireless gateways were installed in the plenum in the open office area. The gateways were connected to the control system panel located in the electrical closet using dedicated wired Ethernet connections.

Control signal transmission method – Control signals from fixtures, multi-sensors and switches to the gateways were wireless using a Zigbee protocol.

Zoning – The G1 area was subdivided into nine occupancy zones near the window and eight occupancy zones in the interior open plan area. In the interior open plan area, four fixtures (two rows of two) created a single zone corresponding to a workstation group. Each of these zones were controlled by an occupancy sensor. Each of the seven private offices near the window had two fixtures that were defined as an occupancy zone. In the open plan area adjacent to the window (to the north of the private offices along the same west window wall), two zones with two fixtures each were also defined as occupancy zones. Each occupancy zone was also subdivided into daylight zones. Zone 1 corresponded to the first row of lights nearest the window. Zones 2 and 3 corresponded to the second and third row of lights further from the window.

Control configuration – The owner requested that the lighting control system be configured to meet the sequence of operations defined by the lighting designer (see Appendix B). The actual configuration implemented by the manufacturer during the commissioning phase was as follows:

Open plan areas

> South end, open plan offices toward the core: During the work day, upon occupancy, both the up and downlights in each occupancy zone were turned on to the defined setpoint illuminance level. When unoccupied, lights were dimmed down with a 1-2 sec fade rate then shut off after a 15-min delay.
>
> North end, open plan offices near both the window and the core: Same as the south end, but in addition, if there was sufficient light detected by the photosensor, then the up- and downlights in the daylit zones were dimmed (and turned off if there was sufficient daylight).

During after hours (weekday nights, weekends, and holidays), only the downlights in this area were turned on when zones were occupied. Operation of the lights was the same in all areas as during normal operating hours.

During both the work day and after hours, the downlights of the emergency fixtures were left on at a low dimmed level irrespective of occupancy.

Private offices near the windows

During the work day and after hours, the up- and downlights were turned on to the defined setpoint illuminance level or the light level selected by the end user using the wall dimmer. When on, both the up- and downlights were dimmed based on daylight availability. When unoccupied, lights were dimmed down with a 1-2 sec fade rate then shut off after a 15-min delay.

3.4.2d – Area G2 (northwest quadrant)

Fixtures – In the open plan area, the existing lighting was replaced with (3) 8 ft long and (1) 4 ft long pendant LED fixtures placed end to end to form a 28 ft long continuous row of pendant LED fixtures with a 40%-60% ratio of uplight to downlight (TYPE FB/28 ft; 4 ft section was placed near the core). Fixture rows were maintained at the original spacing of 10 ft on center and mounted 18-inches below the ceiling. There were a total of 56 fixtures forming 14 rows, 10 of which were emergency fixtures. The fixture profile was an inverted rectangular U-shaped profile where the inside planar surfaces of the U were diffusely lit.

Fixture controllers – All fixtures were dimmable. Although fixtures were butted together to form continuous rows, each of the four fixtures per row were supplied with an LED Digital Addressable Lighting Interface (DALI) driver to switch and dim the lights. Because of the design of the fixture, the uplight could not be separately controlled from the downlight. In addition, the LED drivers were remotely installed in junction boxes in the plenum. The drivers were connected to the gateways via a dedicated low-voltage bus located in the plenum. Emergency power feeds were routed to fixture segments closest to original EM fixture locations to provide emergency egress lighting similar to the original design. Input power was reported by the vendor as 168 W per 28 ft fixture run; 6 W per linear foot.

Sensors and switches – 7 wired photosensors and 7 wired occupancy sensors were installed in the open office area. Three wall switches were provided that enabled manual ON/OFF switching of the lights.

Control system panel and gateways – A new control system panel was installed in the electrical closet. DALI distribution hubs were installed in the panel located in the electrical closet (as well as DALI power supplies and other related components). Therefore, no additional “gateways” were required in the open office space. In addition to the panel controlling normal lighting functions, a separate “phase-loss sensor” panel was also installed to comply with applicable EM lighting codes.

Control signal transmission method – Control signals from fixtures to the control system panel was wired using a non-proprietary protocol (DALI). Control wiring was run through the plenum to the fixtures. The control signal from the sensors and switches to the control system panel was wired, using a proprietary protocol.

Zoning – The G2 area was subdivided into seven occupancy zones where two 28-ft rows of fixtures created a single zone corresponding to an open plan workstation group. Each of these zones were controlled by an occupancy and photosensor. Each occupancy zone was subdivided into daylight zones, similar to Area G1.

Control configuration – The owner requested that the lighting control system be configured to meet the sequence of operations defined by the lighting designer (see Appendix B). The actual configuration implemented by the manufacturer during the commissioning phase for the open plan areas was as follows:

> During the work day in the open plan areas, upon occupancy, both the up and downlights in each occupancy zone were turned on (fade up over 1 sec) to the defined setpoint illuminance level. When unoccupied, lights were dimmed down with a 1-2 sec fade rate then shut off after a 15-min delay.
>
> During after hours (weekday nights, weekends, and holidays), lights were operated the same way as during the work day.
>
> During both the work day and after hours, the downlights of the emergency fixtures were operated in the same way as the regular fixtures.
>
> Daylight dimming was not implemented due to incompatibilities between the DALI driver and control system.

3.4.2e – Area G3 (southeast quadrant)

Fixtures – In the open area, the existing lighting was replaced with 5 ft long pendant LED fixtures with a 74%-26% ratio of uplight to downlight (TYPE FC). Both the up- and downlights were shielded with a microprismatic lens. Each fixture was spaced 5 ft apart end to end (so instead of six fixtures for a total length of 30 ft as in the reference case, there were only three fixtures for the same length). Fixture rows were maintained at the original spacing of 10 ft on center and mounted 20-inches below the ceiling. There were a total of 56 fixtures, 13 of which were emergency fixtures.

In a limited area adjacent to the south façade, a different fixture type was installed for evaluation purposes. This fixture was a 2x2 ft decorative pendant LED fixture with an 80%-20% ratio of uplight to downlight (TYPE FC-1). There were a total of 6 fixtures forming 2 rows, 1 of which was an emergency fixture.

Fixture controllers – All fixtures were dimmable. For fixture Type FC, two LED DALI drivers were installed in each fixture to separately control the uplight and downlight components. Emergency power feeds were routed to fixtures closest to original EM fixture locations to provide emergency egress lighting similar to the original design. The digital drivers were connected to the gateways via a dedicated low-voltage bus located in the plenum.

For fixture Type FC-1, one LED DALI driver was installed with each fixture so the uplight could not be controlled separately from the downlight. The LED drivers were remotely installed in a junction box in the plenum. Input power was reported by the vendor as 63 W per fixture.

Sensors and switches – 6 wired photosensors and 12 wired occupancy sensors were installed in the open office area. Three wall switches were provided that enabled manual ON/OFF switching of the lights.

Control system panel and gateways – A new control system panel was installed in the electrical closet. DALI distribution hubs were installed in the panel located in the electrical closet (as well as DALI power supplies and other related components). In addition to the panel controlling normal lighting functions, a separate "phase-loss sensor" panel was also installed to comply with applicable EM lighting codes.

Control signal transmission method – Control signals from fixtures, sensors and switches to the control system gateways were wired using a proprietary digital protocol. Control wiring was run through the plenum to fixtures, sensors and switches. Wiring for fixture control was separate from wiring for sensors and switches.

Zoning – The G3 area was subdivided into nine occupancy zones along the east façade where two rows of three fixtures each created a single zone corresponding to an open plan workstation group. Each of these zones was controlled by an occupancy and photosensor. Each occupancy zone was subdivided into daylight zones, similar to Area G1. A tenth occupancy zone was defined for the south façade at the southeast corner of the floor, corresponding to workstations at the south window wall. Three occupancy zones were defined for the six FC-1 fixtures along the south façade and these zones were further subdivided into two parallel daylighting zones corresponding to the first and second row of fixtures from the window.

Control configuration – The owner requested that the lighting control system be configured to meet the sequence of operations defined by the lighting designer (see Appendix B). The actual configuration implemented by the manufacturer during the commissioning phase was as follows:

Open plan areas – Type FC

> During the work day in the open plan areas, upon occupancy, both the up and downlights in each occupancy zone were turned on to the defined setpoint illuminance level. If there was sufficient light detected by the photosensor, the up- and downlights in the daylit zones were dimmed according to daylight availability. Daylighting was implemented throughout the entire open plan area. When unoccupied, lights were dimmed down with a 1-2 sec fade rate then shut off after a 15-min delay.
>
> During after hours (weekday nights, weekends, and holidays), the lights were operated the same way as during the work day.
>
> During both the work day and after hours, the emergency fixtures were operated in the same way as the regular fixtures.

Open plan area – Type FC-1 (six decorative fixtures)

With the exception that the FC-1 up and downlights were controlled together as opposed to separately, the FC-1 fixtures were controlled in the same way as the FC fixtures.

3.4.2f – Area G4 (northeast quadrant)

Fixtures – In the open area, the existing lighting was replaced with 5 ft long pendant LED fixtures with a 50%-50% ratio of uplight to downlight (TYPE FD). Both up- and downlights had an acrylic diffusing lens. Each fixture was spaced 5 ft apart end to end (so instead of six fixtures for a total length of 30 ft as in the reference case, there were only three fixtures for the same length). Fixture rows were maintained at the original spacing of 10 ft on center and mounted 18-inches below the ceiling. There were a total of 48 fixtures, 12 of which were emergency fixtures.

Fixture controllers – All fixtures were installed with integral DALI drivers. Two DALI drivers and two DALI-compatible multi-sensors were factory installed in each fixture to separately control the uplight and downlight components. Emergency power feeds were routed to fixtures closest to original EM fixture locations to provide emergency egress lighting similar to the original design. Each driver communicated with its respective multi-sensor, which in turn communicated wirelessly with the lighting control system's gateways. Therefore, no separate fixture controllers were required to switch or dim the drivers.

Sensors and switches – In this system, every fixture had its own integral multi-sensors - incorporating PIR occupancy sensors as well as photosensors. Since the uplight and downlight components could be separately controlled, every fixture contained two multi-sensors (one for each component), wired to their respective controllers and drivers. Four wireless switches were installed in the open office area.

Control system panel and gateways – A new control system panel was installed in the electrical closet. Two wireless gateways were installed in the open office space. The gateways were connected to the control system panel located in the electrical closet using dedicated wired Ethernet connections.

Control signal transmission method – Control signals from multi-sensors and switches to the control system gateways were wireless using a proprietary protocol. Therefore, no additional control wiring was run through the plenum.

Zoning – Along the east façade, two fixtures were grouped together and controlled based on occupancy and daylight availability. On the north side, each individual fixture was controlled based on occupancy and daylight availability.

Control configuration – The owner requested that the lighting control system be configured to meet the sequence of operations defined by the lighting designer (see Appendix B). The actual configuration implemented by the manufacturer during the commissioning phase was as follows:

During the work day in the open area (which constituted all of the space in the G4 Area), both the up and downlights in each occupancy zone were turned on to the defined setpoint illuminance level. If there was sufficient light detected by the photosensor, the up- and downlights in the daylit zones were dimmed in response to daylight availability. When unoccupied, lights were first dimmed down then shut off after a 15-min delay.

During after hours (weekday nights, weekends, and holidays), the lights were operated the same way as during the work day.

During both the work day and after hours, the emergency fixtures were operated in the same way as the regular fixtures.

3.5. Description of Automated Shades

3.5.1. Reference floor shading system

On the reference floor and on the test floor in Areas G1 and G4, automated roller shades were installed with the original building. Each shade band was about 10 ft wide and 9.5 ft high, spaced about 7 inches inboard from the interior face of the window glazing, and lowered by a tubular motor mounted in a cove 11 inches above the ceiling plane. One side edge of the shade was pocketed behind the column while the other side edge was spaced 0.75 inches away from the center vertical window mullion. Two shade bands were placed side-by-side in each 20-ft wide window bay and a single motor was used to control both shades. The shade cloth was a broken twill grey shadecloth (Mechoshade series 6429, Dove Grey, 3% openness factor) with the light side of the fabric faced indoors and the dark side faced toward the outdoors.

The shade motor was a 120 VAC-operated Electronic Drive Unit (EDU) mounted directly within the roller of the shade (MechoSystems ICON 506 – 6Nm, 34 rpm). Motors were controlled through an EchelonTM NeuronTM free topology (FTT10) based communication and control network which operated at 78 kbps over a two-twisted pair backbone (low voltage power, network). Each motor was individually addressable as well as supporting up to nine different levels of group addressing. Motors were wired to a 2-motor splitter in order to connect to the network which was connected digitally to the main supervisory control system (MechoSystems SolarTrac Infinity, version 3.5). Motors were sound rated for no greater than 47 dbA per manufacturer’s specification.

Sensors measuring global horizontal irradiance (5 times/minute) were installed on the roof of the building. Indoor photosensors with a 148° horizontal viewing angle and -17° to +53° vertical viewing angle were ceiling mounted in the cove at the interior face of the window glazing and within 3-4 inches down from the top of the window head.

All shade motors along the length of a façade in the open plan areas were grouped and controlled to the same height. Six discrete shade heights were pre-programmed in the system: fully raised, 4 intermediate heights, and fully lowered (Table 5).

Table 5. Shade heights for the reference floor shading system.

position	height above sill (inches)	height above floor (inches)
0	107	117
1	85	95
2	64	74
3	43	53
4	21	31
5	0	10

The shade control system used a combination of sensor inputs, computations, and schedules derived from a virtual 3D model of the building and urban surroundings to control the shades.

Direct sun, glare, and daylight control logic –

The sun was determined to be obscured by cloud cover using solar irradiance data from a pyranometer on the roof and comparisons of that data to modeled radiation levels for ASHRAE clear sky conditions.

If the sun was unobscured, then:

1) The "total solar load" was calculated. If this solar load was less than a specified threshold level (25 Btu/ft^2 in this case), then the shades were not adjusted.
2) If the solar load was equal to or greater than the threshold level, then the shades were adjusted to an optimum position to control solar penetration to a specified depth of penetration (3 ft from the shade at floor level) to maximize daylight and eliminate direct solar radiation on the occupants.
3) If the window brightness (the vendor's equivalent of discomfort glare) exceeded the light level threshold detected by the window sensor (3500 lux), then the shades were moved to the next lower position to control window brightness.

If the sun was obscured (conditions were cloudy or the sun was not in the plane of the window or if the sun was in the plane of the window but the window was shaded by an exterior obstruction (e.g., adjacent building)), then:

1) If the window brightness exceeded the light level threshold detected by the window sensor (3500 lux), then the shade was positioned to an intermediate height (position 3, 53 inches above finished floor).
2) If the window brightness did not exceed the light level threshold, then the shades were fully raised.

In the case of the curved façade, the façade was divided into three separate zones (with aa corresponding solar orientation and view for each zone) and shades in each zone were controlled independently.

Scheduled control logic –

- During weekdays, the shades were fully raised at sunset then later in the evening, the shades were set to "sleep" mode and fully lowered to reduce light pollution of the night sky and improve thermal insulation at night. From October to April, the shades were lowered at 8 PM. From April to October when sunsets occur later in the day, the shades were to be lowered at 9 PM. Changes in schedule, however, were made in consultation with the owner and the April 2016 sleep mode was not put in to effect. At 6 AM, shades were set to “wake” mode where all shades were fully raised.

- During weekends, shades were fully lowered at 6 PM and raised at 6 AM. The regular automatic mode was in effect between 6 AM and 6 PM thereafter.

Manual control – No manual override switches were installed in the open plan areas. Override of the automatic system in these areas was accomplished via phone request to the facility manager. Manual keypads were installed in the perimeter private offices in Area G1 of the test floor. When overridden, shades were returned to the automatic mode of control either when sunset, sleep, or wake modes went into effect.

Response time of shades – Shades were lowered within 10 seconds (brightness) or 55 seconds (cloudy to clear skies) when direct sun or glare was detected. Shades were raised after a 15 min (clear to cloudy skies) or 10 min (brightness) delay after direct sun or glare was no longer detected.

3.5.2. Test floor shading systems

In Areas G1 and G4 on the test floor, the existing, pre-retrofit shading system was the same as the reference floor (Table 6).

Table 6. Location of existing and new shades on the reference and test floors.

Area	Reference floor	Test floor
G1	Existing	Existing
G2	Existing	New
G3	Existing	New
G4	Existing	Existing

In Areas G2 and G3 of the test floor, a new, alternate automated shading system (Lutron Hyperion Solar Adaptive System) was installed to evaluate both the effectiveness of a more densely woven fabric to control glare at the west façade and to investigate the operational characteristics and performance impacts of a different control system.

The physical set-up of the shades was identical (same size shade and installation details) to that of the reference floor with the exception that the shade cloth was more densely woven on the west façade. To the degree possible, the fabric color was matched to the existing reference shades. In Area G2 facing west, the new test fabric had a 1% openness factor (Lutron S0207-E-1, SheerShade, E Screen 1% white/pearl). In Area G3 facing east and south, the test fabric had a 3% openness factor (Lutron S0207-E-3, SheerShade, E Screen 3% white/pearl) which matched the openness level of the reference shade.

The shade motor was a 24 V low-voltage powered electric tubular motor mounted directly within the roller of the shade (Lutron Sivoia QS, 2.5” aluminum). Each 10 ft wide shade band had its own motor, so none of the shade bands were coupled. Motors were sound rated for no greater than 44 dbA measured 3 ft from the tubular motor's electronic drive unit. Each motor had its own ac-to-dc power converter so that all shades on a single façade could be adjusted simultaneously. Power and communications were supplied with a 4-conductor twisted/ shielded pair to each motor.

Motors (and the dimmable lighting in Area G3) were connected to the main supervisory control system (Quantum Hub) via a proprietary network (QS Shade Link). Each shade was digitally addressable. The control system could be linked to the owner's building management system (BMS) via BACnetIP and linked to its server for configuration, display, and evaluation of the system's performance over the corporate intranet network.

One sensor (Lutron Radio Window Sensor, LRF2-SSW) measuring illuminance was installed on the transparent face of the window for each window orientation in each of the areas. Sensors were installed at a height of about 9 ft above the floor and about 1 ft from the jamb of the window. The sensors were battery powered (estimated 7-10 year battery life) and communicated wirelessly via radio frequency with receivers located on the ceiling.

All shade motors along the length of a façade in the open plan areas were grouped and controlled to the same height. Shade heights were programmed to be continuous between a 0-100% range of control (100% is defined as fully raised). In other words, the shade height could be set to anywhere within the height of the window. Manual override of individual shades was possible but the switches were accessible only by the facility managers.

The shade control system used a combination of sensor inputs, computations, and schedules to control the shades.

Scheduled control –

- From 5 AM to sunset, automated control (direct sun, brightness, or daylight modes) was active.
- When activated at 5 AM, the shades were automatically adjusted to the lower of the direct sun or "visor" (50% of full height or 4.5 ft above the floor) positions.
- The "visor" position was defined by the manufacturer as:
  - the horizon line of sight for occupants in the space;
  - the height of the shade where contrast from a bright sky is blocked without further impacting view or daylight availability; and,
  - the position that accounts both for direct sun glare and bright sky glare conditions.
- From sunset to 5 AM, shades were inactive – shades were fully raised at sunset every day to enable unobstructed views to the outdoors then not adjusted until 5 AM the following day.
- The vendor explained the reason for the lowered shade even before sunrise (and before sunset): around sunrise, it is very difficult to determine if it is a bright cloudy or bright sunny morning; a bright sunny morning will still cause glare even at low light levels; as the sun gets higher in the sky and it becomes easier to differentiate between cloudy and sunny conditions (about 1 hour after sunrise and 1 hour before sunset), control enters into the fully automated mode.

Daylight control – When in automatic mode, if the window sensor reading was lower than the "dark" threshold of 150 fc, the shades were fully raised (after a user-defined delay).

Brightness control –

- If the window brightness measured by the window sensor was between the dark and "bright" threshold, then the shade was positioned to the lower of the direct sun and visor positions.
- Brightness override: If the window brightness measured by the window sensor was greater than the bright threshold, then the shade was fully lowered.
- The visor position is defined by the end user, which at the LL site was set to 50% or 4.5 ft above the floor.
- The bright threshold was set to 2000 fc on the west and south facades and 5000 fc on the east façade.
- The shades were always adjusted to reduce window brightness without delay.

Direct sun control – Sunlight penetration was controlled to a maximum depth of 14 inches from the window at a height of 29 inches above the floor. The presence of direct sunlight in the space was determined by a combination of data from the window mounted sensor and calculations of solar position relative to the building. The direct sun control mode was in effect when the sensor signal was above the dark threshold value and when the sun was in the plane of the window.

The definition of "maximum depth" differed from the shading system in the reference zone. Since the depth is defined at desk height, direct sun is permitted to penetrate further than 14 inches at heights lower than desk height. If the shade is fully raised (system assumes a maximum shade height of 108 inches), then the maximum depth of sunlight penetration at floor level would be 19 inches. If the shade is at a height of 30 inches above the floor, then the maximum depth of sunlight penetration at floor level would be 35 ft. The sun angle for this depth would be very low (near sunset) and sunlight would be incident on the lower portion of an occupant seated next to the window.

Manual control – No manual override switches were installed in the open plan areas. Override of the automatic system in these areas was accomplished via phone request to the facility manager. When overridden, shades were returned to the automatic mode of control at sunset. (The manufacturer indicated that wireless manual override switches could be added later in the project, if so desired.)

Response time of shades – At the beginning of each day, shades were lowered when direct sun or glare was detected and thereafter shade movements up or down were limited to no more than once per hour.

3.6. M&V Test Plan

The M&V phase of this study evaluated the energy performance and end user comfort, acceptance, and satisfaction with the lighting and shading technologies and the resultant indoor environment.

- Lighting energy use was monitored for a 12-month period prior to the retrofit to assess comparability between the two parallel floors, one of which would serve as the reference floor while the other served as the "test" floor. Sub-metered areas within each floor did not match between floors because monitoring occurred at the circuit breaker level.
- Lighting energy use and other environmental conditions were then monitored simultaneously on both floors for another six month, solstice-to-solstice period following installation of the shading and lighting technologies on the Living Lab test floor. For the post-retrofit comparisons, the metered areas of the four quadrants on the reference and test floors were made to match exactly using metering at the sub-circuit level.
- Detailed measurements and site observations were made during visits that occurred during the winter and summer solstices and the equinox periods.
- Subjective surveys were issued on both floors at the end of the six-month, post-retrofit period.

Monitoring occurred over the following periods:

- Pre-retrofit monitoring — March 2014 to June 2015
- Construction and commissioning — June 2015 to November 2015
- Post-retrofit monitoring — December 2015 to June 2016
- Detailed site visits — October, January, March, July 2016
- Occupant surveys — Last two weeks of June 2016

The fenestration system affects both lighting energy use and window heat gains, the degree of which depends on the design of the façade (e.g., window type and size), outdoor weather conditions, internal load conditions, and the operating characteristics of the equipment. Performance impacts from these synergistic systems therefore cannot be decoupled and isolated to the two individual component technologies (i.e., shading and lighting). When results are presented, performance reflects the impacts of both of these technologies.

3.6.1. Baseline conditions

With these technological advancements, energy use due to facades and lighting is expected to be reduced significantly compared to standard practice, where standard practice in office buildings uses manually operated shades and overhead fluorescent lighting that is switched on or off based on scheduling and in some cases (such as private offices) based on occupancy. Field studies have characterized the use of manually-operated shades: occupants tend to lower the shades when uncomfortable and then not readjust the shades thereafter for weeks or months at a time, reducing daylight in the remainder of the perimeter zone.

In both of the buildings investigated in this study, the existing shading and lighting control systems were not following standard practice. The buildings were occupied in 2008-2009 and both had LEED ratings (Platinum or Gold). In the case of the LL building, the lighting control system included large-area occupancy-based controls in the open plan office areas in addition to scheduling and daylight dimming within the "primary" zone (in this case, the first 10 feet from the window). It also included automated shading.

Results in this study therefore were determined for two baseline conditions: a) standard code-compliant practice (scheduled lighting controls only, based on the ASHRAE/ IESNA Standard 90.1-1999 to which the buildings were built), and b) existing conditions, which has a lower energy use intensity than code. Since the installed lighting power density and control requirements for offices (open plan) did not change between ASHRAE 90.1-1999 and ASHRAE 90.1-2007, savings for the first baseline condition are applicable to commercial office buildings built to these standards. And because daylighting was not required by these standards, manual shade operations (which influence daylight admission) had no impact on lighting energy savings.

Compared to the code-compliant baseline, the incremental difference in energy use between the ASHRAE Standard 90.1-1999 and the Living Lab test floor with new installed technologies were due to:

- Reduction in installed lighting power density due to the use of LEDs versus fluorescent lighting sources, number of lamps per fixture, and increased fixture efficiency;
- Reduction in minimum dimming and standby power use between LED drivers and fluorescent dimming ballasts;
- Addition of high-resolution occupancy-based controls;
- Reduction in nominal illuminance setpoint from 50 fc (538 lux) to 25-30 fc (270-323 lux) in all zones (actual setpoint differed from these values);
- Addition of daylight-responsive control of the dimmable electric lighting system throughout the entire Area and increase in daylight admission due to the automated shades;
- Reduction in heat gains from the pendant lighting fixtures due to changes in hardware and controls, which reduced cooling energy use and potentially raised heating energy use; and,
- Reduction in fabric openness on the west façade (Area G2) and change in shade control, which reduced cooling energy use and potentially raised heating energy use.

Compared to the existing conditions, the incremental difference in energy use between the reference floor with dimmable fluorescent lighting and automated shading and the Living Lab test floor with more advanced LED lighting and a different automated shading system were due to:

- Reduction in installed lighting power density due to the use of LEDs versus fluorescent lighting sources, number of fixture, and changes in fixture efficiency (same as the code-compliant baseline);
- Reduction in minimum dimming and standby power use between LED drivers and fluorescent dimming ballasts (same as the code-compliant baseline);
- Addition of high-resolution occupancy based controls (resolution of approximately 100 ft^2 per zone) versus occupancy based controls that switched lights off in an entire area; differences in patterns of occupancy between the reference and test floors, however, are included in this impact;
- Reduction in illuminance setpoint from 50 fc (538 lux) to 25-30 fc (270-323 lux) in all zones (same as the code-compliant baseline);
- Addition of daylight-responsive control of the dimmable electric lighting system in the entire perimeter zone (40 ft deep) versus the first 15 ft from the windows, including differences in the efficiency and control of the two systems;

- Difference in the amount of daylight and solar heat gains admitted by the different automated shades in test Areas G2 and G3 compared to the existing automated shades, and therefore differences in both lighting and HVAC energy use; and,
- Reduction in heat gains from the pendant lighting fixtures, which will affect HVAC energy use (same as the code-compliant baseline).

Note that results are given for different combinations of lighting and shading technologies in each area. Each of these areas on the floor has different orientations relative to the sun. Therefore, the results for each quadrant or test area are not directly comparable with each other. Savings of 40% on the northeast quadrant versus savings of 20% in the southwest quadrant does not mean that the technologies in the northeast area performed better than the southwest area.

Differences in visual and thermal comfort and indoor environmental quality (interior brightness, access to view, etc.) were due to the combination of different lighting sources, fixture output distributions, lighting control patterns, shade fabric density, shade operations, and potential changes in HVAC operations due to changes in shade and lighting control patterns.

3.6.2. Confounding factors

Reported savings relative to the existing conditions on the parallel floor with the same orientation (i.e., solar and daylight exposure) were assumed to have similar occupancy patterns and exposure to daylight. In most of the areas, use of the spaces was nominally the same. There were differences: in the G1 area, there were private offices at the window wall on the Living Lab test floor that were not replicated on the reference floor; in the G4 area, there was a conference room on the reference floor instead of open plan offices. These differences were evaluated in a pre-retrofit monitoring phase that occurred for a year prior to the installation and are discussed in Section 4.1.1.a.

The study was conducted in a "Living" Laboratory – that is, a fully occupied office building. The owners did their best to maintain the same conditions over the course of the study both for the year before and the six months after the installation of the new technologies so the differences in performance could be isolated to the new technologies. Physical changes to the space that would affect daylighting or occupant response to the indoor environment were kept to a minimum (e.g., installation of demising walls, change in furniture layout, paint color, changes in computer monitor size or brightness, HVAC supply air temperature, etc.).

There were other uncontrolled variables, such as lack of physical separation between the test floor areas and changes in the location of occupants. These are discussed in detail in the applicable sections of the report.

3.6.3. Measured data

3.6.3a – Lighting energy use

Lighting energy use was determined using a combination of measured current and voltage at the circuit level and in the ceiling at the sub-circuit level. Metered lighting circuits were matched between the reference and test floors to the extent possible so that energy use per floor area could be matched for zones that have exposure to approximately the same daylight conditions. For the areas covered by the circuits that did not match the same areas between floors, metering at the sub-circuit level was conducted to obtain energy data for the non-coincident areas. Energy data were presented either as an annualized energy use intensity (EUI) or as an average energy use or power draw over an hourly basis. The annualized value was derived from the six-month monitored data using a simple ratio of monitored to 365 days/year and where sky/ cloud cover conditions were assumed to be similar between the two solstice-to-solstice periods.

Monitored data provided a total energy use value. In order to determine savings by lighting control strategy, dimming status data were required for each fixture along with sensor data and the exact control sequence of operations for each zone. Because remote access to the lighting control servers was not permitted by the owner, the manufacturers did not provide LBNL with this information and data. Instead, incremental savings on weekdays were estimated for a) the increase in source and fixture efficacy from fluorescent to LEDs (assuming an 18 hour schedule per weekday), b) setpoint tuning, and c) occupancy and daylighting controls. The loading order of computing the savings affects the percentage savings attributable to each incremental change in hardware and software. For example, if savings due to occupancy were first computed, then savings due to setpoint tuning would be less. Therefore, in the results presented in Section 4.1.1, it is important to note that while the total percentage savings is accurate, the incremental savings per strategy is approximate.

To determine energy savings due to the change from fluorescent to LED fixtures, we needed to determine the energy consumption level when all lights were turned on and set to produce the reference area's average light level in each of the test areas. Unfortunately, LBNL was not permitted to change the commissioned lighting control systems on the test floor to match the reference floor light level. Therefore savings due to the changes in source and fixtures were determined indirectly. Monitored energy data for each test area and the corresponding electric light level (e.g., 0.285 W/ft^2 produced 248 lux in test Area G2) were available. The average maximum power use was determined from monitored data taken during late afternoon hours during the winter when full occupancy and low daylight levels occurred. The average test area's electric light level was measured using a hand-held illuminance sensor during site visits. Assuming a zero intercept (power use and light output are both zero), we generated a linear fit to these two data points then extrapolated the power use needed by the test area's lighting system to produce the reference light level (i.e., 517 lux average illuminance). Weekday test area energy use was computed using this extrapolated value, assuming an 18 hour period per day when the lights were turned on, then compared to the monitored reference area energy use. This calculation method made the simplifying assumption that the relationship between LED power use and workplane illuminance is linear (it is a better fit with a quadratic equation), ignoring the variety of combinations of direct and indirect light output that could be used to produce the average illuminance at the workplane.

To determine energy use savings due to the reduction in average light in the reference area of 517 lux to the light levels in each of the test areas, we used the same measured data used to determine LED savings: The average maximum power use was determined from monitored data taken during late afternoon hours during the winter when full occupancy and low daylight levels occurred. The average test area's electric light level was measured using a hand-held illuminance sensor during site visits. Weekday test area energy use was computed assuming an

18 hour period per day when the lights were turned on, then compared to the reference area energy use.

To determine energy use savings due to daylight and occupancy-based controls, the monitored test area lighting energy use was used directly.

3.6.3b – HVAC energy use

HVAC energy use was not metered. The LL building did not have thermally isolated zones between the test areas since it had an open plan floor plan; metering would not have yielded conclusive results. Estimates of HVAC energy use impacts were derived analytically as described in Section 4.3.1. Additional results from prior simulation studies and full-scale field studies are reported in Section 4.3.

3.6.3c – Lighting controls

Analysis of the lighting control system did not rely on data from the lighting control vendors' building management system. These data varied in resolution, its definitions between vendors, and were not available for the full period from all vendors. When available, the data were used to confirm that the system was operating as intended and to evaluate transparency and ease of use for running diagnostics and evaluating performance from the facility management's perspective. Lighting control system performance was evaluated using the metered lighting energy use data, illuminance sensor data, complaint logs from the facility management team, and through occupant surveys.

Lack of high resolution, fixture by fixture control data prevented an independent evaluation of how and why the system controlled the lighting. Scheduling of special tests needed to disaggregate daylight from electric light contributions to workplane illuminance was also unsuccessful: in the end, the owner did not permit these tests to go forward due to concerns about potential negative impacts on employees working long hours on the floors. These tests would have provided the critical data on how much daylight was actually available in the space and whether the lights and shades were working as intended to fulfill daylighting objectives.

3.6.3d – Shading controls

Analysis of the shading control system did not rely on data from the shading control vendors' building management system. Similar to the lighting system, these data were not available for the full period from both vendors. When available, the data were used to understand how the system was operating and to evaluate transparency and ease of use for running diagnostics and evaluating performance from the facility management's perspective. Shading control system performance was evaluated using sensor data related to comfort, complaint logs from the facility management team, and through occupant surveys.

3.6.3e – Thermal comfort

Continuous measurements

Environmental variables relevant for thermal comfort were measured in each of the four quadrants on the reference and test floors (Figure 6). Sensors were located at a distance of 2.4-3.0 ft from the indoor face of the window glazing and a distance of 4.13-4.27 ft above the floor. The sensors were aligned with the vertical window mullion, which was 8.75 inches wide. Measurements consisted of room dry-bulb air temperature (DBT), mean radiant temperature (MRT), relative humidity, and air velocity. The MRT sensors were never exposed to direct sunlight, but were exposed to filtered direct sunlight transmitted through the automated shades. The DBT sensors were shielded completely from direct and diffuse sunlight. Swirl diffusers were located 6-7 ft away and did not influence the readings. All measurements were sampled and recorded at a 1-minute interval over the entire six-month monitoring period.

Figure 6. Air velocity and MRT sensors mounted on the spline between work surfaces.

These data were used to compute several indices related to thermal comfort [Fanger, 1970]:

- predicted mean vote (PMV) – provides information on how occupants will perceive the space's thermal conditions (values range from -3 to 3; values of -3, -2, -1, 0, 1, 2, 3 imply the space being perceived as "cold", "cool", "slightly cool", "neutral", "slightly warm", "warm" and "hot", respectively), and,
- predicted percentage of dissatisfied (PPD) – represents the percentage of people who would be dissatisfied with the thermal conditions in the space.
- Occupants were assumed to be sedentary, seated and performing computer-based tasks (metabolic rate (met) = 1.1). Occupants were also assumed to be wearing a long-sleeve shirt, pants, socks, shoes, and underwear with a clo value of 0.61 (summer) or a clo value of 1.0 (mild winter) with the addition of a light jacket or sweater.
- Target values between -0.5 and 0.5 for PMV and below 20% for PPD meet the ASHRAE 55 Standard for thermal comfort [ASHRAE 55, 2013].

Infrared imaging

Infrared (IR) images were captured near the window wall to evaluate in detail the thermal environment at the perimeter. Measurements were taken with a FLIR SC660 infrared camera using a microbolometer focal plane array sensor with 640x480 pixels [FLIR 2016]. The sensitivity of the sensor is less than 0.03°C. The infrared camera was fitted with a 45° opening angle lens allowing it to measure a relatively wide subject area from a limited distance. IR images were collected at 10-minute intervals over the course of a work day during periodic site visits.

Occupant surveys

Thermal comfort was also assessed using survey data. The survey contained questions about temperature sensitivity and degree of thermal comfort. Survey data that indicated a statistically significant difference in levels of comfort between the reference and test areas were deemed to be conclusive (i.e., $p<0.05$) for this evaluation.

3.6.3f – Visual comfort

Field-of-view luminance measurements

Hemispherical field-of-view luminance measurements were taken during periodic site visits. Measurements were taken at seated eye height 4 ft above the floor, 4.5 ft from the window both parallel and perpendicular to the window in each of the four quadrants on the test floor over the weekend.

Measurements were made using commercial-grade digital cameras (Canon 60D) equipped with an equidistant fisheye lens (Sigma Ex 4.5 mm f/2.8). Bracketed low dynamic range (LDR) images were taken automatically at 10-min intervals with a fixed f-stop of 5.6 using in-house modified software (*hdrcaposx*). Four to seven images were taken per time interval depending on the brightness of the scene. A lesser number of bracketed images were taken at low light levels to avoid excessively long exposures.

Table 7. Suggested definition of daylight glare comfort classes [Wienold 2009].

Max DGP of 95% of period		Avg DGP of 5% of period	Class	Meaning
≤ 0.35 imperceptible		≤ 0.38 perceptible	A	Best
		> 0.38	B	Good
≤ 0.40 perceptible		≤ 0.42 disturbing	B	Good
	and	> 0.42	C	Reasonable
≤ 0.45 disturbing		≤ 0.53 intolerable	C	Reasonable
		> 0.53	Discomfort	Discomfort
> 0.45 disturbing		> 0.53	Discomfort	Discomfort

The LDR images were compiled into a single high dynamic range (HDR) image using the *hdrgen* tool. The camera response function was determined by the software. The vignetting function of the fisheye lens was determined from prior laboratory tests at LBNL. A vertical illuminance measurement was taken adjacent to each camera's lens, immediately before and after the bracketed set of images, and used in the *hdrgen* compositing process to convert pixel data to photometric data.

These HDR images were used to assess discomfort glare from daylight and identify glare sources within the field of view. The Daylight Glare Probability (DGP) index relies on high resolution, field-of-view HDR luminance images to assess glare. The index was derived through a comprehensive statistical analysis of HDR data and subjective response in a full-scale private office testbed that was retrofit with a variety of daylighting measures [Wienold & Christoffersen, 2006]. DGP was calculated using the *evalglare* software [Wienold, 2012] and default software settings.

The DGP does not reflect the magnitude of glare perceived by the observer. Instead it gets around the problem of person-to-person variability in response to perceived glare by estimating the probability that a person is "disturbed" by glare (the DGP formulation defined "disturbed" based on the subject rating the daylight glare source to be "disturbing" or "intolerable"). Wienold derived a method to account for the frequency of glare over a time period, where within a defined category of comfort, 3-5% exceedance of a threshold limit is allowed. Glare ratings ranging from "imperceptible" to "intolerable" were related to DGP values in a descriptive one-way analysis of the study's user assessment data. Discomfort glare classes were defined based on these ratings (Table 7).

Occupant surveys

Visual comfort was also assessed using survey data. The survey contained questions about glare sensitivity and degree of visual comfort. Survey data that indicated a statistically significant difference in levels of comfort between the reference and test cases were deemed to be conclusive (i.e., $p>0.05$) for this evaluation.

Figure 7. Workplane illuminance sensors mounted on the spline between work surfaces.

3.6.3g – Interior illuminance levels

Measurements of illuminance on the workplane, **Iwp**, were taken at night during periodic weekend site visits using a handheld photometric sensor. All lights were turned on for at least 15 min prior to the measurements.

Interior horizontal illuminance, **Iwp'**, was also measured at 1-min intervals over the six-month period using photometric sensors (Li-Cor LI-210) located on the partition spline of the workstation desks at a height of 4.3 ft above the floor (1.8 ft above the desk), perpendicular from the window, and at distances of 2.5, 9.9, 17.2, and 24.5 ft from the window (Figure 7). This sensor location was above all equipment on the desk.

The difference between measurements taken 1.8 ft above the desk versus at desk level was approximately 17- 27 lux (at night).

3.6.3h – Occupant response

Occupant surveys were designed to enable a between-subject (reference versus test floor) and within-subject analysis (before and after the retrofit), where occupants were issued the survey in late June 2016 after the retrofit had been completed. The survey posed questions about the shading and lighting systems, visual and thermal comfort, indoor lighting quality, access to views, and general satisfaction with the space and technologies. The survey and protocol for its issuance were developed in collaboration with BEEx and the owner. Survey length was kept to a minimum in order to minimize disruption and maximize participation. The survey questionnaire and protocol are given in Appendix D.

For both the lighting and shading systems, occupants did not have the ability to override the controls. A log of occupant complaints and changes to the control systems was maintained by the facility managers and conveyed to the analysis team.

4. MONITORED RESULTS

4.1. Performance of Advanced Lighting Controls

4.1.1. Lighting energy use and peak demand

4.1.1a – Comparability between reference and test floors

Prior to the installation of the new technologies, lighting energy consumption measurements were performed on the test and reference floors in order to establish an energy use baseline and assess comparability between the two floors. A detailed analysis assessing comparability in lighting energy use between the two floors is given in Appendix C.

The conclusion from this analysis was that deviations in energy use between the two floors were generally within acceptable limits. Differences in energy use between floors were attributed primarily to operating lighting power density and differences in patterns of evening occupancy. The operating LPD was viewed as an inherent property of the existing lighting system. In the post-retrofit case, the difference in in LPD between the reference and test floors was normalized to the same workplane illuminance level. Differences in occupancy could not be attributed to a specific quadrant given the limited available data. However, occupancy tended to be higher on the test floor so estimated savings from the post-retrofit period are conservative if the same patterns of occupancy continued on the two floors.

4.1.1b – Interactions between test floor areas

Because the test floor layout was open plan, there was no physical separation between adjacent Areas G1 and G2 on the west side or between Areas G3 and G4 on the east and north sides of the floor. This lack of physical separation was estimated to have negligible impacts on the data as follows:

- Daylight dimming was not implemented in Area G2; its electric light would positively affect the daylight savings in Area G1, but given the low sensitivity settings of the G1 lighting control system to daylight, this impact on G1 lighting energy was estimated to be negligible.
- Daylight dimming was implemented in Areas G3 and G4.
    - In the case of Area G3, the control system used input from an open-loop ceiling-mounted photosensor near the window that was not influenced by the electric

lights in Area G4 so the impact on lighting energy use was estimated to be negligible.
   - In Area G4, light from the G3 area did affect operations of the first row of two G4 fixtures, but given the size of the G4 area, the effect on energy results was estimated to be negligible. In addition, since the automated shades control the depth of direct sun penetration into the space, the impact of daylight from adjacent areas was estimated to be minor.

4.1.1c – Setpoint and actual workplane illuminance due to the electric lights

Reference floor

Setpoint illuminance – The electric lighting system installed throughout the building was designed to provide 538 lux (50 fc) at the workplane (desk height of 2.5 ft above finished floor).

Actual workplane illuminance (Iwp) – Photometric measurements were made using a hand held sensor on workplane (desk) surfaces throughout the reference floor at night during periodic site visits. Workplane illuminance levels at night ranged from 275 to 719 lux depending on proximity to the light fixtures. On average, the actual workplane illuminance level was 517 ± 109 lux.

Test floor

Setpoint illuminance –As mentioned in Section 3.4.2, the electric lighting systems in each of the quadrants on the test floor were not designed to provide a specific illuminance level at the workplane. The lighting designer selected the highest light output offered by each vendor for the specified fixture types, allowing the owner to adjust up- and downlight output levels and visualize the impact on lighting quality throughout the space. Initially, vendors commissioned their systems to provide a workplane illuminance level of 215 lux (20 fc), except Area G4, which was set to 538 lux (50 fc). In February-March 2016, the systems were adjusted to 269 lux (25 fc) on all areas on the test floor (Table 8). The period before this change is called “period 1” and the period after the change is called “period 2” in the analysis below.

Actual workplane illuminance (Iwp) – Similar to the reference floor, handheld photometric measurements were taken at the workplane in Areas G2-G4. Average illuminance levels in each area and for the two periods, before and after the setpoint change are given in Table 9. All measurements were taken during site visits on weekends. In the G1 test area, LBNL could not measure nighttime electric lighting levels due to limited site access on weekdays and the atypical control sequence during weekends (only the downlights were turned on). To determine workplane illuminance levels due to the electric lights during weekday hours, we used illuminance sensor data (Iwp’) at 17.2 and 24.5 ft from the window to compute average illuminance, when occupancy levels were likely to be high and all up- and downlights were likely to be turned on.

Table 8. Test dates for the two different setpoint illuminance levels on the test floor.

Area	Period 1 (p1)	Period 2 (p2)
G1	Dec 1 to Mar 1	Mar 2 to Jun 30
G2	Dec 1 to Feb 10	Feb 11 to Jun 30
G3	Dec 1 to Feb 26	Feb 27 to Jun 30
G4	Dec 1 to Feb 5	Feb 6 to Jun 30

Table 9. Setpoint and average workplane illuminance, Iwp (lux), due to electric lights.

Area		Iwp for period 1 (lux)		Iwp for period 2 (lux)	
		setpoint	avg ± stdev	setpoint	avg ± stdev
Ref	All	538	517 ± 109	538	517 ± 109
Test	G1	215	263*	269	276*
Test	G2	215	153 ± 22	269	248 ± 22
Test	G3	215	167 ± 49	269	172 ± 15
Test	G4	538	517 ± 117	269	201 ± 54

Note: Iwp was measured using a handheld illuminance sensor on desk surfaces throughout the reference area and G2-G4 test areas at night.
* G1 test area values are average sensor illuminance, Iwpi', for the two installed photometric sensors located 17.2 and 24.5 ft from the window.

4.1.1d – Dimming power profile

Dimmable fluorescent lighting

For older dimming fluorescent ballasts, the typical power dimming range is about 35-100% of full power, with a standby power consumption when "off" of 2-4%, and 0% power when turned off by relay. An example of this relationship is given in Figure 8 for a common 3-lamp T8 fixture (T5 lamps exhibit a similar relationship). Minimum and standby power levels are important because if the dimming lighting control system has a high minimum power, then the energy savings potential for daylighting strategies can be significantly less, particularly when daylight levels are sufficient to satisfy the setpoint illuminance level.

In the case of the LL building, the dimming ballasts had a design power dimming range of 18-100%. Actual fixture power consumption was not measured.

Dimmable LED lighting

The minimum power for LED lighting prior to off is significantly lower than that of fluorescent ballasts. To verify this, the dimming power characteristics for the test floor lighting systems in Areas G1 and G4 were measured on the bench at LBNL. Fixtures and controls for the test floor G2 and G3 systems could not be obtained.

The LED sources were shipped by the vendor with the up- and downlight drivers installed in the fixtures for testing. The control voltage was stepped down incrementally every 15 minutes, allowing the temperature of the source to stabilize prior to measurement. The power-to-control voltage relationship is shown in Figure 9.

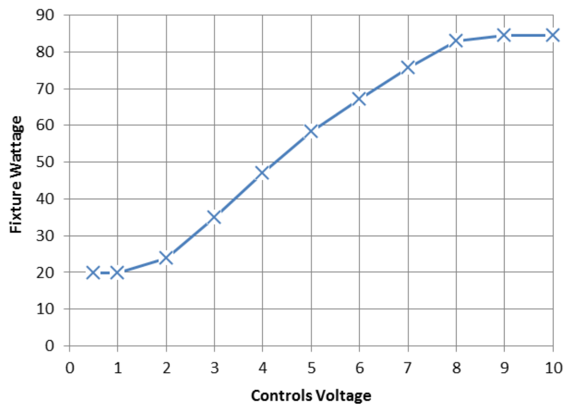


Figure 8. Power consumption (W) profile of a 3-lamp T8 fixture with a 0-10 V dimmable ballast (2015 equipment).

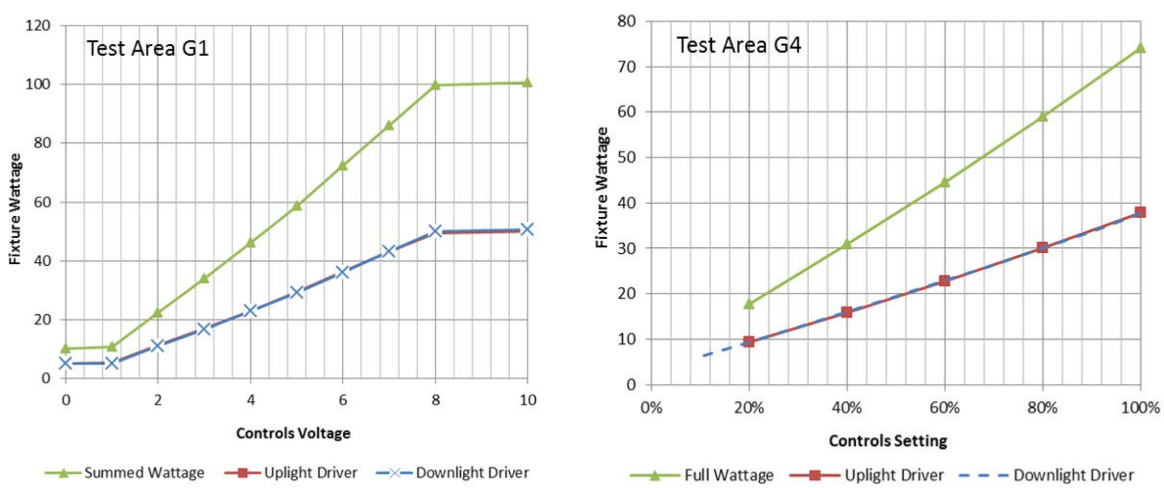


Figure 9. Power consumption (W) profile of the test Area G1 dimmable LED lighting system (left) and Area G4 dimmable LED lighting system (right).

Power consumption of one G1 5 ft LED fixture measured on the bench was as follows:

- The downlight component of the fixture used 5.14-50.6 W over a 0-10 V control range. The minimum power of 5.14 W was 10.2% of full power.
- The uplight component of the fixture used 5.23-50.0 W over a 0-10 V control range with a 10.5% minimum power.

- The total power consumption was 10.4-100.6 W per fixture with a minimum power of 10%. The maximum power use was within 6% of the rated input power of 95 W specified by the fixture manufacturer.
- Standby power when the fixture was turned off by relay was less than a watt for associated control electronics.

Power consumption of one G4 5 ft LED fixture measured on the bench was as follows:

- The downlight component of the fixture used 6.3-37.7 W over the vendor's 10-100% control range. The minimum power of 6.3 W was 16.7% of full power.
- The uplight component of the fixture used 9.37-37.8 W over the vendor's 20-100% control range (the 10% control range was not measured).
- The total power consumption was 12.6-74.2 W per fixture over the 10-100% control range with a minimum power of 17.0%. The actual maximum power use was 76.5% of the rated input power of 97 W specified by the fixture manufacturer.
- Standby power when the fixture was set to the 0% control range was 0.93 W, which likely powered the radio communications with the network.

Note that the output light level (at the workplane) per unit power (lumens/W) was not the same between the LED or fluorescent fixtures. Differences in power use between the reference and test floors were due to the inherent differences in lighting efficacy or fixture power use per unit light level at the workplane over the full dimming range. The exact relationship could not be characterized at the LL site due to lack of access to actual dimming level or power consumption data on a per fixture basis.

4.1.1e – Area G1 (southwest quadrant)

The southwest quadrant (Area G1) provided a unique case between the four quadrants, where private offices were located along the curved west window wall and open plan offices were located on the interior. The private offices were separated from the open plan area by floor-to-ceiling clear glass partitions and doors, giving the open plan area behind them access to borrowed daylight from the windows and views to the outdoors. On the north end of the quadrant, there were no private offices so the open plan area extended to the window wall – a condition that was typical of the remaining quadrants.

In the perimeter private offices, automatic control of the roller shades could be manually overridden using a wall switch. The end user could set the shade to one of six heights and control would be returned to automatic mode typically at sunset. Shades in the open plan area in contrast were automated with no switch available for manual override.

The lighting control system had a flexible software topology, allowing photosensor(s) to be assigned to multiple fixture/ zones within the area, unique dimming factors to be assigned to each zone for each photosensor, and use of automatic nighttime commissioning tools to ensure proper control during the daytime. Daylight dimming was implemented in the private offices and in the open plan areas at the north end of the quadrant. The vendor set "dependency" dimming factors (d = 0.3, 0.2, and 0.1) for the single photosensor located near the window for each of the three rows of fixtures, with greatest dimming responsiveness assigned to the zone closest to the window. Daylighting was not implemented in the daylit open plan area behind the perimeter private offices.

Examination of both the vendor's control system data and the metered data indicated that the settings were commissioned conservatively – savings due to daylighting were low in the private offices and open plan zone closest to the large-area windows and in the areas further from the window. Figure 10 compares monitored lighting energy use of Area G1 to the same area on the reference floor for a sample week – note the classic downward bow shaped curve indicating the reduction in lighting energy use during the daytime due to daylighting (in the first 15 ft from the window) in the reference area. The test area demonstrated little change in energy use; dimming may have occurred in the afternoon hours for this west-facing orientation just prior to end of day reductions in occupancy. Figure 11 shows lighting energy use for each monitored day over the six-month period. The effect of daylight savings as daylight availability increased is evident in the plot with the reference case: energy use decreased from winter to summer. With the test case however, weekday energy use was fairly steady over the entire monitored period, indicating little sensitivity overall to changes in daylight availability.

Figure 10. Area G1. Monitored lighting energy use in the reference and test areas.
The reference area exhibited daylight dimming for this west-facing orientation in the afternoon and low-resolution occupancy controls provided shut-off of lighting once the entire zone was unoccupied (two separate business units operated within Area G1). There was potentially some daylight dimming towards the tail end of the day in the test area.

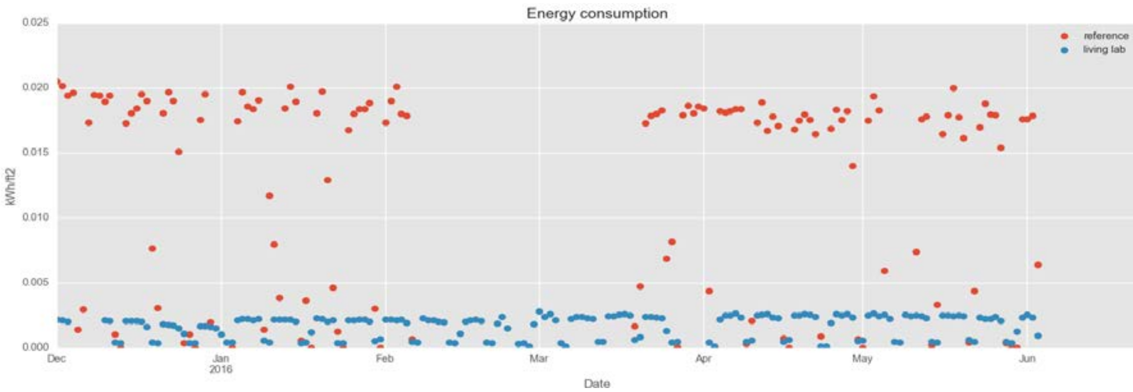


Figure 11. Area G1. Daily lighting energy use (kWh/ft^2-day) for the reference and test areas. Gaps in the data occurred due to problems with the wireless communications.

The manufacturer who commissioned the system offered an explanation for why daylighting was not implemented in the interior open plan area and why daylighting savings were minimal in the private offices and in the open plan areas next to the perimeter windows: the illuminance levels were already low and any deficiencies in lighting would likely cause occupant complaints. The manufacturer weighed the possible negative impacts on employee productivity against the energy savings and adjusted the system conservatively. In a prior field study in a full-scale testbed of the same G1 test area lighting control system, we found that the complex zoning strategies for up- and downlights could be implemented and correctly controlled for scheduling, setpoint tuning, occupancy, and daylighting [McNeil et al. 2014].

Table 10. Average workplane illuminance, Iwp (lux), due to the electric lights in Area G1 on the reference and test floors.

	October 2015		March 2016		June 2016	
Space type	Ref.	Test*	Ref.	Test*	Ref.	Test*
Perim private offices	N/A	130	N/A	180	N/A	167
Interior open plan	577	93	610	108	591	117
Perimeter open plan	477	86	532	76	476	83

* G1 test area values are for the LED <u>downlights only</u> on the weekend. Weekday levels with both up- and downlights could not be measured.

Table 11. Average sensor illuminance, Iwp' (lux), due to the electric lights and daylight in Area G1 on the reference and test floors, weekdays 9 AM to 3 PM.

	Oct-Nov 2015		Mar-Apr 2016		May-Jun 2016	
Space type	Ref.	Test	Ref.	Test	Ref.	Test
Interior open plan	614	263	600	276	577	291
Perimeter open plan	546	N/A	696	N/A	628	N/A

A significant share of energy savings was due to the change from fluorescent to LED lighting (see the next section on savings). These savings were estimated based on assumptions delineated in Section 3.6.3c. A second large reduction in energy use was due to setpoint tuning. Vendors were asked to tune their system to a setpoint illuminance level of 30 fc, reduced from the reference floor setpoint of 50 fc.

Occupancy-based controls also contributed to significant energy savings. Examination of hourly energy use patterns over the monitored period provides some insights into when these savings occurred (Figure 12). In the reference area, scheduled controls turned the lights on at 7 AM and off at around 7 PM (varied with business unit). Occupancy-based controls maintained lights on thereafter until each entire business unit area was vacated – from the plots, the entire floor was not vacated until about 1:00-1:30 AM the next day. During weekends, occupants were required to call the facility managers to request that the lights be turned on (in the entire business unit area) for a specified period. The lighting energy use pattern in the test G1 Area, in contrast, indicated that there was significantly less use outside of core weekday hours of 7 AM to 7 PM. When occupancy did occur, lights were turned on only in the areas where the occupant(s) were working with the remainder of the lights turned off. Lighting energy use in the test area during these hours reflected actual patterns of use. Note also that about a third of the test floor area were private offices, so savings due to use of the wall dimming switch (there was an abundance of daylight in these offices) or occupancy/ vacancy may have been greater (assuming that the individuals spent less time in their offices) than if the area had been open plan offices.

Operationally, the lighting designer specified delays and fade rates when switching the lights between different operational modes. According to the controls data provided by the manufacturer, power levels were reduced by about 50% six minutes prior to shutting the lights off, providing a gradual change in light level in the surrounding, potentially occupied areas. Lights were turned on within a fraction of a second upon entry into the occupancy zone. Occupant comfort and survey data regarding lighting system operations are given in Section 4.4.

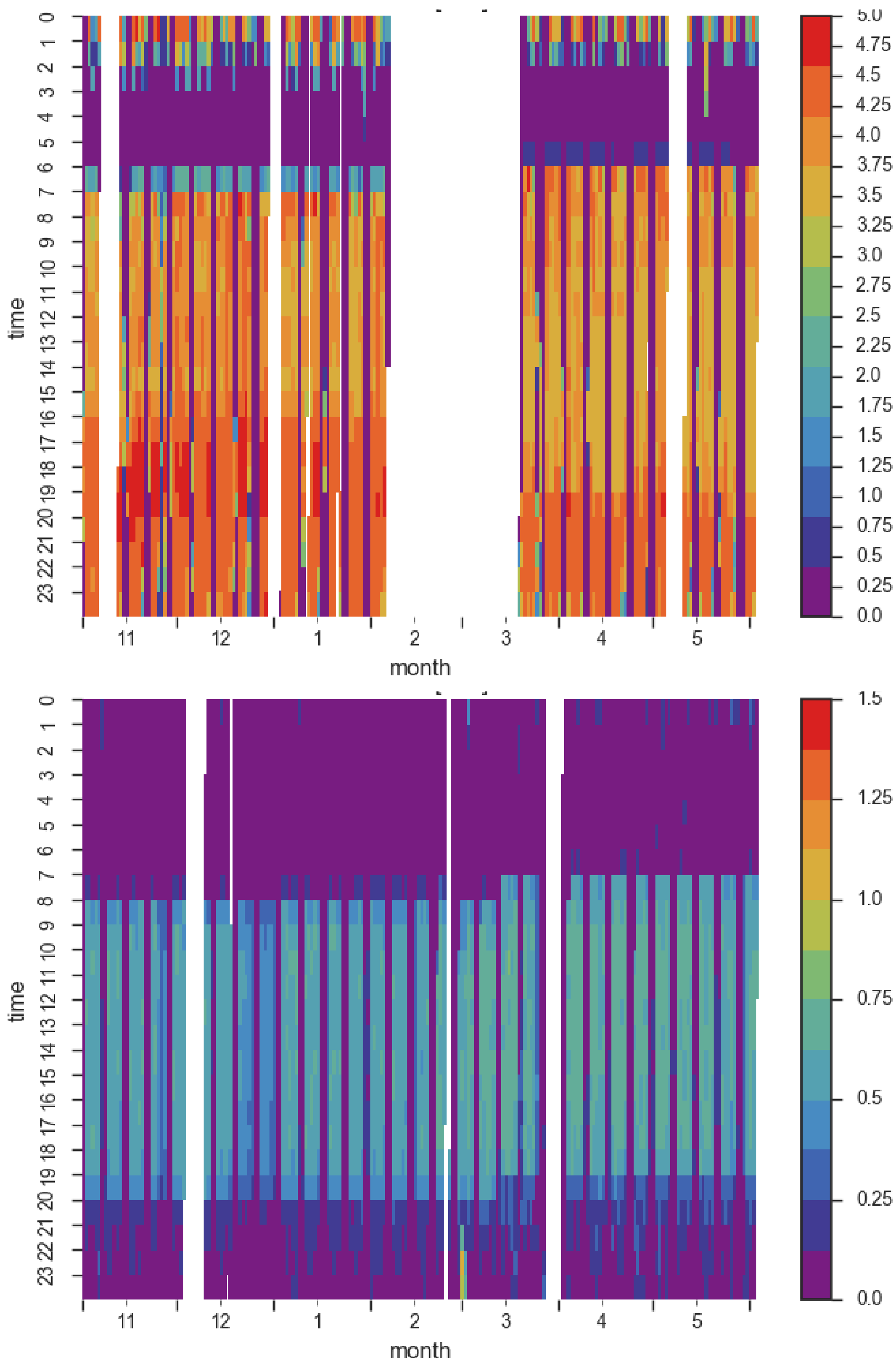


Figure 12. Area G1. Hourly lighting energy use (kWh) for the reference area (upper graph) and test area (lower graph).

Time units are in Standard Time (ST) so during the winter, lights were turned on at 7AM ST and during the summer, lights were turned on at 6 AM ST (7 AM DST) in the reference area. During weekdays in the test area, the uplights were turned on 7 AM to 7 PM local time (LT).

Weekday savings compared to ASHRAE Standard 90.1-1999

ASHRAE 90.1-1999 Reference area energy use

- The ASHRAE Standard 90.1-1999 mandated a maximum installed lighting power density (LPD) of 1.3 W/ft^2. In the reference area, lights were operated about 18 hours per day on weekdays (7 AM to 1 AM). With an assumed 18 hour schedule, the ASHRAE baseline energy use was 23.4 Wh/ft^2 per weekday.

Weekday savings due to LEDs, scheduling, and tuning –

- When the fixture and source hardware were changed to LED direct/ indirect pendant fixtures, the weekday lighting energy use (assuming an 18 hour schedule) was reduced from the ASHRAE 90.1-1999 level of 23.4 Wh/ft^2-day to 9.2 Wh/ft^2-day (61%). In both the reference and test area cases, the illuminance setpoint was 517 lux. See Table 12.
- With setpoint tuning (assuming an 18 hour schedule), average weekday lighting energy use in the test area was reduced to 4.4 Wh/ft^2-day and 5.1 Wh/ft^2-day or a savings of 81% and 78%, respectively for periods 1 and 2, compared to the ASHRAE 90.1-1999 baseline. For period 1, power use for each LED light fixture was 25.6 W (27% of rated input power) when the output level was commissioned to produce an average illuminance level of 263 lux. For period 2, power use was 29.3 W per fixture (31% of rated input power) for an illuminance level of 276 lux (see Table 9 for summary data on the test periods).

Weekday savings due to occupancy and daylighting –

- With occupancy controls at a resolution of 440 ft^2 per zone for a group of four fixtures (as specified by the lighting designer) and daylighting in some zones, average weekday lighting energy use was decreased to 2.5 Wh/ft^2-day both before and after the setpoint illuminance change or a total 89% savings compared to the ASHRAE baseline.
- Weekday lighting energy use in the G1 test area was consistent over the monitored period with little if any change in daily usage with seasons.

Weekday savings compared to the monitored reference area

Monitored reference area energy use

- With an installed lighting power density of 1.04 W/ft^2 and 18-hour schedule, the nominal reference area energy use was 18.7 Wh/ft^2 per weekday.
- The actual monitored reference area energy use with scheduled controls and low-resolution occupancy sensing was 18.8 and 18.2 Wh/ft^2-day for periods 1 and 2 before and after the setpoint illuminance change in the test area, respectively (energy use decreased with increased daylight availability in period 2 (spring to summer)).

Weekday savings

- When compared to actual monitored energy use in the reference area, weekday lighting energy savings of 15.7-16.3 Wh/ft^2-day (86-87%) were due to a change from T5 fluorescents to LEDs, use of half the number of fixtures, a reduction in average workplane illuminance from 517 lux to approximately 270 lux, and use of daylighting and high-resolution occupancy controls in test area G1. See Table 12.

- Incremental savings due to the upgrade to LED fixtures were 9.5 Wh/ft^2-day (59% of total savings)[3].
- Incremental savings due to setpoint tuning were an additional average 4.4 Wh/ft^2-day (27% of total savings).
- Incremental savings due to occupancy and daylighting were an additional 2.3 Wh/ft^2-day (14% of total savings).
- Total energy use and incremental savings are shown in Figure 13.

Table 12. Area G1 (WEST). Average weekday daily lighting energy use (Wh/ft^2-day) and cumulative savings*

		Energy use	Cumulative Savings					
			Ref1 baseline		Ref2 baseline		Ref3 baseline	
		(Wh/ft^2-day)	(Wh/ft^2-day)	(%)	(Wh/ft^2-day)	(%)	(Wh/ft^2-day)	(%)
ASHRAE 90.1-1999								
Ref1	LPD=1.3 W/ft^2, 18-hr	23.4						
LL Building								
Ref2	LPD=1.04 W/ft^2, 18-hr	18.7	4.7	20%				
Ref3a	Actual, period 1	18.8	4.6	20%	-0.1	-1%		
Ref3b	Actual, period 2	18.2	5.2	22%	0.5	3%		
Test0	LED source, 18-hr	9.2	14.2	61%	9.5	51%	9.5**	51%
Test1a	Test0+tuning, per.1	4.4	19.0	81%	14.3	76%	14.4	76%
Test1b	Test0+tuning, per.2	5.1	18.3	78%	13.6	73%	13.2	72%
Test2a	Test1+occ+daylt, per.1	2.5	20.9	89%	16.2	87%	16.3	87%
Test2b	Test1+occ+daylt, per.2	2.5	20.9	89%	16.2	87%	15.7	86%

Notes: Ref=Reference; per.1=period 1; per.2=period 2; 18-hr=18 hour schedule.
* Note: Quadrant level savings are not comparable to other quadrants because the quadrants differed in window orientation, floor layout, etc.
** Source savings were computed relative to the installed reference LPD with the equivalent output illuminance (Ref2). Tuning, occupancy, and daylighting savings were computed relative to Ref3 baseline.

[3] These savings also include the difference in energy use between the assumed 18-hour schedule of the reference case and the actual reference energy use with low-resolution occupancy controls, the latter of which was greater or less than the 18-hour scheduled energy use.

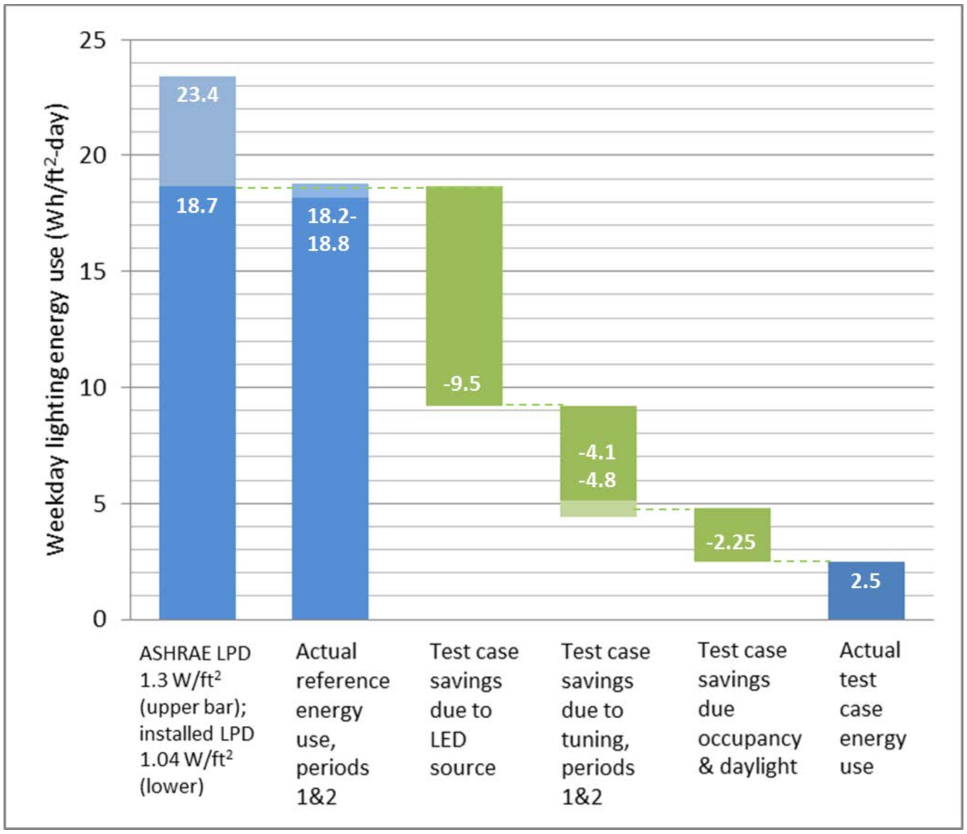


Figure 13. Area G1. Weekday lighting energy use and incremental savings due to the various control strategies.

Annual lighting energy use and peak demand savings

Annual lighting energy savings (including weekend energy use) were determined from summing monitored data, irrespective of gaps in the data, then normalizing the data to an equivalent full year. Total lighting energy use for the reference and G1 test areas was 4.81 and 0.62 kWh/ft^2-yr, respectively. Annualized savings were 4.19 kWh/ft^2-yr (87%).

Peak lighting demand was reduced from 0.87-0.90 W/ft^2 to 0.17-0.18 W/ft^2 during summer weekday afternoon hours between 2-5 PM (Table 13). Savings were 0.70-0.73 W/ft^2 (80-81%).

Table 13. Area G1 (WEST). Average lighting power density (W/ft^2) during peak afternoon periods, March 1 -- June 30, 2016.*

Area	Floor	2-3 PM	3-4 PM	4-5 PM
G1	Reference	0.870	0.877	0.895
	Test	0.175	0.170	0.166
	Savings	0.695	0.707	0.729
	% savings	80%	81%	81%

* Note: Quadrant level savings are not comparable to other quadrants because the quadrants differed in window orientation, floor layout, etc.

4.1.1f – Area G2 (northwest quadrant)

The northwest quadrant consisted of open plan workstations across the entire area, where the layouts of the workstations were identical in the reference and G2 test areas. In this quadrant, we were able to investigate the energy savings associated with the more efficient dimmable LED lighting system with medium resolution, occupancy-based controls. Daylighting was not implemented due to unspecified incompatibilities between the lighting controls and LED drivers.

Operationally, both up and downlights in the G2 area were commissioned to the desired illuminance level then turned on or off according to scheduling and occupancy. Occupancy zones were approximately 640 ft^2 each in floor area and were implemented per 30 ft long table group in accordance to the lighting designer's specifications. In other words, the up- and downlights of two 30-ft long rows of fixtures were turned on or off as a single zone. Automated shades were operated with no option for manual override but since there were no daylighting controls implemented in this area, use of automated shades had no impact on lighting energy use.

Occupancy control was implemented using sensors located in the center between the two rows of continuous fixtures that spanned either side of the 30 ft long table group. Between each table group were round tables for casual gatherings or impromptu meetings. When occupancy levels were low and if one was sitting at the round table, lights were turned off and were difficult to trigger back on. The occupancy sensor's narrow field of view helped to realize energy savings and potentially reduced false triggers, given that the primary occupancy occurred at the desks, but there were discontinuities in coverage just outside of these zones. The sensors' field of view could be adjusted to include the table groups if desired by the occupants. Indoor lighting quality resulting from occupancy-based control is discussed in Section 4.1.2.

Based on the rated power of the fixture, the G2 test area had an installed lighting power density of 0.51 W/ft^2 at full light output. The G2 lighting system was tuned to provide a workplane illuminance of 153 lux (20 fc), then raised to 248 lux in February 2016. When tuned, the LPD was 0.26 W/ft^2 or 0.29 W/ft^2, respectively for these two illuminance levels. Photometric measurements of work plane illuminance from the electric lights are given for the perimeter and interior open plan areas in Table 14. Average illuminance levels due to daylight and electric lighting during the day are given in Table 15.

Figures 14 and 15 show the lighting energy use profile for a typical week and daily lighting energy use levels for the six-month monitored period. Figure 16 provides a detailed view of energy use over the entire monitored period. The G2 test area reduced lighting loads during the evening hours by providing additional spatial resolution on occupancy-based control compared to the reference area. The reference area reduced loads through daylight dimming and low-resolution occupancy control (4580 ft^2 resolution), the latter of which caused evening lighting loads to be on for nearly the same amount of time as during the daytime when full occupancy occurred.

Table 14. Average workplane illuminance, Iwp (lux), due to the electric lights in Area G2 on the reference and test floors.

	October 2015		March 2016		June 2016	
Space type	Ref.	Test	Ref.	Test	Ref.	Test
Interior open plan	594	163	N/A	246	651	235
Perimeter open plan	387	123	N/A	194	417	196

Table 15. Average sensor illuminance, Iwp' (lux), due to the electric lights and daylight in Area G2 on the reference and test floors, weekdays 9 AM to 3 PM.

	Oct-Nov 2015		Mar-Apr 2016		May-Jun 2016	
Space type	Ref.	Test	Ref.	Test	Ref.	Test
Interior open plan	587	323	554	406	551	403
Perimeter open plan	661	616	523	662	600	739

Figure 14. Area G2. Monitored lighting energy use (kW) in the reference and test areas.
The reference area exhibited daylight dimming for this west-facing orientation in the afternoon and low-resolution occupancy controls provided shut-off of lighting once the entire zone was unoccupied. Daylight dimming was not implemented in the test area.

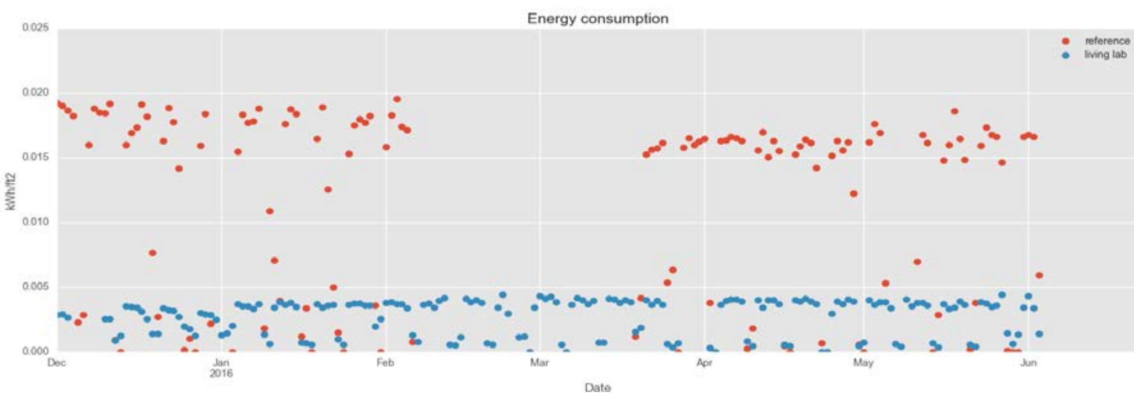


Figure 15. Area G2. Daily lighting energy use (kWh/ft^2-day) for the reference and test areas.
Gaps in the data occurred due to problems with the wireless communications.

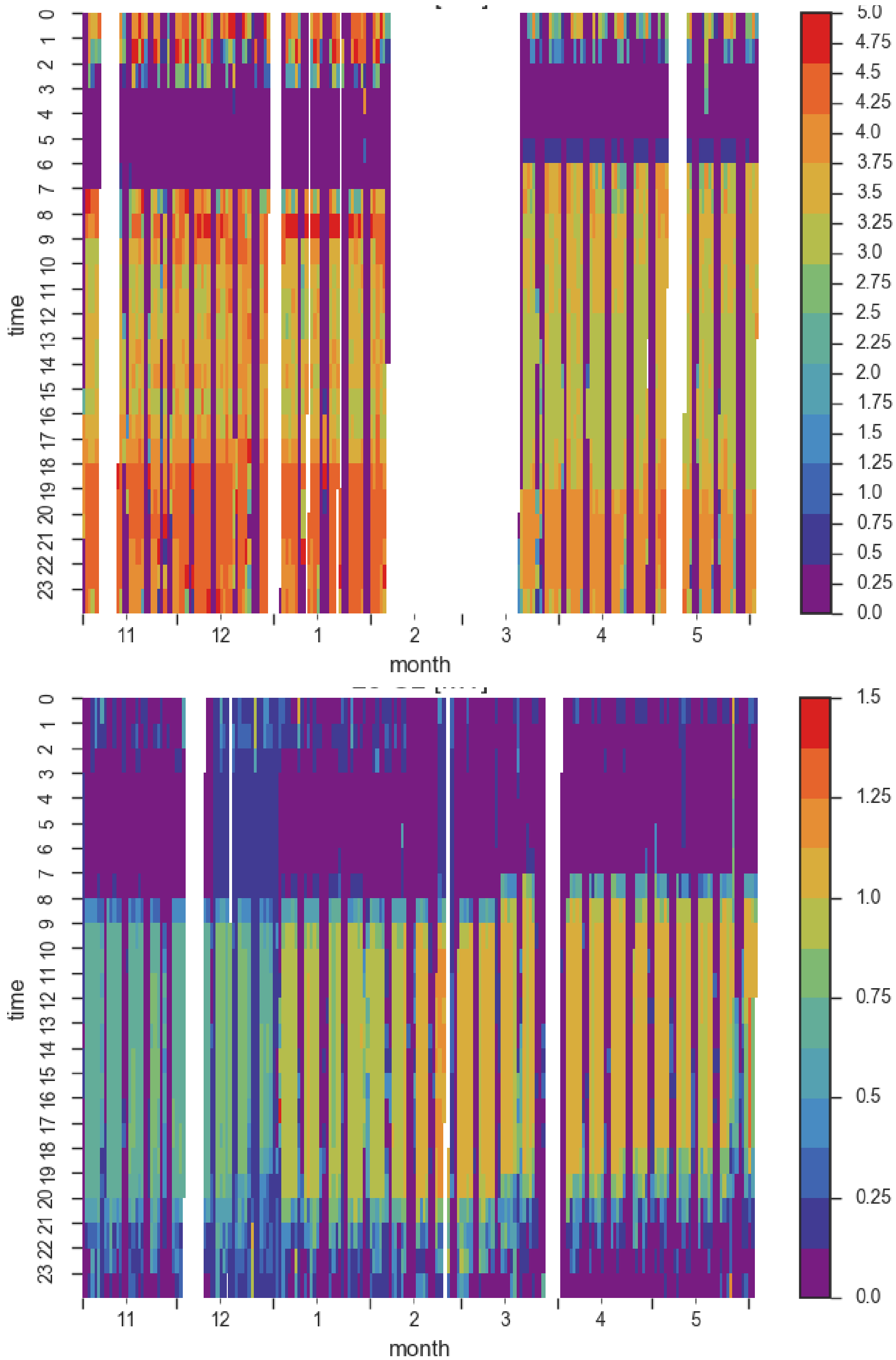


Figure 16. Area G2. Hourly lighting energy use (kWh) for the reference area (upper graph) and test area (lower graph). Time units are in Standard Time (ST).

Weekday savings compared to ASHRAE Standard 90.1-1999

The baseline lighting energy use for the ASHRAE Standard 90.1-1999 was 23.4 Wh/ft^2-day, assuming an installed LPD of 1.3 W/ft^2 and 18-hour operating schedule as discussed in Section 4.1.1e.

Weekday savings due to LEDs, scheduling and tuning –

- Use of LED fixtures (assuming an 18 hour schedule) resulted in a weekday lighting energy use of 12.5 Wh/ft^2-day, a savings of 47% compared to the ASHRAE 90.1-1999 level of 23.4 Wh/ft^2-day. In both the reference and test area cases, the illuminance setpoint was 517 lux.
- With setpoint tuning (assuming an 18 hour schedule), average weekday lighting energy use was 4.5 and 5.1 Wh/ft^2-day, a savings of 81% and 78% for periods 1 and 2, respectively, compared to the ASHRAE baseline (Table 16).

Weekday savings due to medium-resolution occupancy controls –

- Average weekday lighting energy use decreased to 3.4-3.8 Wh/ft^2-day in periods 1 and 2, respectively, due to medium-resolution occupancy controls over a simpler scheduling strategy.
- Savings were 86% and 84% total compared to the ASHRAE 90.1-1999 Standard.

Weekday savings compared to the monitored reference area

Monitored reference area energy use

- With an actual installed lighting power density of 1.04 W/ft^2 and average workplane illuminance level of 517 lux, monitored reference area lighting energy use was 18.2 and 16.7 Wh/ft^2-day (for the periods before and after the setpoint illuminance change in the test area, respectively).

Weekday savings

- Compared to the actual reference case energy use, the test case produced a total savings of 77-82% through the use of LEDs, a reduction in average workplane illuminance from 517 lux to 153 lux and 248 lux in periods 1 and 2, respectively, and use of moderate-resolution occupancy controls.
- Monitored test area energy use was 3.4 and 3.8 Wh/ft^2-day.
- Total energy use and incremental savings are shown in Figure 17.

Annual lighting energy use and peak demand savings

Annual lighting energy use, including weekend energy use, was 4.46 kWh/ft^2-yr in the reference area and 1.01 kWh/ft^2-yr in the test area, resulting in savings of 3.45 kWh/ft^2-yr or 77%.

Peak lighting demand was reduced from 0.78-0.81 W/ft^2 to 0.28 W/ft^2 or 64-66% between the summer afternoon hours of 2-5 PM (Table 17).

Table 16. Area G2 (WEST). Average weekday daily lighting energy use (Wh/ft^2-day) and cumulative savings.*

		Energy use	Cumulative Savings					
			Ref1 baseline		Ref2 baseline		Ref3 baseline	
		(Wh/ft^2-day)	(Wh/ft^2-day)	(%)	(Wh/ft^2-day)	(%)	(Wh/ft^2-day)	(%)
ASHRAE 90.1-1999								
Ref1	LPD=1.3 W/ft^2, 18-hr	23.4						
LL Building								
Ref2	LPD=1.04 W/ft^2, 18-hr	18.7	4.7	20%				
Ref3a	Actual, period 1	18.2	5.2	22%	0.5	3%		
Ref3b	Actual, period 2	16.7	6.7	29%	2.0	11%		
Test0	LED source, 18-hr	12.5	10.9	47%	6.2	33%	6.2**	33%
Test1a	Test0+tuning, per.1	4.5	18.9	81%	14.2	76%	13.6	75%
Test1b	Test0+tuning, per.2	5.1	18.3	78%	13.6	73%	11.6	69%
Test2a	Test1+occ+daylt, per.1	3.4	20.0	86%	15.4	82%	14.8	82%
Test2b	Test1+occ+daylt, per.2	3.8	19.6	84%	14.9	80%	12.9	77%

Notes: Ref=Reference; per.1=period 1; per.2=period 2; 18-hr=18 hour schedule.

* Note: Quadrant level savings are not comparable to other quadrants because the quadrants differed in window orientation, floor layout, etc.

** Source savings were computed relative to the installed reference LPD with the equivalent output illuminance (Ref2). Tuning, occupancy, and daylighting savings were computed relative to Ref3 baseline.

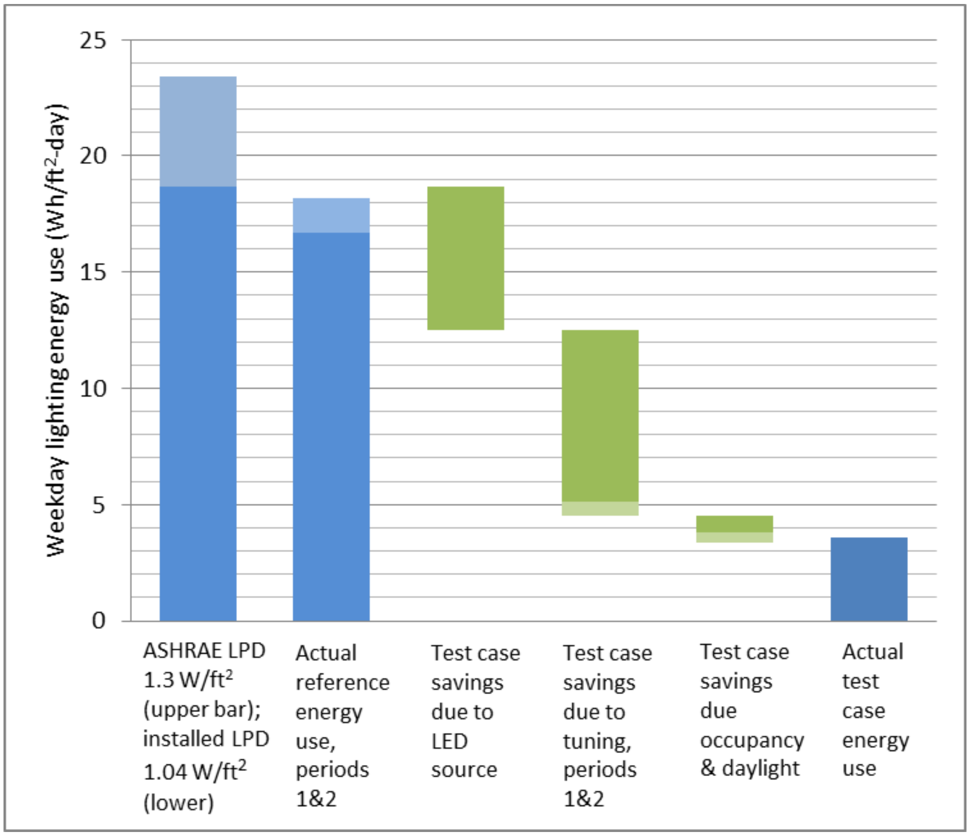


Figure 17. Area G2. Weekday lighting energy use and incremental savings due to the various control strategies.

Table 17. Area G2 (WEST). Average lighting power density (W/ft^2) during peak afternoon periods, March 1 -- June 30, 2016.*

Area	Floor	2-3 PM	3-4 PM	4-5 PM
G2	Reference	0.784	0.793	0.806
	Test	0.282	0.281	0.276
	Savings	0.503	0.513	0.530
	% savings	64%	65%	66%

* Note: Quadrant level savings are not comparable to other quadrants because the quadrants differed in window orientation, floor layout, etc.

4.1.1g – Area G3 (southeast quadrant)

Area G3 had a predominantly east-facing orientation with a planar (non-curved) façade. On the south end, there were significant obstructions from tall buildings a few blocks away in the south-easterly direction (16-58° profile angle). Area G3 included a corner condition with some south-facing windows that were also obstructed partially with tall buildings (38° profile angle). On the north end of the Area, horizon obstructions were significantly less (1-2° profile angle). In general, the lighting control system was commissioned to meet the requirements specified by the lighting designer (see Section 3.4.2e). Each fixture's up- and downlight were commissioned to dim based on available daylight while grouped with other fixtures to form an occupancy zone.

We were unable to determine exactly, after examining the two different interfaces to the control system, how the control system was configured. Hourly dimming status data for each of the occupancy zones in Area G3 were provided by the manufacturer. Because these data represented the dimming status of the up- and downlights of *all* fixtures within each zone, the control modes of operation of *each* fixture were deduced from this data and verified through site observations.

An example day is plotted in Figure 18 illustrating the dimming pattern during the equinox period (March 10, 2016) based on dimming status data provided by the manufacturer starting at 0:30 in hourly increments. Partial occupancy occurred in the early morning hours (5:30, 6:30 AM) then during hour 7:30 AM all uplights in Area G3 were likely turned on and occupancy levels increased (hour 7:30 AM includes the hour of operations prior to 7:30 AM). During the 8:30 and 9:30 AM hours, the dimming level in the east-facing zones decreased by 30-37% then continued to increase until about hour 6:30 PM, after which the uplights were turned off as scheduled at 7:00 PM and lighting use in general decreased as occupancy declined. Savings during the daytime period were due to a combination of occupancy and daylighting. Given the window orientation and shape of the load reduction, much of the savings during the day were likely due to daylight dimming.

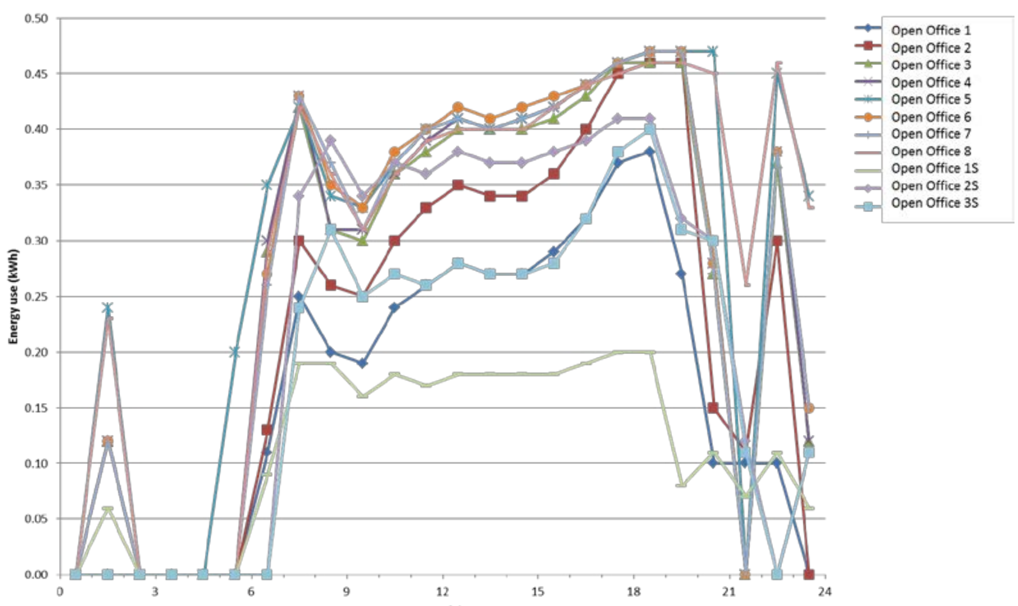


Figure 18. Dimming status of lighting control zones within the G3 test area as reported by the manufacturer on March 10, 2016.
Each numbered zone is an area next to the window along the east façade and south ("S") façade.

Monitored lighting energy use for a week in April is shown in Figure 19. Daily lighting energy use is shown in Figure 20. Average hourly lighting energy use is also shown in Figure 21 for all days and hours over the monitored period. These plots illustrate the impact of daylight dimming in the reference and test areas. Maximum dimming occurred in the early morning hours then gradually increased throughout the day. Daily lighting energy use declined noticeably in the test and reference areas from December to June as daylight availability increased toward the summer. This pattern is also evident in the falsecolor plots during the morning hours – energy use levels were distinctly lower during this period from about the equinox in March to the summer solstice in June.

Figure 19. Area G3. Monitored lighting energy use in the reference and test areas.
The reference area exhibited daylight dimming for this east-facing orientation in the morning and low-resolution occupancy controls provided shut-off of lighting once the entire zone was unoccupied. Daylight dimming also occurred in the test area, with medium-resolution occupancy control providing shut-off of lights earlier in the evening. The last two profiles to the right of the plot are weekend days.

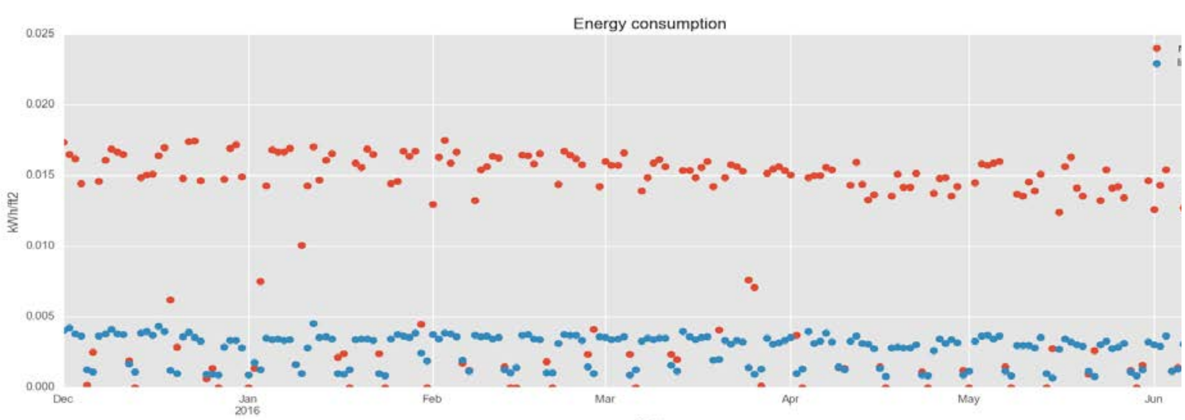


Figure 20. Area G3. Daily lighting energy use (kWh/ft^2-day) for the reference and test areas.

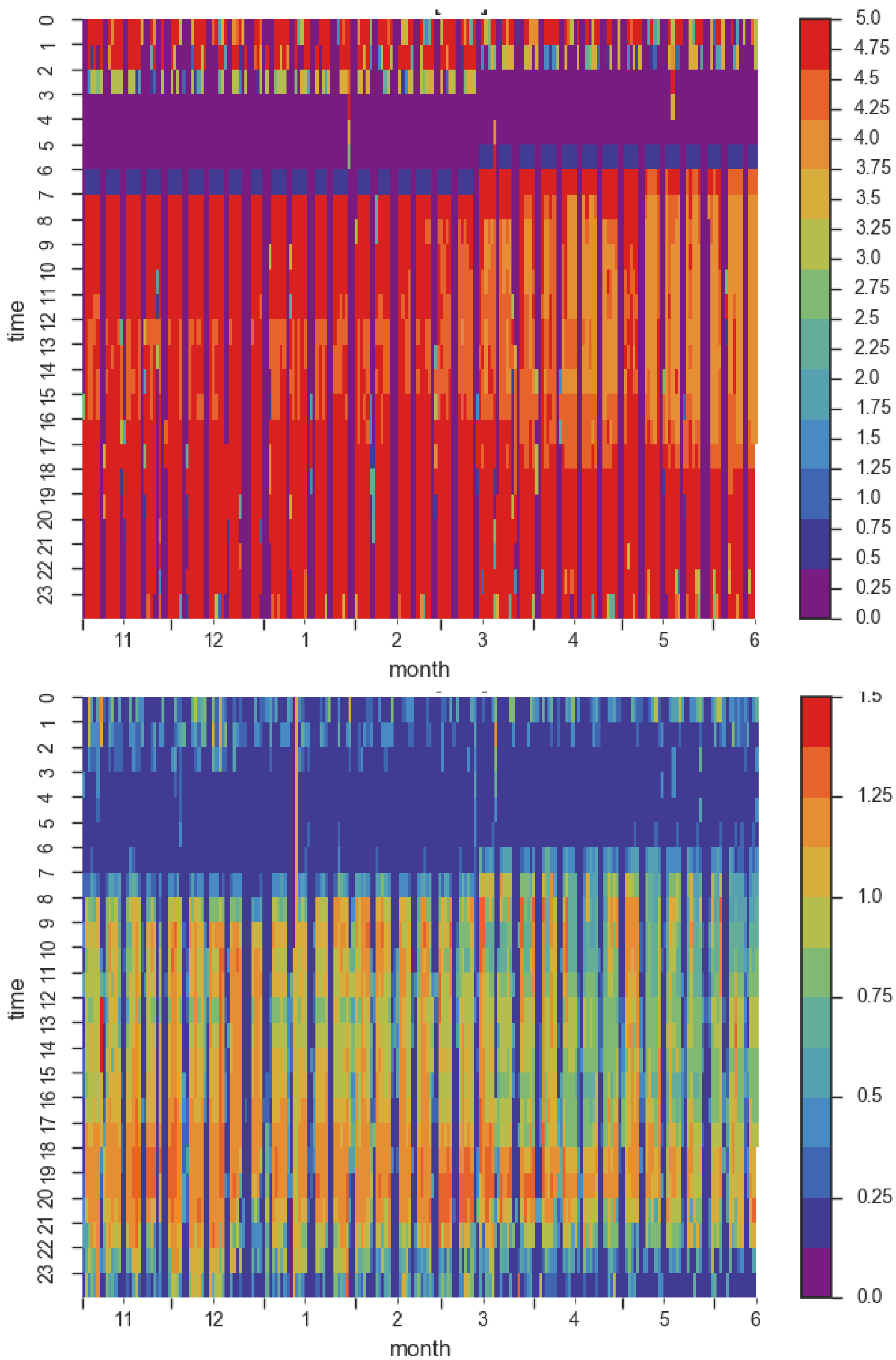


Figure 21. Area G3. Hourly lighting energy use (kWh) for the reference area (upper graph) and test area (lower graph). Time units are in Standard Time (ST).

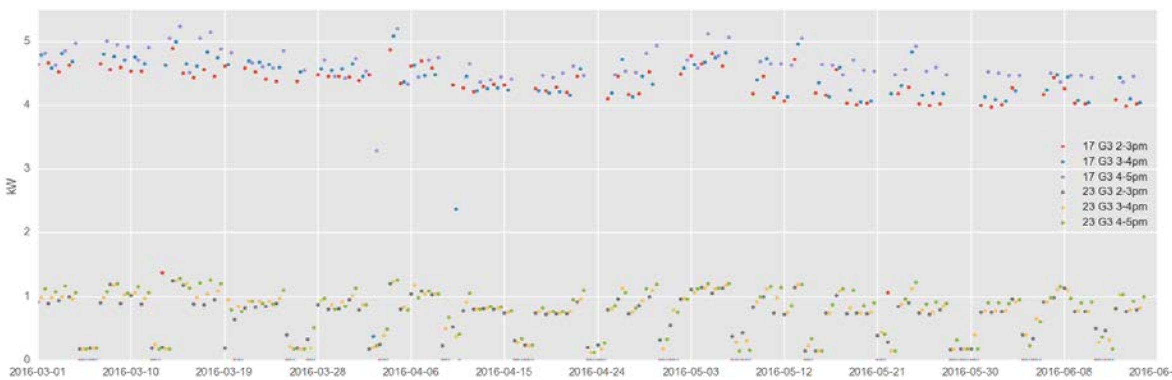


Figure 22. Area G3. Average hourly lighting energy use (kWh) for the reference and test areas during peak afternoon periods over the six-month monitored period.
Energy use levels in the latter half of the period (March to June) are indicative of energy levels in the late summer period (June to September) since the sun path is symmetrical over the summer solstice (June 21). Weekend data are the very low points on the graph.

Despite Area G3 being an east- to southeast-facing zone, there were peak electric lighting demand reductions due to daylight in the afternoon hours, as exemplified by the hourly profile data (Figure 19) for both test and reference areas, and the decline in hourly consumption during peak hours between December and June in the reference area (Figure 22). The decline in peak load for the test area is subtle given that the overall demand is at a significantly lower level.

Observations of the dimming pattern of lighting across the space appeared logical and proportional to available daylight – the up- and downlights in the row nearest the window were observed to be dimmed to a minimum output when there was sufficient daylight and the two rows of lights were dimmed less as distance increased from the window. Handheld measurements made at various times throughout the day during the June site visit confirmed that total workplane illuminance levels on the desks at different distances from the window were maintained within or above the setpoint illuminance level and that the fixture output levels were reduced or minimal when sufficient daylight was present. Additional measurements were made during the night and day to document workplane illuminance levels (Tables 18 and 19).

Savings due to occupancy were most evident in comparing lighting energy use in Figure 21. The reference area exhibited full occupancy from about 7 AM until about 2 AM the next day while the test area showed that occupancy occurred from about 8 AM then tailed off after about 10 PM in the evening. There were some dead areas that were undetected by the occupancy sensors between the primary work tables, requiring some activity to trigger the lights back on. The lights exhibited a pleasant fade rate when turned on and off. Quality of light as a result of medium-resolution occupancy control during the day and night is discussed in Section 4.1.2.

Table 18. Average workplane illuminance, Iwp (lux), due to the electric lights in Area G3 on the reference and test floors.

	October 2015		March 2016		June 2016	
Space type	Ref.	Test	Ref.	Test	Ref.	Test
Interior open plan	510	182	567	179	579	164
Perimeter open plan	381	142	440	112	463	124

Table 19. Average sensor illuminance, Iwp' (lux), due to the electric lights and daylight in Area G3 on the reference and test floors, weekdays 9 AM to 3 PM.

	Oct-Nov 2015		Mar-Apr 2016		May-Jun 2016	
Space type	Ref.	Test	Ref.	Test	Ref.	Test
Interior open plan	523	144	551	185	569	212
Perimeter open plan	579	297	692	384	852	588

Weekday savings compared to ASHRAE Standard 90.1-1999

The baseline lighting energy use for the ASHRAE Standard 90.1-1999 was 23.4 Wh/ft^2-day, assuming an installed LPD of 1.3 W/ft^2 and 18-hour operating schedule as discussed in Section 4.1.1e.

Weekday savings due to LEDs, scheduling and tuning –

- When the fixture and source hardware were changed to LED direct/ indirect pendant fixtures, the weekday lighting energy use (assuming an 18 hour schedule) was reduced to 10.3 Wh/ft^2-day (56%). In both the reference and test area cases, the illuminance setpoint was 517 lux.
- With setpoint tuning, average weekday lighting energy use in the test area was reduced to 4.6 and 4.7 Wh/ft^2-day, a savings of 80% for periods 1 and 2, respectively, compared to the ASHRAE baseline (Table 20).

Weekday savings due to medium-resolution occupancy controls and daylighting –

- Average weekday lighting energy use decreased to 3.4-3.6 Wh/ft^2-day in periods 1 and 2, respectively, with occupancy and daylighting controls.
- Savings were 85% total compared to the ASHRAE 90.1 Standard.

Weekday savings compared to the monitored reference area

Monitored reference area energy use

- With an actual installed lighting power density of 1.04 W/ft^2 and average workplane illuminance level of 517 lux, monitored weekday reference area lighting energy use was 15.3 and 14.6 Wh/ft^2-day (for the periods before and after the setpoint illuminance change in the test area, respectively).

Weekday savings

- Monitored test area energy use was reduced to 3.4 and 3.6 Wh/ft^2-day in periods 1 and 2, respectively.
- Compared to the actual reference area energy use, the test area produced a total savings of 75-77% through the use of LEDs, a reduction in average workplane illuminance from 517 lux to 167 lux and 172 lux in periods 1 and 2, respectively, and use of moderate-resolution occupancy and daylighting controls.
- Total energy use and incremental savings are shown in Figure 23.

Annual lighting energy use and peak demand savings

Annual lighting energy use, including weekend energy use, was 4.03 kWh/ft^2-yr in the reference area and 0.99 kWh/ft^2-yr in the test area, resulting in savings of 3.04 kWh/ft^2-yr or 75%.

Peak lighting demand was reduced from 0.73-0.78 W/ft^2 to 0.17-0.19 W/ft^2 or 75-77% between the summer afternoon hours of 2-5 PM (Table 21).

Table 20. Area G3 (EAST). Average weekday daily lighting energy use (Wh/ft^2-day) and cumulative savings.*

		Energy use	Cumulative Savings					
			Ref1 baseline		Ref2 baseline		Ref3 baseline	
		(Wh/ft^2-day)	(Wh/ft^2-day)	(%)	(Wh/ft^2-day)	(%)	(Wh/ft^2-day)	(%)
ASHRAE 90.1-1999								
Ref1	LPD=1.3 W/ft^2, 18-hr	23.4						
LL Building								
Ref2	LPD=1.04 W/ft^2, 18-hr	18.7	4.7	20%				
Ref3a	Actual, period 1	15.3	8.1	35%	3.4	18%		
Ref3b	Actual, period 2	14.6	8.8	37%	4.1	22%		
Test0	LED source, 18-hr	10.3	13.1	56%	8.5	45%	8.5**	45%
Test1a	Test0+tuning, per.1	4.6	18.8	80%	14.1	75%	10.7	70%
Test1b	Test0+tuning, per.2	4.7	18.7	80%	14.0	75%	9.9	68%
Test2a	Test1+occ+daylt, per.1	3.4	20.0	85%	15.3	82%	11.9	78%
Test2b	Test1+occ+daylt, per.2	3.6	19.8	85%	15.1	81%	11.0	75%

Notes: Ref=Reference; per.1=period 1; per.2=period 2; 18-hr=18 hour schedule.
* Note: Quadrant level savings are not comparable to other quadrants because the quadrants differed in window orientation, floor layout, etc.
** Source savings were computed relative to the installed reference LPD with the equivalent output illuminance (Ref2). Tuning, occupancy, and daylighting savings were computed relative to Ref3 baseline.

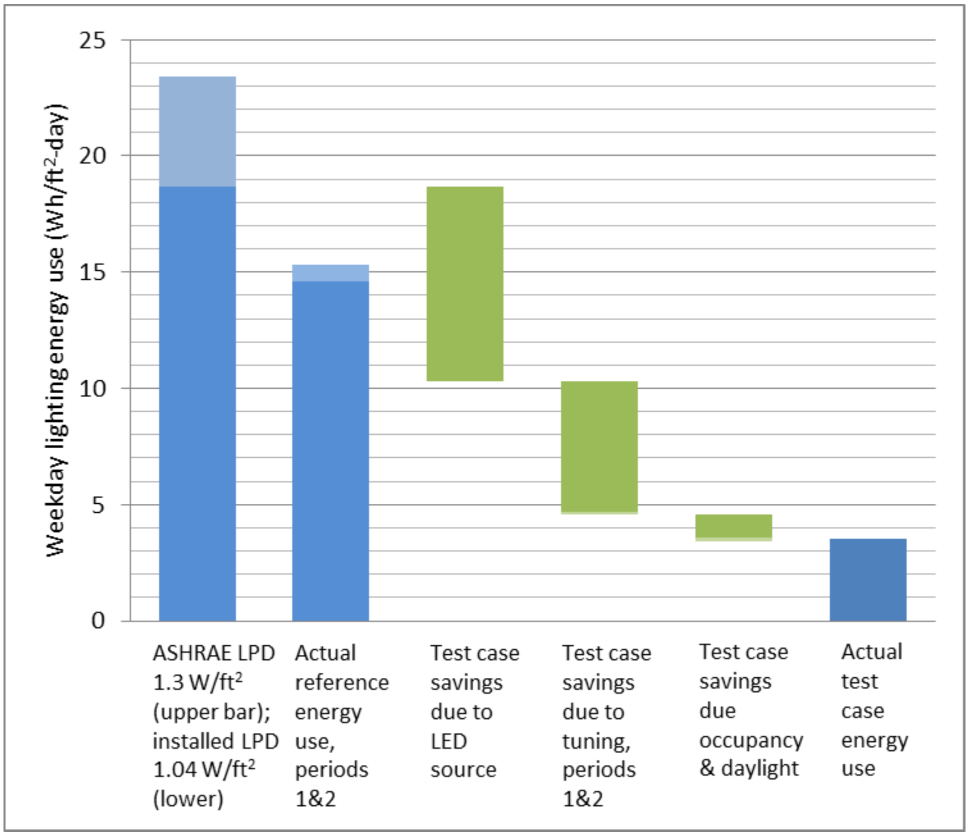


Figure 23. Area G3. Weekday lighting energy use and incremental savings due to the various control strategies.

Table 21. Area G3 (EAST). Average lighting power density (W/ft^2) during peak afternoon periods, March 1 -- June 30, 2016.*

Area	Floor	2-3 PM	3-4 PM	4-5 PM
G3	Reference	0.726	0.742	0.775
	Test	0.168	0.179	0.190
	Savings	0.558	0.564	0.585
	% savings	77%	76%	75%

* Note: Quadrant level savings are not comparable to other quadrants because the quadrants differed in window orientation, floor layout, etc.

4.1.1h – Area G4 (northeast quadrant)

The lighting controls in test Area G4 implemented the highest spatial resolution of control over occupancy and daylighting of all four areas. On the north, an occupancy zone was defined by a single fixture with its 5 ft length parallel to the window (100 ft^2). On the east, occupancy zones were defined by a group of two fixtures spanning the width of each work area (defined by a group of adjacent desks) with its 5 ft length running perpendicular to the window wall (200 ft^2). The zones are shown in Figure 3. Each fixture had its own occupancy and photosensor but the up- and downlight components could be zoned independently on a zonal or fixture level. For example, all uplights in the area could be grouped together and controlled as a single zone to achieve a uniform ceiling brightness across the entire space, while the downlights could be controlled individually according to scheduled, setpoint tuning, occupancy, and daylighting controls. As a result of the requested sequence of operations by the lighting designer (see Appendix B), the vendor commissioned the system to limit control of the uplights to between 70-90% of full output while the downlights were controlled to between 0-70% during weekday work hours (7 AM to 7 PM). See Section 411d for the relationship between control range and power consumption of the Area G4 light fixtures.

In a prior field study in a full-scale testbed of the same G4 test area lighting control system, we found that the complex zoning strategies for up- and downlights could be implemented and correctly controlled for scheduling, setpoint tuning, and occupancy. Attaining reliable control with daylighting was found to be challenging, however, requiring detailed finetuning to achieve proper control [McNeil et al. 2014].

At the LL site, we could not perform this same level of detailed analysis. Site observations and spot measurements using a handheld photometer indicated that dimming of the up- and downlights near the window was occurring and that the two further rows of fixtures were also dimming when conditions were sunny. Dimming levels were observed to diminish as distance from the window increased and as daylight levels increased. Workplane illuminance levels were documented for night and daytime conditions (Tables 22 and 23).

Lighting energy use for Area G4 on the reference and test floors is given in Figures 24-26. Test area G4 displayed very slight changes in lighting energy use during the day (Figure 24) and over the six-month monitored period (Figure 25). Daylight levels tend to be less variable and of lower intensity on north façades even without automated shading. Area G4 had nearly equal areas of windows on the north and east facades so there was some dampening of evidence of daylighting savings when looking at the entire area's energy use in aggregate (Figure 24). Urban obstructions toward the southeast (20-50° profile angle) obliquely shaded the east-facing façade in the late morning. The north facade was minimally obstructed (1-2° profile angle) and included views of the river. Neither of these conditions would have significantly lowered daylight availability at the window wall. Daily lighting energy use did exhibit a slight decline (Figure 25) in the period 2 transition to the summer.

Table 22. Average workplane illuminance, Iwp (lux), due to the electric lights in Area G4 in the reference and test areas.

	October 2015		March 2016		June 2016	
Space type	Ref.	Test	Ref.	Test	Ref.	Test
Interior open plan	600	530	478	207	581	334
Perimeter open plan	478	471	337	185	481	288

Table 23. Average sensor illuminance, Iwp' (lux), due to the electric lights and daylight in Area G4 in the reference and test areas, weekdays 9 AM to 3 PM.

	Oct-Nov 2015		Mar-Apr 2016		May-Jun 2016	
Space type	Ref.	Test*	Ref.	Test	Ref.	Test
Interior open plan	732	NA	657	312	659	313
Perimeter open plan	836	NA	718	478	744	496

* Note: amplifier malfunctioned during this period.

Note that lack of significant daylight dimming in the test area was also due to the specification that all uplights remain on (54-108 lux, 5-10 fc output at the task, varying with depth from window) irrespective of occupancy or daylighting between 7 AM to 7 PM in order to maintain a bright ceiling plane across the depth of the open plan perimeter zone. This reduced the daylight dimming potential of the direct/ indirect lighting system.

Note the step change in test area daily lighting energy use in early February in Figures 25 and 26, when average workplane illuminance levels were adjusted from 517 lux down to 201 lux. Because daily lighting energy use showed little variation over both periods, data from the second period were used to compute the annualized lighting energy use value.

Hourly lighting energy use data illustrates the occupancy patterns in the test and reference areas (Figure 26). Reference area occupancy levels were more sparse after about 8 PM, so late evening savings due to occupancy were lower than had the reference area been more continuously occupied. During the daytime, savings were due to partial vacancy and daylighting in the temporal plot (Figure 20).

For the single-fixture occupancy zones, control did operate as intended, switching off individually after a time delay of 15 min. Luminance across the ceiling plane tended to be non-uniform, which was more noticeable at night with sparse occupancy. Lighting quality and visual comfort was evaluated in Section 4.1.2. Occupant response regarding lighting quality was evaluated in Section 4.4.

Figure 24. Area G4. Monitored lighting energy use in the reference and test areas.

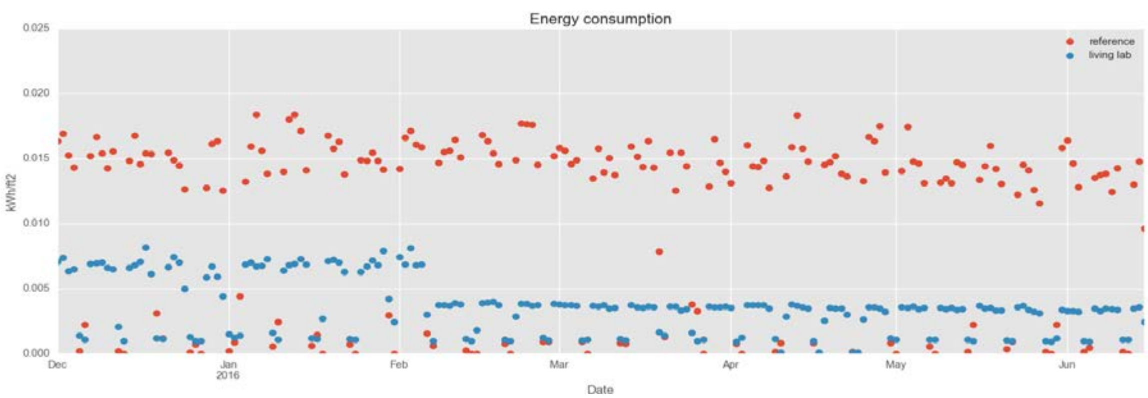


Figure 25. Area G4. Daily lighting energy use (kWh/ft^2-day) for the reference and test areas.

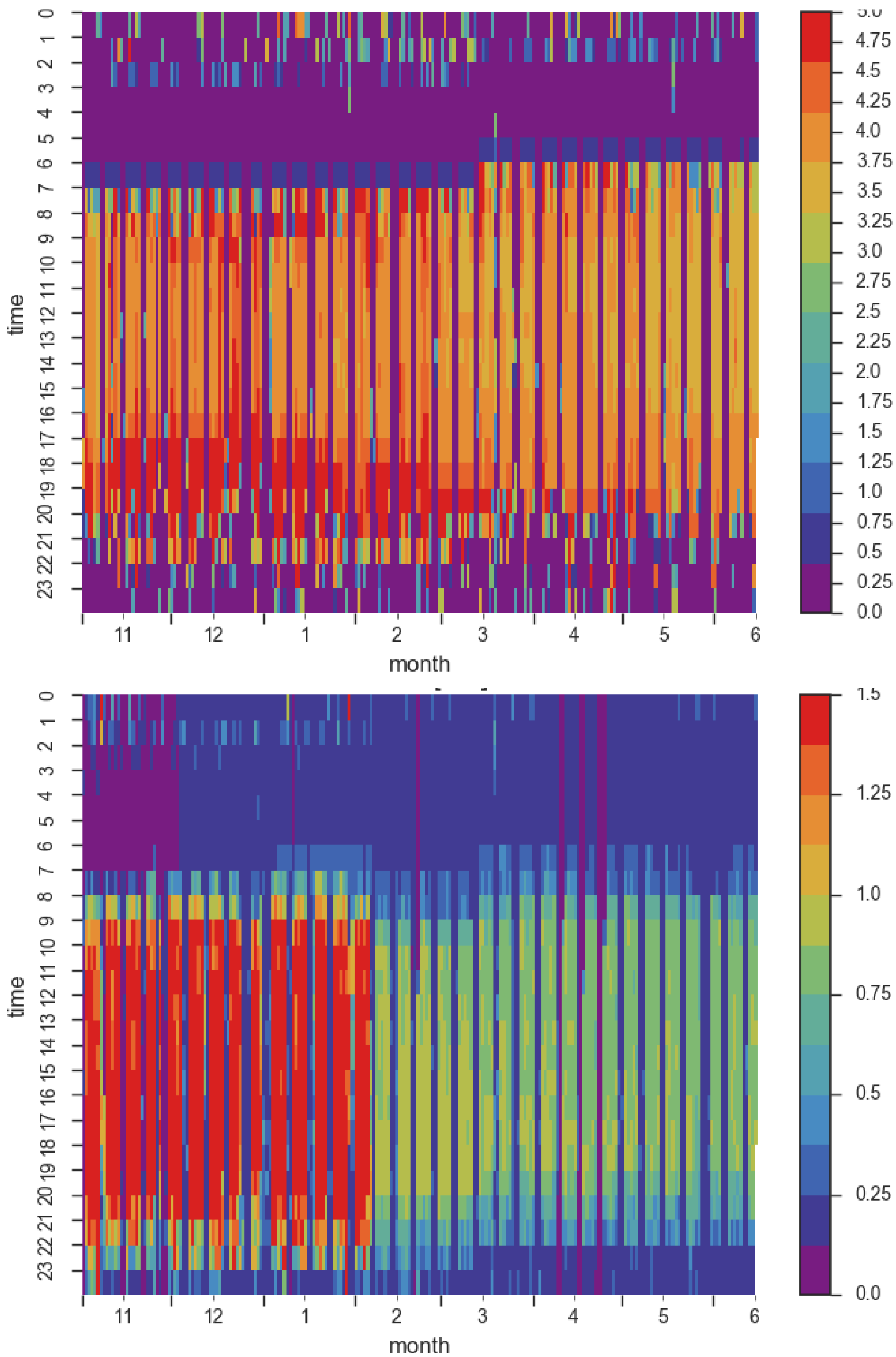


Figure 26. Area G4. Hourly lighting energy use (kWh) for the reference area (upper graph) and test area (lower graph). Time units are in Standard Time (ST).

Weekday savings compared to ASHRAE Standard 90.1-1999

On the test floor, Area G4 was commissioned to produce two distinctly different light levels: a) 517 lux average during period 1, matching the illuminance level of the reference area, and b) 201 lux average, which was near the light level specified by the lighting designer (30 fc, 322 lux) and later by the owner (25 fc, 269 lux). Therefore below, we discuss energy savings from period 2 when the system was adjusted as intended.

The baseline lighting energy use for the ASHRAE Standard 90.1-1999 was 23.4 Wh/ft^2-day, assuming an installed LPD of 1.3 W/ft^2 and 18-hour operating schedule as discussed in Section 4.1.1e.

Weekday savings due to LEDs, scheduling and tuning –

- Use of LED fixtures (assuming an 18 hour schedule) resulted in a weekday lighting energy use of 11.2 Wh/ft^2-day, a savings of 52%. In both the reference and test areas, the illuminance setpoint was 517 lux.
- With setpoint tuning (assuming an 18 hour schedule), average weekday lighting energy use was 4.9 Wh/ft^2-day. Savings were 79% for period 2 compared to the ASHRAE baseline (Table 24). The test area average workplane illuminance from the electric lighting was 201 lux during this period.

Weekday savings due to occupancy and daylighting –

- With high resolution occupancy controls and daylighting, weekday energy use was decreased to 3.7 Wh/ft^2-day with a total savings of 84% compared to the ASHRAE baseline.

Weekday savings compared to the monitored reference area

Monitored reference area energy use

- With an actual installed lighting power density of 1.04 W/ft^2 and average workplane illuminance level of 517 lux, monitored reference area lighting energy use was 14.7 Wh/ft^2-day.

Weekday savings

- Compared to the actual reference area energy use, the test case energy use was reduced to 3.7 Wh/ft^2-day, with a total savings of 11 Wh/ft^2-day (75%).
- These savings were the result of the use of LED fixtures, setpoint tuning from 517 lux to 201 lux, high-resolution occupancy, and daylighting controls (Table 24).
- Total energy use and incremental savings are shown in Figure 27.

Annual lighting energy use and peak demand savings

Period 2 data were used to determine annual lighting energy use for the G4 test area with the same setpoint illuminance as the other three quadrants. Annual lighting energy use, including weekend energy use, was 3.85 kWh/ft^2-yr in the reference area and 1.00 kWh/ft^2-yr in the test area, resulting in savings of 2.85 kWh/ft^2-yr or 73%.

Peak lighting demand was reduced from 0.90-0.94 W/ft^2 to 0.23-0.24 W/ft^2 or 74-75% between the summer afternoon hours of 2-5 PM (Table 25).

Table 24. Area G4 (EAST and NORTH). Average weekday daily lighting energy use (Wh/ft^2-day) and cumulative savings.*

		Energy use	Cumulative Savings					
			Ref1 baseline		Ref2 baseline		Ref3 baseline	
		(Wh/ft^2-day)	(Wh/ft^2-day)	(%)	(Wh/ft^2-day)	(%)	(Wh/ft^2-day)	(%)
ASHRAE 90.1-1999								
Ref1	LPD=1.3 W/ft^2, 18-hr	23.4						
LL Building								
Ref2	LPD=1.04 W/ft^2, 18-hr	18.7	4.7	20%				
Ref3b	Actual, period 2	14.7	8.7	37%	4.0	21%		
Test0	LED source, 18-hr	11.2	12.2	52%	7.5	40%	7.5**	40%
Test1b	Test0+tuning, per.2	4.9	18.5	79%	13.8	74%	9.8	67%
Test2b	Test1+occ+daylt, per.2	3.7	19.7	84%	15.0	80%	11.0	75%

Notes: Ref=Reference; per.2=period 2; 18-hr=18 hour schedule.
* Note: Quadrant level savings are not comparable to other quadrants because the quadrants differed in window orientation, floor layout, etc.
** Source savings were computed relative to the installed reference LPD with the equivalent output illuminance (Ref2). Tuning, occupancy, and daylighting savings were computed relative to Ref3 baseline.

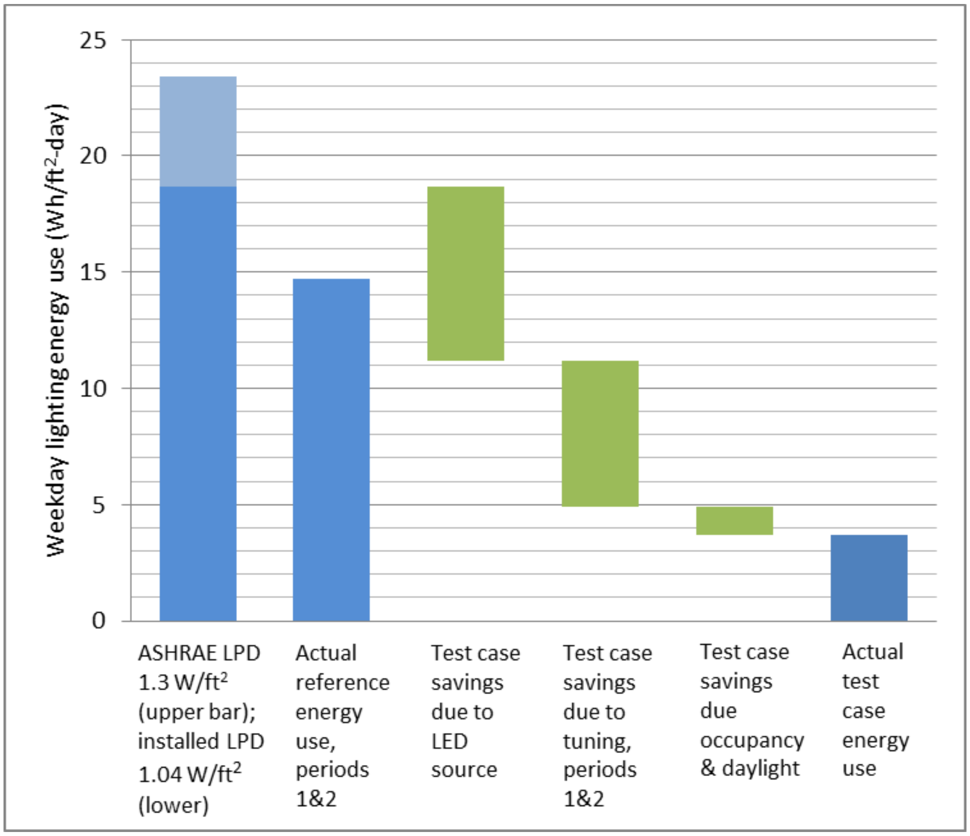


Figure 27. Area G4. Weekday lighting energy use and incremental savings due to the various control strategies.

Table 25. Area G4 (EAST and NORTH). Average lighting power density (W/ft^2) during peak afternoon periods, March 1 -- June 30, 2016*

Area	Floor	2-3 PM	3-4 PM	4-5 PM
G4	Reference	0.901	0.913	0.943
	Test	0.228	0.233	0.237
	Savings	0.672	0.679	0.705
	% savings	75%	74%	75%

* Note: Quadrant level savings are not comparable to other quadrants because the quadrants differed in window orientation, floor layout, etc.

4.1.2. Lighting Quality

Direct-indirect lighting with fluorescent sources have typically been used to improve lighting quality and comfort by increasing overall room cavity luminance and uniformity and reducing direct source glare. The Illuminating Engineering Society of North America (IESNA) recommended practice for office lighting [IES RP-1-12, 2012] advises that ceiling luminance should not exceed 10 times the average computer screen luminance, the maximum ceiling or source luminance within the field of view should be limited to 850 cd/m^2, and luminance contrasts across the ceiling should not exceed 8:1.

With linear LED fixtures, the source size is considerably smaller than T5 fluorescent tubes and of higher intensity so the luminance across the ceiling plane can be non-uniform, particularly if the fixtures are widely spaced. Direct source glare can also be a problem if the LED source is not adequately shielded. (See Sections 3.4.1 and 3.4.2 for a description of the pendant LED fixtures used in this study.) With high-resolution occupancy controls, uniformity of ceiling luminance can also be diminished during periods when there is partial occupancy.

High dynamic range images were captured at the site at night in October 2015 to measure source (lamp) luminance and luminance contrast from the different fixtures installed in the reference and test areas (Figures 28-31). Values for minimum and maximum luminance and vertical illuminance at the eye are summarized in Table 26 for seated positions looking horizontally toward the computer monitors.

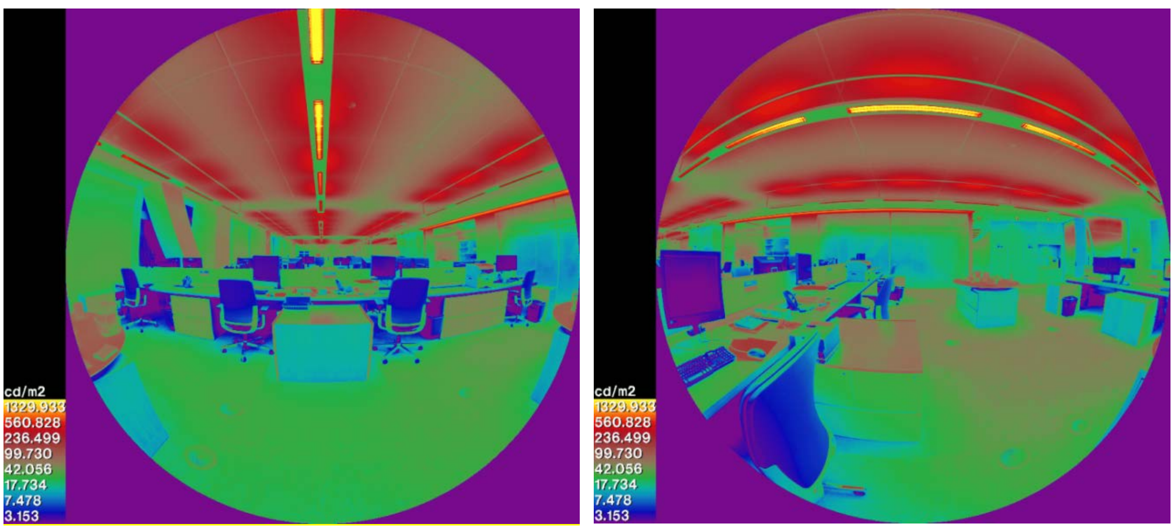
On the test floor, all of the fixtures produced luminance conditions that significantly exceeded the limits of the IESNA RP-1 guidelines (Table 26). Most produced a bright region of light on the ceiling that extended about 2.0-2.5 ft on either side of the fixture and about 1 ft off the ends of the non-continuous fixtures. The 30-ft linear fixture produced the most even light across the ceiling. The test floor Area G4 fixtures were particularly bright since they were tuned to an output level that was significantly greater than the other three test floor fixtures.

On the reference floor, the limits of the RP-1 guidelines were also exceeded. For the view parallel to the fixture, however, and for the same approximate workplane illuminance, the reference fixture was able to better control contrast across the ceiling plane compared to the test floor G4 LED fixture. For a maximum luminance of 105,000 cd/m^2, the luminance ratio was 181:1, whereas for the G4 fixture on the test floor, the maximum luminance was 150,000 cd/m^2 with a luminance ratio of 441:1. Similar trends were seen for the view perpendicular to the fixture. The LED fixtures produced significantly greater contrast for comparable levels of maximum luminance, compared to the reference fluorescent fixture, with the exception of the G2 continuous 30-ft long fixture which had an inverted U-shaped reflector that blocked direct views of the LED source (Figure 31).

Table 26. Luminance (cd/m^2) and vertical illuminance (lux) due to the electric lighting in the reference and test areas

		Lmax (cd/m^2)	Lmin (cd/m^2)	Lmax:min	Ivert (lux)
Ref	parallel	10,500	57	181	239
	perpendicular	3,300	42	80	282
G1*	parallel	NA	NA	NA	NA
	perpendicular	1,500	6	268	36
G2	parallel	3,100	26	122	230
	perpendicular	1,900	28	67	211
G3	parallel	2,020	15	135	124
	perpendicular	2,190	11	199	57
G4**	parallel	15,000	34	441	517
	perpendicular	2,590	23	111	197

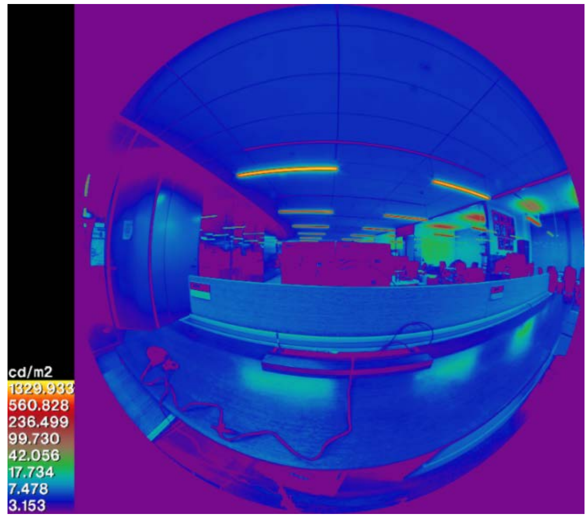
* G1 uplights are not turned on.
** The G4 test area fixture was tuned to a brighter output level than the G1-G3 fixtures.



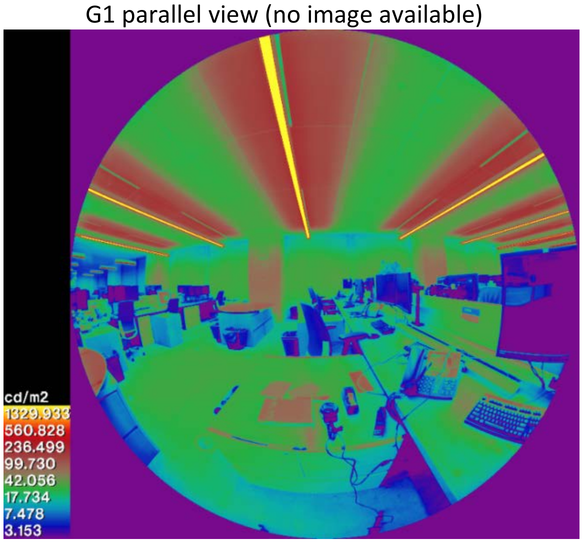
Reference parallel view　　　　Reference perpendicular view

Figure 28. Reference floor electric lighting at night: Falsecolor images showing luminance (cd/m^2) of room cavity surfaces both parallel and perpendicular to the fixture.

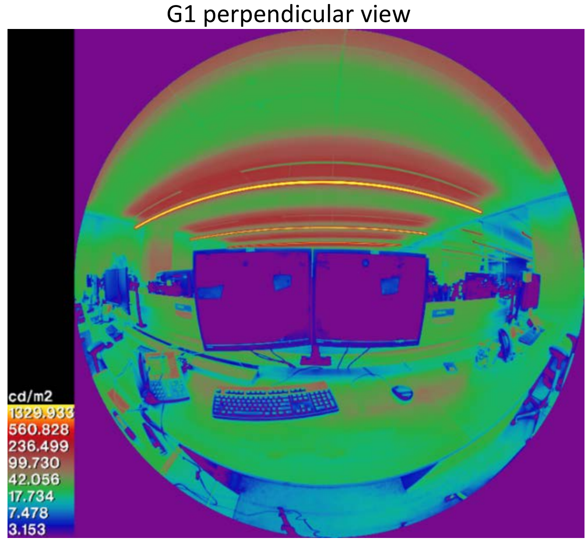
G1 parallel view (no image available)



G1 perpendicular view



G2 parallel view



G2 perpendicular view

Figure 29. Test floor, Areas G1 and G2. Falsecolor images showing luminance (cd/m^2) of room cavity surfaces both parallel and perpendicular to the fixture.
The uplights in the Area G1 fixture were not turned on (weekend condition). Note: No image available for the G1 parallel view.

At this site, the original fixture spacing was replicated for the new fixtures because there were already rigid stems and return air slots installed for the pendant fixtures. The 10 ft spacing and 18-20 inch mounting distance from the ceiling was typical (today, spacing for certain LED fixtures can be spaced up to 15-20 ft on center). The lighting designer calculated the illuminance distribution at the workplane to determine if the setpoint illuminance was met. Luminance distributions were not calculated. The lighting consultant on this project indicated that most LED fixtures do not have widespread output in the uplight direction, making it difficult to achieve uniform ceiling luminance with existing products.

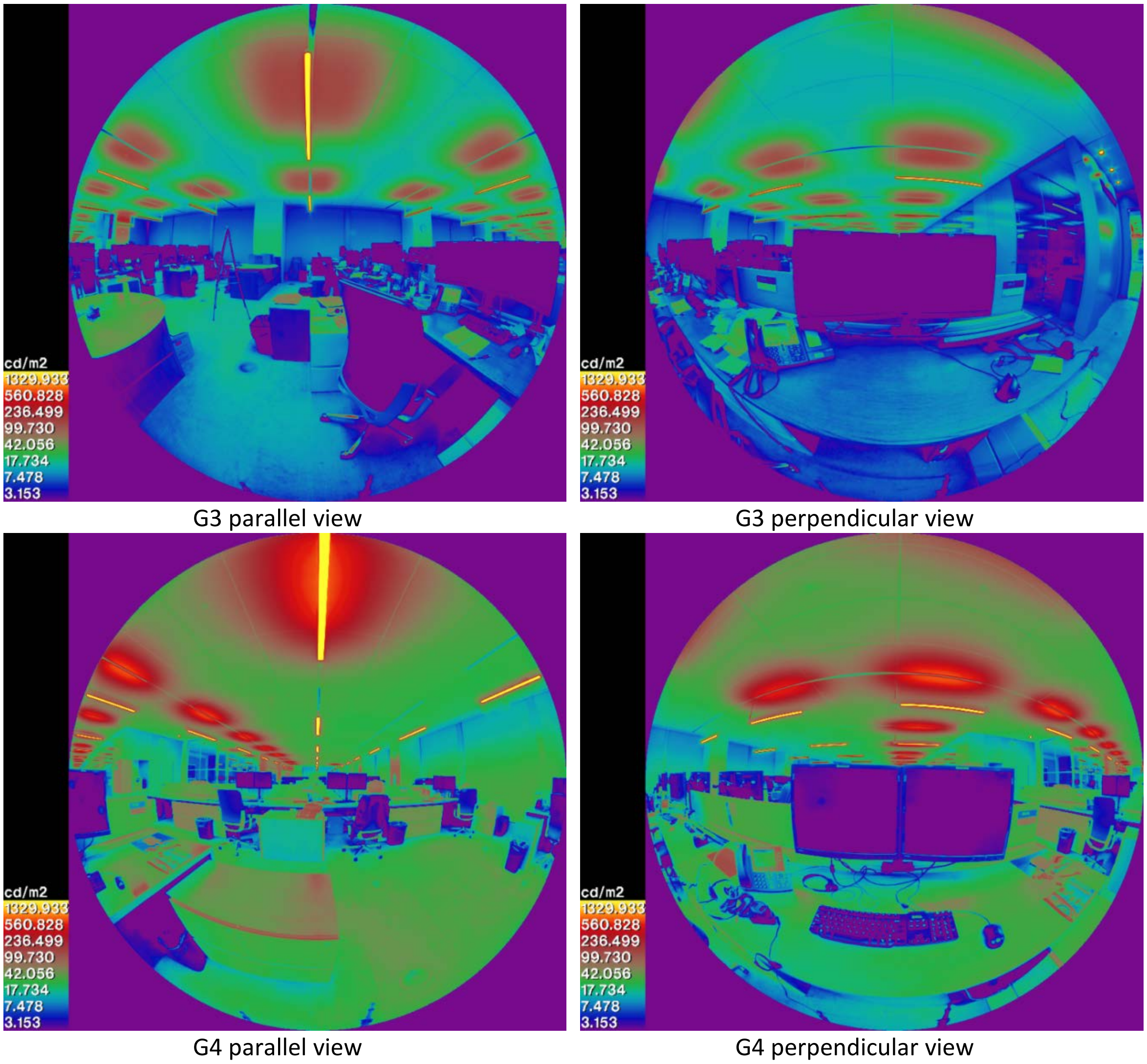
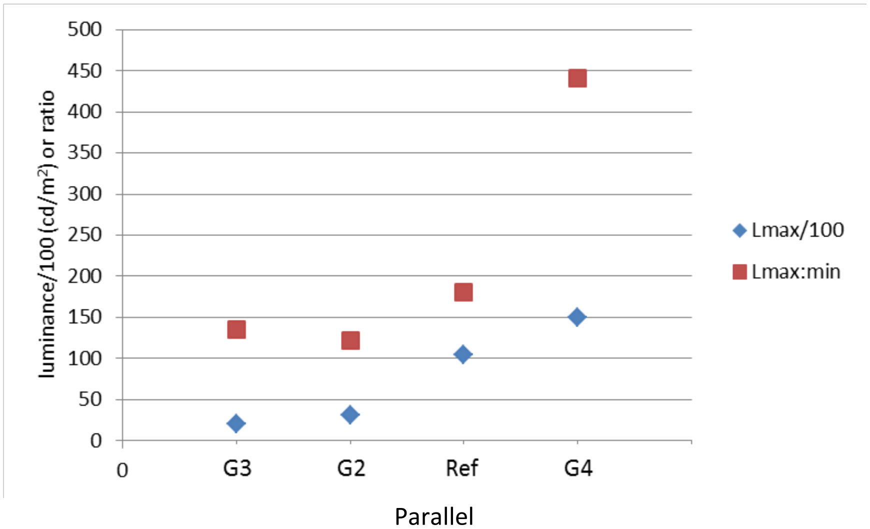


Figure 30. Test floor, Areas G3 and G4. Falsecolor images showing luminance (cd/m^2) of room cavity surfaces both parallel and perpendicular to the fixture.

Time-lapsed images were taken on June 9th, 2016 (weekend) to illustrate the qualitative appearance of the space when fully and partially occupied during the day or night (Figure 32-36). With partial occupancy on weekdays, all uplights would be ON throughout the entire quadrant if between 7 AM and 7 PM. On weekends, up- and downlights are on in only the partially occupied areas of the floor. The camera was set to determine the exposure automatically and so does not depict what would be seen by the human eye. Occupant surveys were used to evaluate comfort and environmental quality associated with the electric lighting (see Section 4.4).



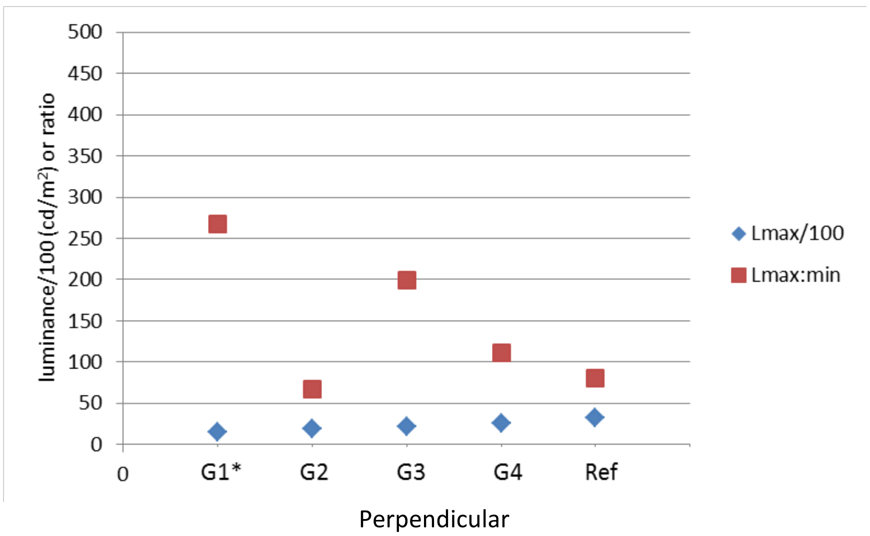
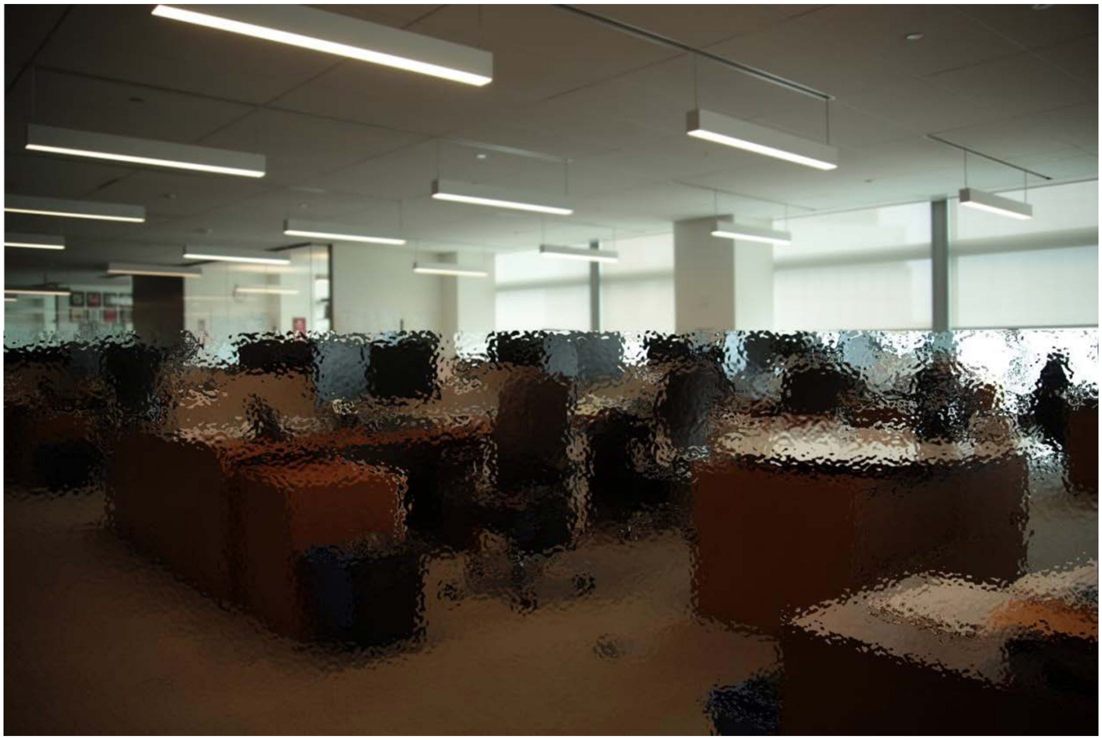
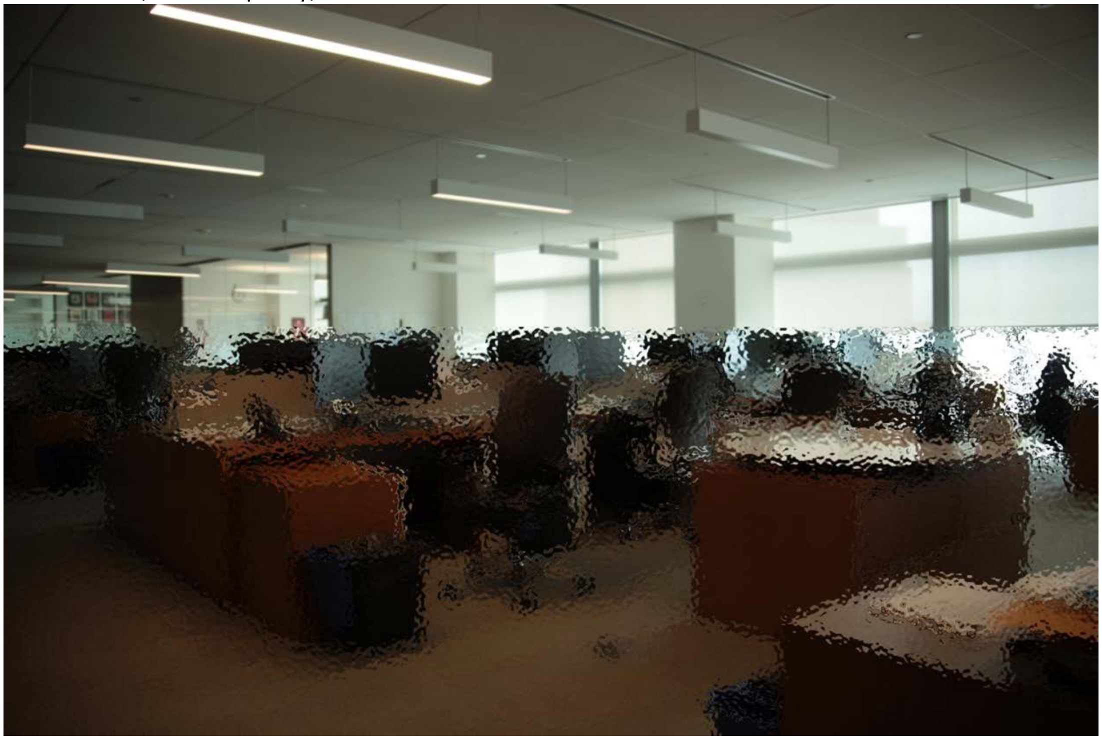


Figure 31. Maximum luminance of source (cd/m^2) versus ratio of maximum to minimum luminance across the ceiling plane.

Data are given for direct-indirect pendant LED light fixtures used on the test floor (Areas G1-G4) and pendant fluorescent light fixture on the reference floor. The reference and test floor Area G4 fixtures were set to provide the same workplane illuminance. The G4 and reference fixtures were also continuous 30 ft long fixtures. (*G1 uplights were not turned on.)

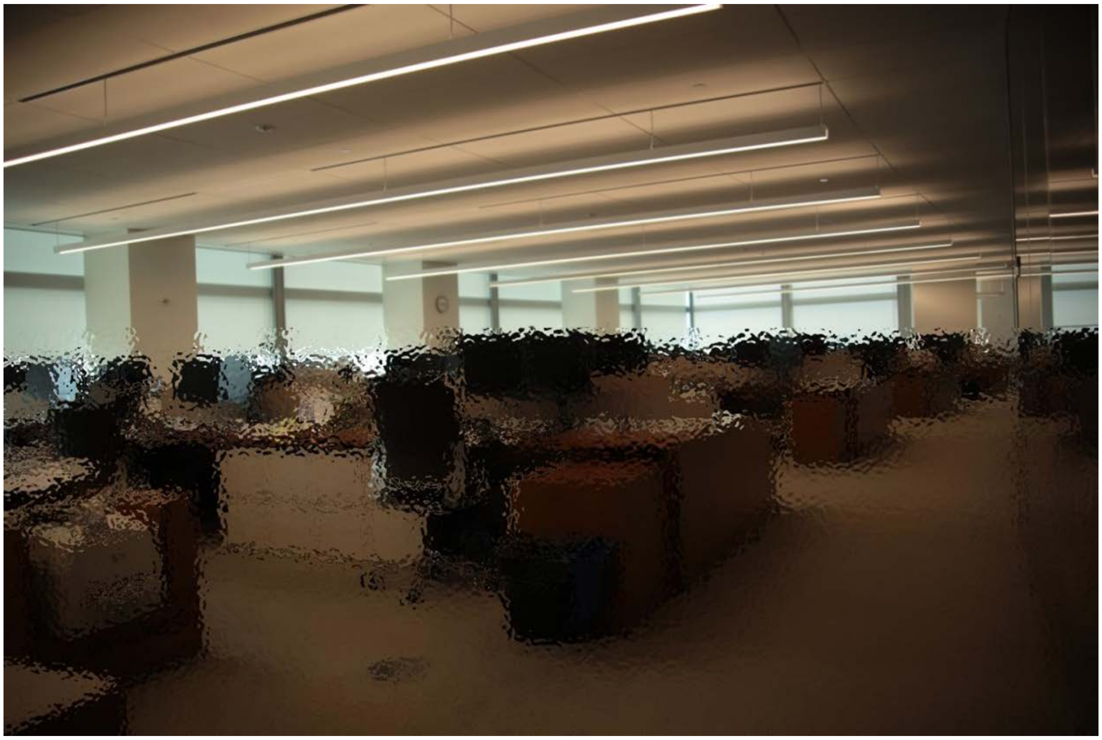


Test Area G1, full occupancy, weekend condition

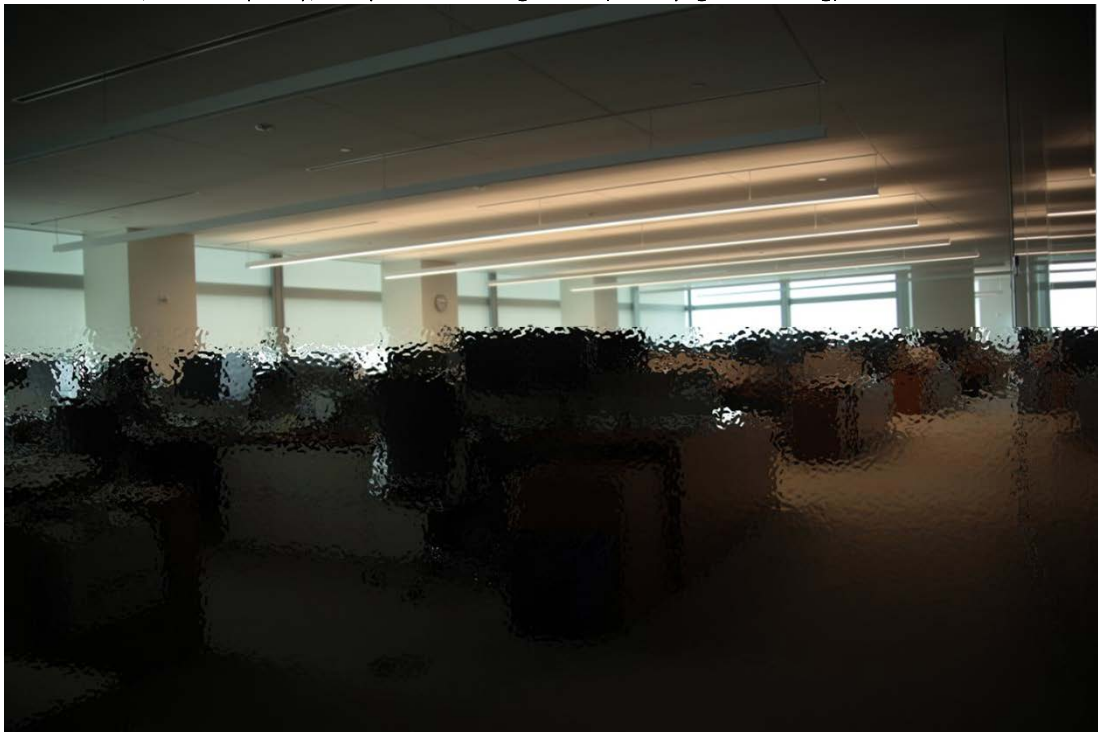


Test Area G1, partial occupancy, weekend condition

Figure 32. Test floor, Area G1 looking west towards the windows and perimeter open plan offices with the private offices with glass rear walls on the south (left) side of the image. July 9, 2 PM.

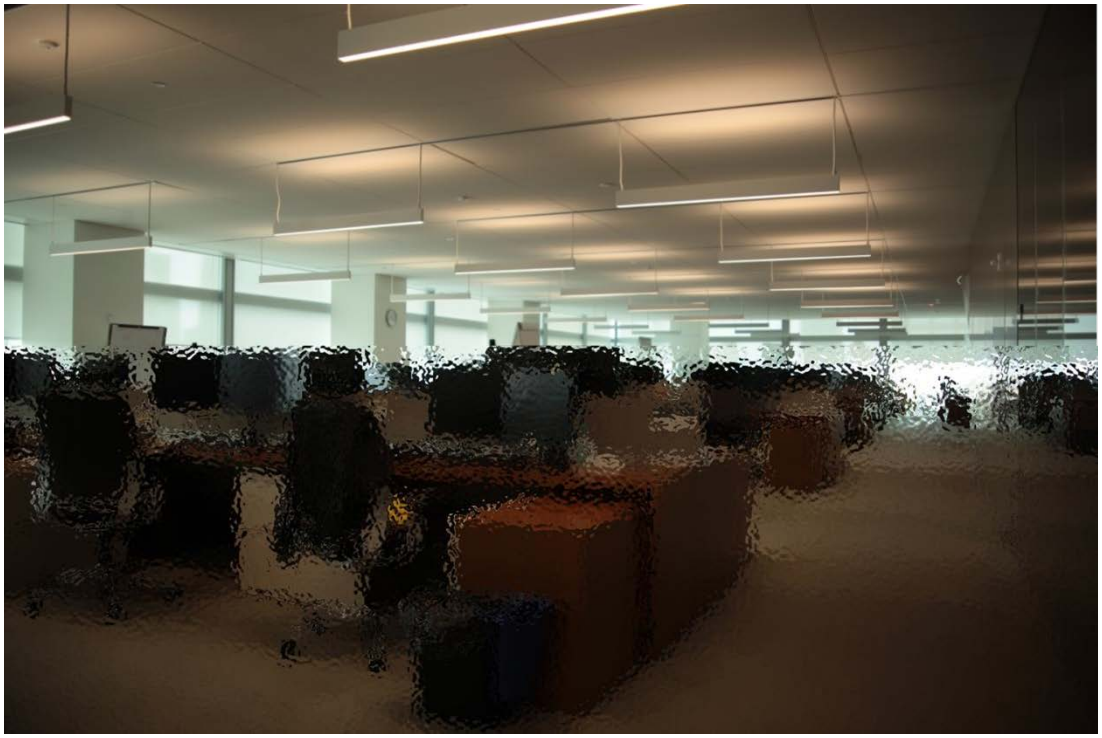


Test Area G2, full occupancy, all up- and downlights on (no daylight dimming)

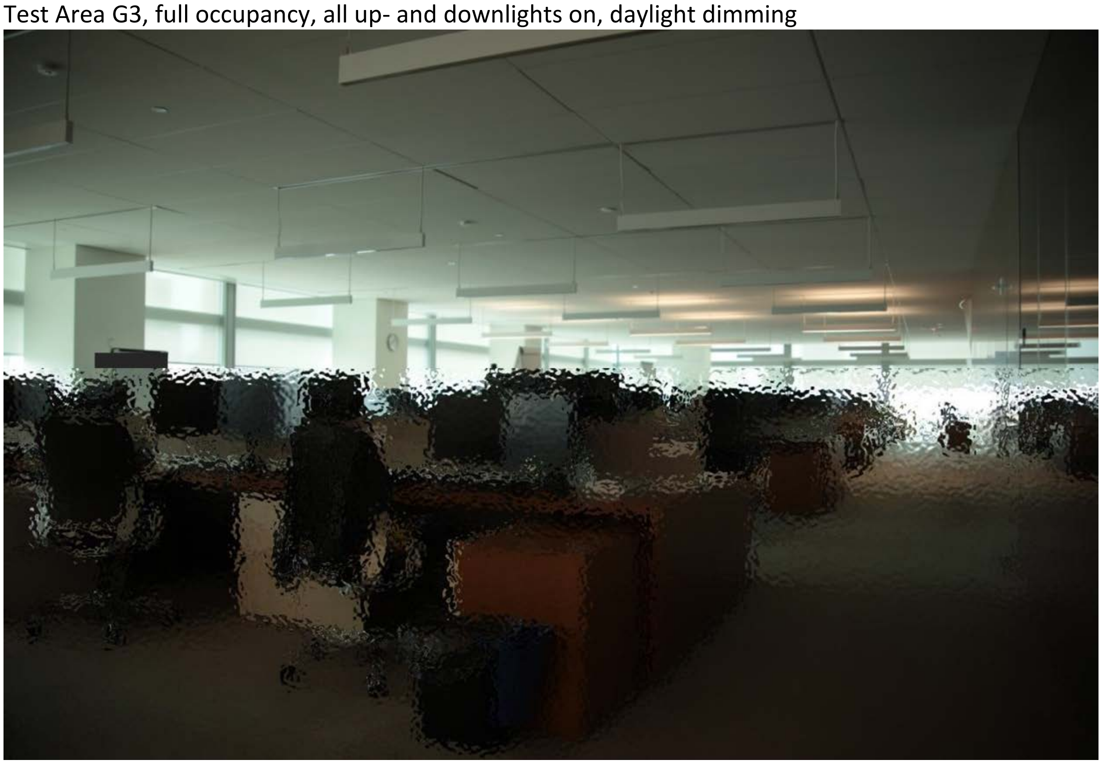


Test Area G2, partial occupancy, weekend (if weekday, all uplights in Area would be ON and downlights in occupied areas would be ON)

Figure 33. Test floor, Area G2 looking northwest towards the curved west windows (on left) and perimeter open plan offices.
North-facing windows are toward the back (right). July 9, 2 PM. This is a weekend so uplights are not all on as they would be on weekdays.

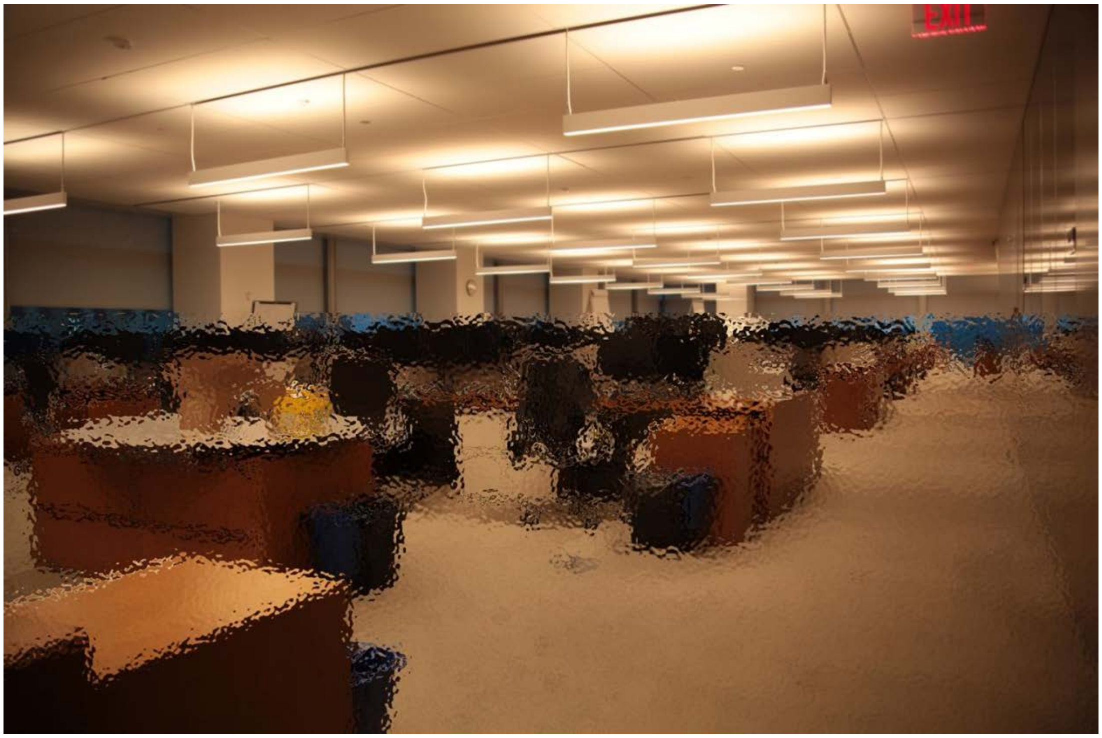


Test Area G3, full occupancy, all up- and downlights on, daylight dimming

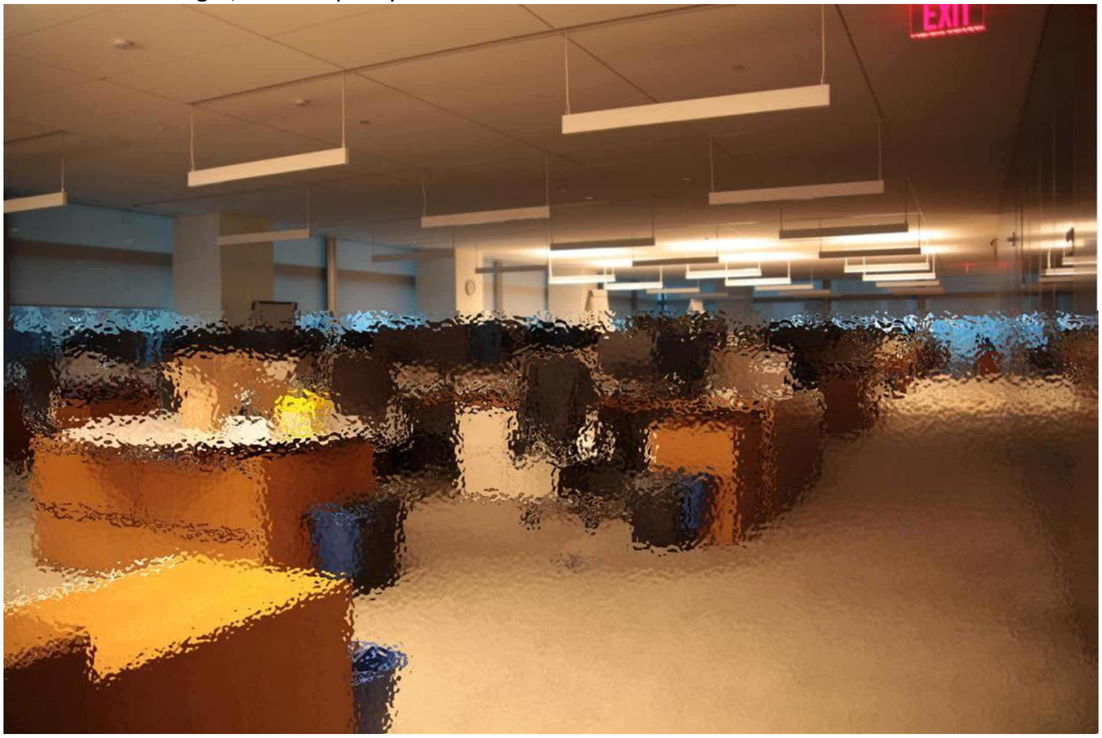


Test Area G3, partial occupancy, weekend (if weekday, all uplights in Area would be ON and downlights in occupied areas would be ON)

Figure 34. Test floor, Area G3 looking southeast towards the east windows and perimeter open plan offices. South-facing windows are at the back of the space. July 9, 10:30 AM.



Test Area G3 at night, full occupancy



Test Area G3 at night, partial occupancy (if weekday before 7 PM, all uplights in Area would be ON and downlights in occupied areas would be ON)

Figure 35. Test floor, Area G3 looking southeast towards the east windows and perimeter open plan offices. South-facing windows are at the back of the space. July 9, 8 PM.

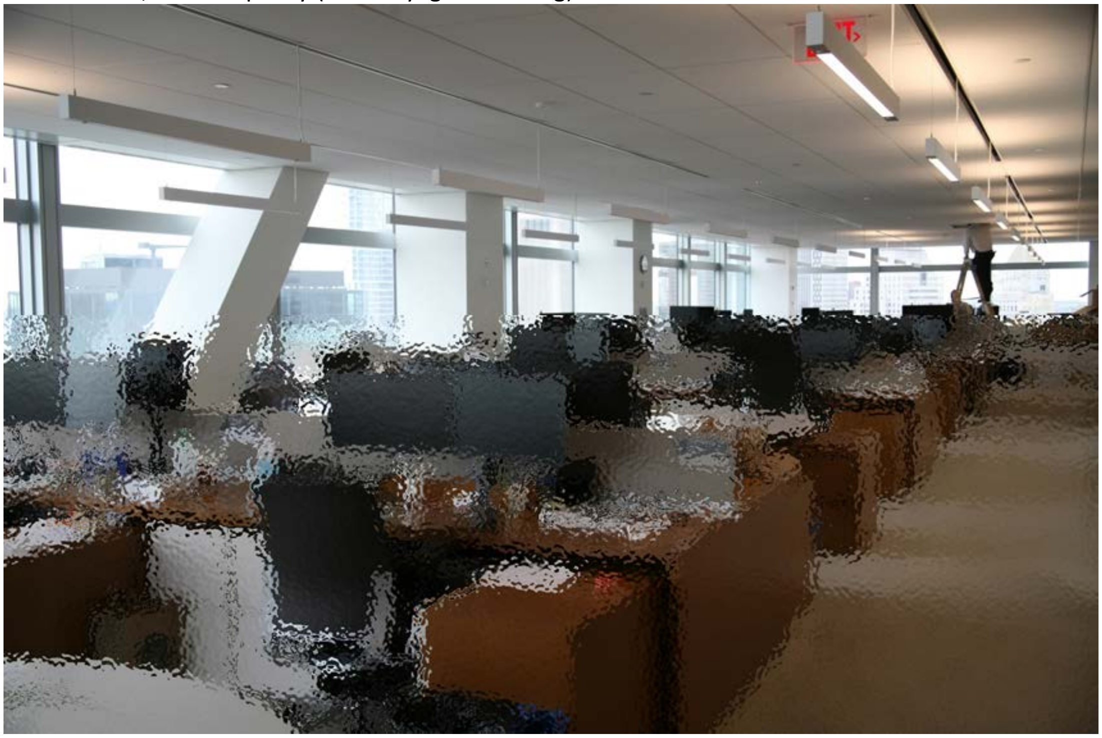

Test Area G4, full occupancy (with daylight dimming)

Test Area G4, partial occupancy (if weekday, all uplights in Area would be ON and downlights in occupied areas would be ON)

Figure 36. Test floor, Area G4 looking northeast towards the east windows and perimeter open plan offices.
North-facing windows are to the left in the image. March 19, 1:40 PM (upper) and 2 PM (lower), weekend.

4.2. Performance of Automated Shades

4.2.1. Operational modes of control

4.2.1a – Areas G1 and G4

The operational modes of the existing reference shade have been verified by LBNL in prior studies [Lee et al., 2013; McNeil et al., 2014]. The system was shown to operate according to the manufacturer's sequence of operations: i.e., raise and lower the shade based on scheduled events, control direct sunlight to the prescribed depth from the window, and control window brightness. This system's unique ability to control window solar heat gains to within a prescribed limit was not verified. Verification of control system operations was not repeated in this study.

Shade position was recorded by the manufacturer through their energy management control system. To explain how the shades were operated, these data were plotted for each façade orientation (Figure 37-38). A few trends can be noted from these plots:

- Shades were lowered as intended from 8 PM to 6 AM in the morning on weekdays and from 6 PM to 6 AM on weekends.
- On the east, shades were lowered starting around 7-8 AM until around noon to control direct sun then raised to position 3 (43 inches above the floor) until about 2 PM during the winter and as late as 7 PM during the summer to control window brightness on sunny days.
- On the west, the reverse pattern occurred. Shades were lowered to position 3 starting around 10 AM until the afternoon to control window brightness, then further lowered to block direct sun in the afternoon on sunny days.
- Shades were raised and lowered throughout the day depending on sky conditions.
- During the winter period, there was a considerable amount of time, in the afternoon on the west for example or on the north, when the shades were fully raised. Otherwise, sky conditions were sufficiently bright for the rest of the year to require use of the shades given the large area, high transmittance windows (visible transmittance of 0.65).

Figure 39 shows time-lapsed images taken in Area G1 on the reference floor, illustrating how the shades operated over a sunny afternoon during the equinox period for a west-facing orientation. Notice how the brightness from the orb of the sun was diffused by the roller shade fabric. Partial view was possible through the fabric itself (3% openness factor).

On any given façade, the shades are as a general rule expected to be aligned: that is, controlled together to the same bottom-of-hem height to maintain a uniform appearance across the façade. During site visits (conducted during equinox and solstices), all shades were observed to have no discernable difference in height between adjacent shade bands throughout the day.

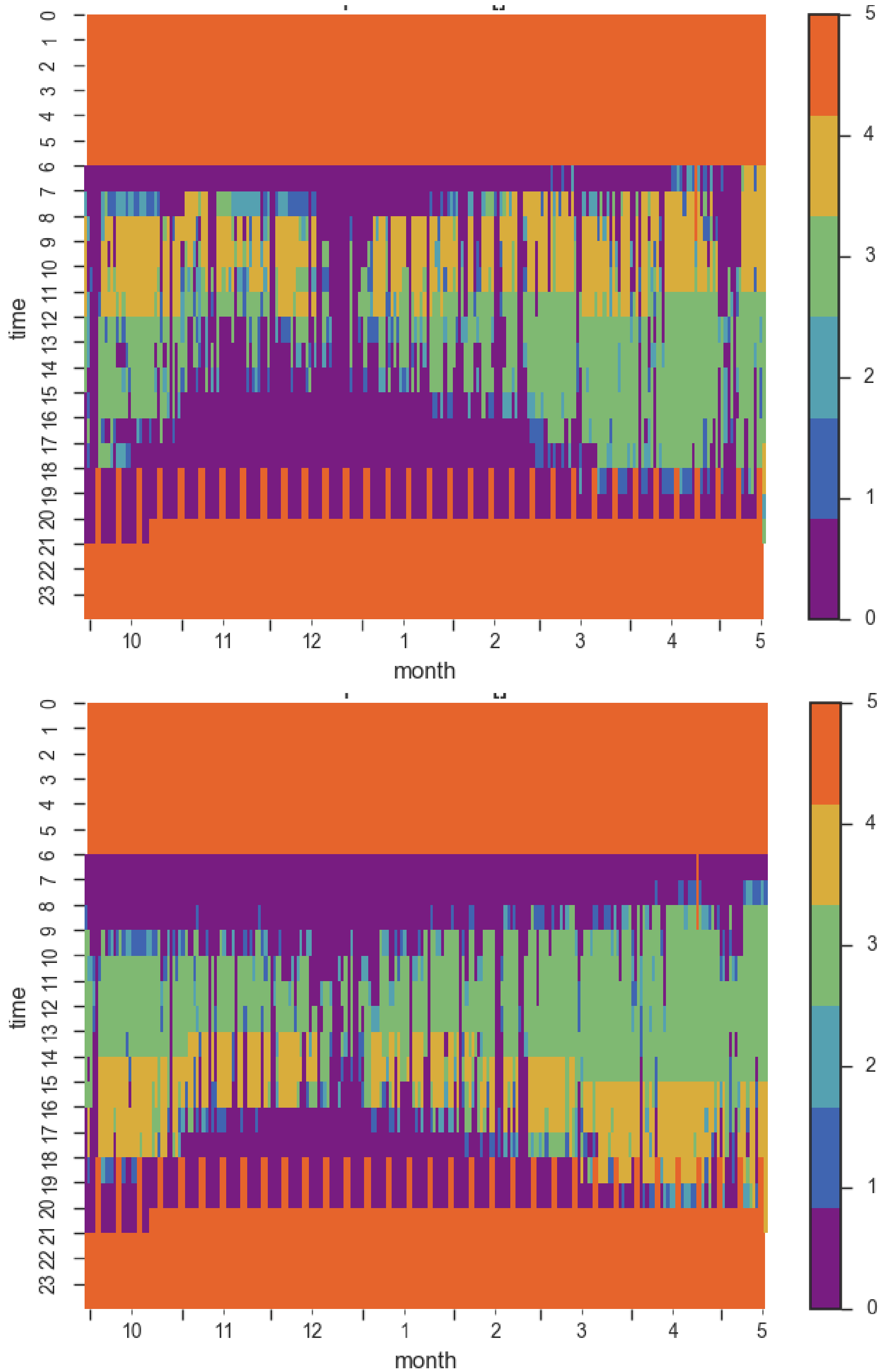


Figure 37. Upper: East, Lower: West-facing façade, Area G3, reference floor. Average hourly shade position for the monitored period from September 29, 2015 to May 16, 2016.
Position 0 is fully raised and position 5 is fully lowered. All data are given in local time (LT).

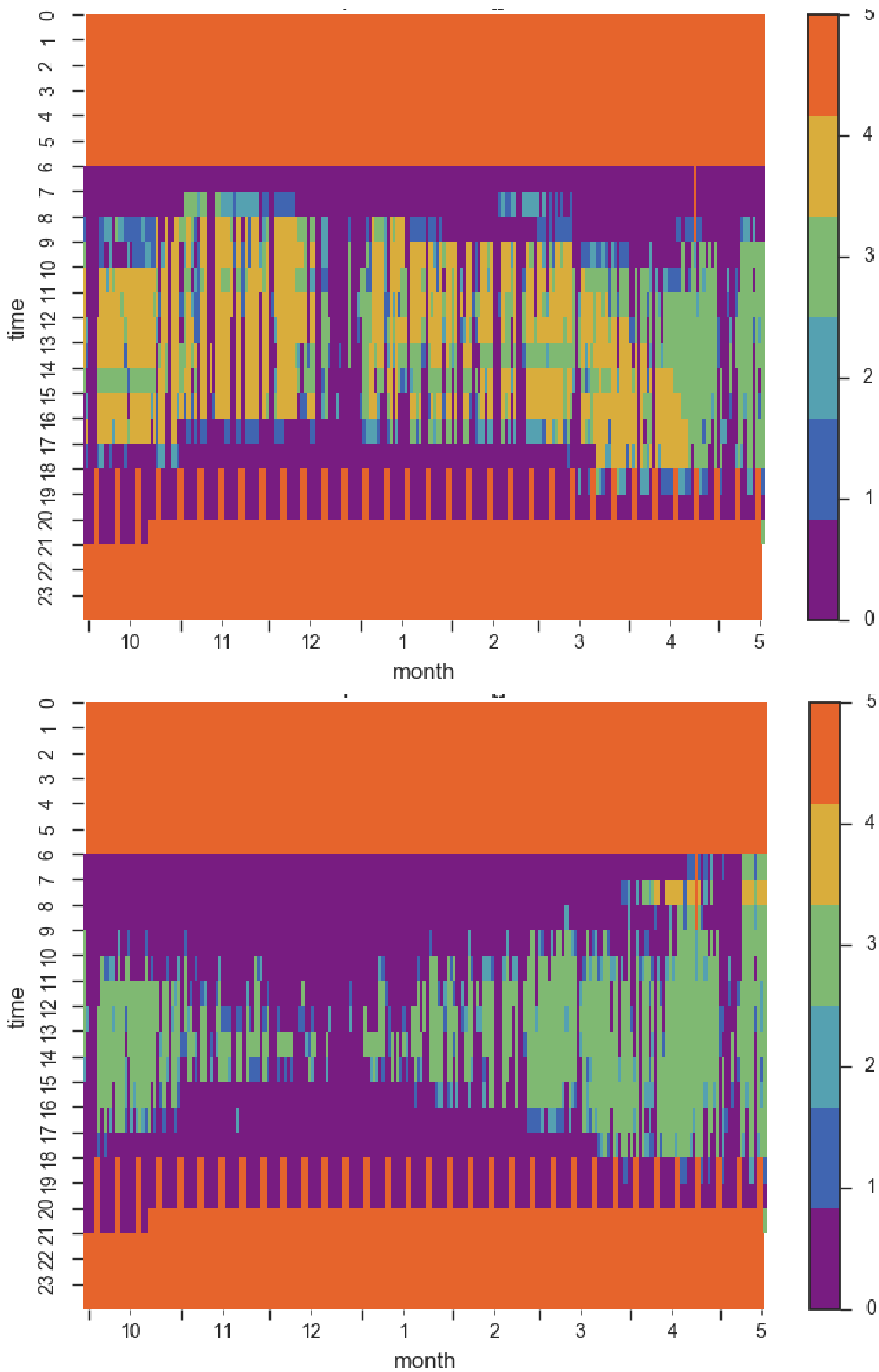
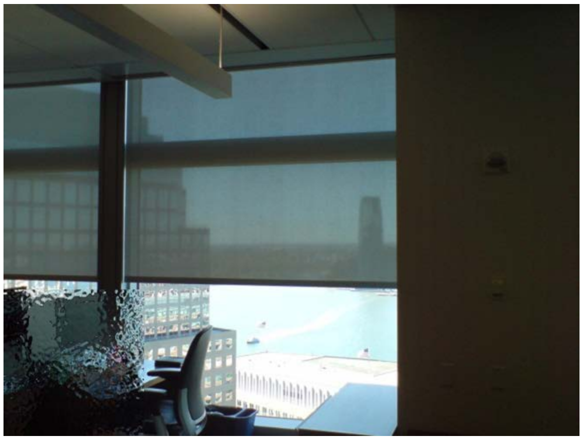


Figure 38. Upper: South, Lower: North-facing façade, Areas G3-G4, reference floor. Average hourly shade position for the monitored period from September 29, 2015 to May 16, 2016.
Position 0 is fully raised and position 5 is fully lowered. All data are given in local time (LT).

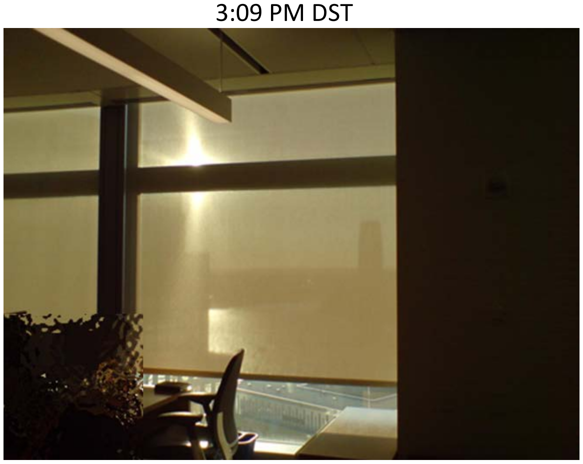


2:00 PM DST

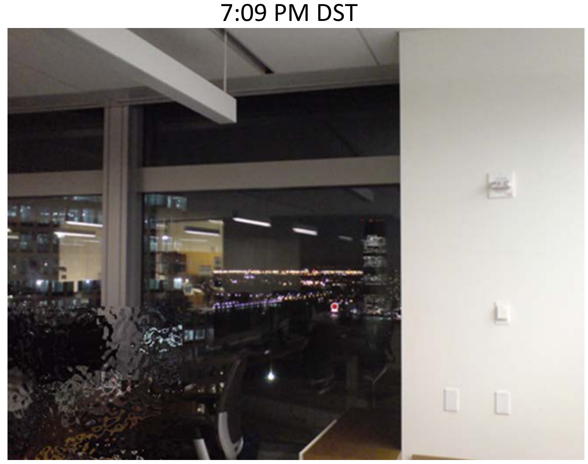
6:39 PM DST

3:09 PM DST

7:09 PM DST



6:09 PM DST



7:59 PM DST

Figure 39. West-facing façade, Areas G1-G2, reference floor. Time sequence showing shade operations on a sunny day, October 23, 2015.

4.2.1b – Areas G2 and G3

The operational modes of the second automated shade system were also verified by LBNL in a prior (unpublished) field study. The system was shown to operate according to the manufacturer's sequence of operations for the schedule, direct sun, brightness, and daylight modes of control.

In the LL building, the owner said that the installation was straightforward and that they encountered minimal issues when installing the shades. They found that correct placement of the window-mounted sensors (one per orientation in each Area) was critical for proper control, particularly in a dense urban environment. One wireless, battery-operated sensor was incorrectly placed and was shaded by the building, causing the control system to raise the shades as if there was no sunlight on the façade. This caused significant discomfort, but was diagnosed and corrected without the trouble of re-wiring.

At the LL site, the vendor logged shade height on their central server, but these data were not available for the study. Screen shots taken during periodic site visits of the vendor's control system interface are given to illustrate the control modes for the east, south, and west-facing window orientation. These images illustrate operations on a partly sunny day during the equinox and summer solstice (Figure 40-41).

For the west-facing façade in Area G2, the automated shades were controlled as follows during equinox conditions (Figure 40 upper graph):

1. From midnight to 5 AM (nighttime) on a weekday (March 18, 2016), the shades were fully raised.
2. From 5 AM until about 7:30 AM (sunrise), the shades were set to the visor position (50% of full height or 4.5 ft above the floor).
3. From 7:30 AM (sunrise) until about 1 PM, the shades remained in the visor position:
    - The sun was not in the plane of the window, so the direct sun control mode was not in effect during this time.
    - The shades were in the visor position because the sensor signal was between 150-2000 fc and it was the lower of the direct sun and visor positions. The shades were in the brightness control mode.
4. Between 1:00 PM and 7:15 PM, the shades were lowered gradually at 1 hour intervals to limit the depth of direct sunlight penetration into the space.
    - The sun was in the plane of the window and the sun signal was between 150-2000 fc, so the direct sun control mode was in effect during this time.
    - The shades were positioned to the direct sun control position since it was the lower of the direct sun and visor positions.
    - The sun sensor signal was on occasion greater than the 2000 fc brightness override threshold but because this control mode was not enabled, the shades were not lowered further.
5. At 7:15 PM (sunset), the shades were fully raised. The sun sensor signal fell below the dark threshold level of 150 fc at this time as well, so the daylight mode also raised the shades.

During summer solstice conditions (Figure 40 lower graph), the shades were controlled the same way. At around 6 PM, the sun signal was below the "dark" threshold of 150 fc so the shades were raised fully for a brief time then lowered. Shades were raised after sunset (after the screen capture was made).

For the east-facing façade, the automated shades were controlled during equinox conditions (Figure 41 upper graph) as follows:

1. From midnight to 5 AM (nighttime) on a weekday (March 18, 2016), the shades were fully raised.
2. From 5 AM to 6 AM (before sunrise), the shades were set to the “visor” position (50% of full height) as described for scheduled control.
3. Between 6 AM and 7:30 AM (before sunrise) and then from sunrise to about noon, the shades were gradually raised at 1 hour intervals to limit the depth of direct sunlight penetration into the space. The sensor reading was between the dark and bright thresholds and the direct sun control mode’s shade height was lower than the visor shade height.
4. From noon to 7:15 PM (sunset), the shades were set to the visor position since the sun sensor signal was between 150-5000 fc during this time.
5. The shades were raised at sunset (after the screen capture was made).

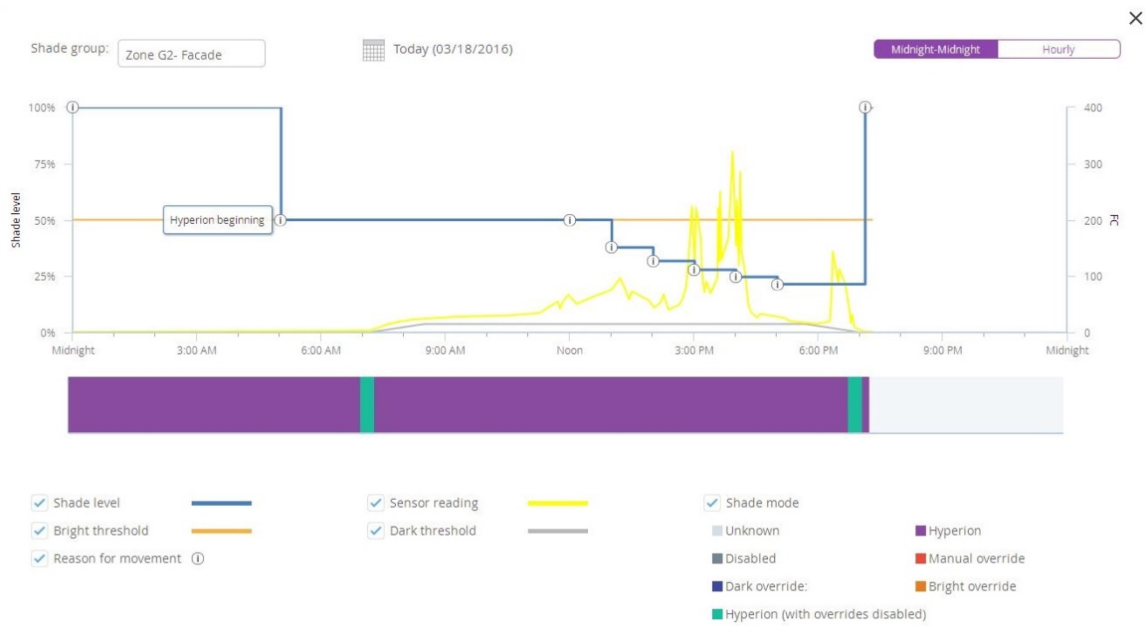
For these examples, the control system adhered to the manufacturer’s sequence of operations with several exceptions:

- the window sensor for the east façade in Area G3 failed or communications to the sensor failed as of May 16, 2016 (no error was reported by the interface); and,
- the window sensor for the south façade also failed as of May 23, 2016.

When this occurred, the east and south shades operated in the same manner as before (Figure 41-42 lower graphs), because the sensor value was reported to be 65,000 fc at all times over the 24-hour period.

Because the dark threshold was set to a very low level (150 fc, which corresponded with the low light level that occurs at sunrise and sunset), the shades were rarely raised above the visor position (50% of full height or 4.5 ft) until after sunset, even on cloudy days.

During site visits (conducted during equinox and solstices), all shades were observed to be aligned, with no discernable difference in height between adjacent shade bands throughout the day.



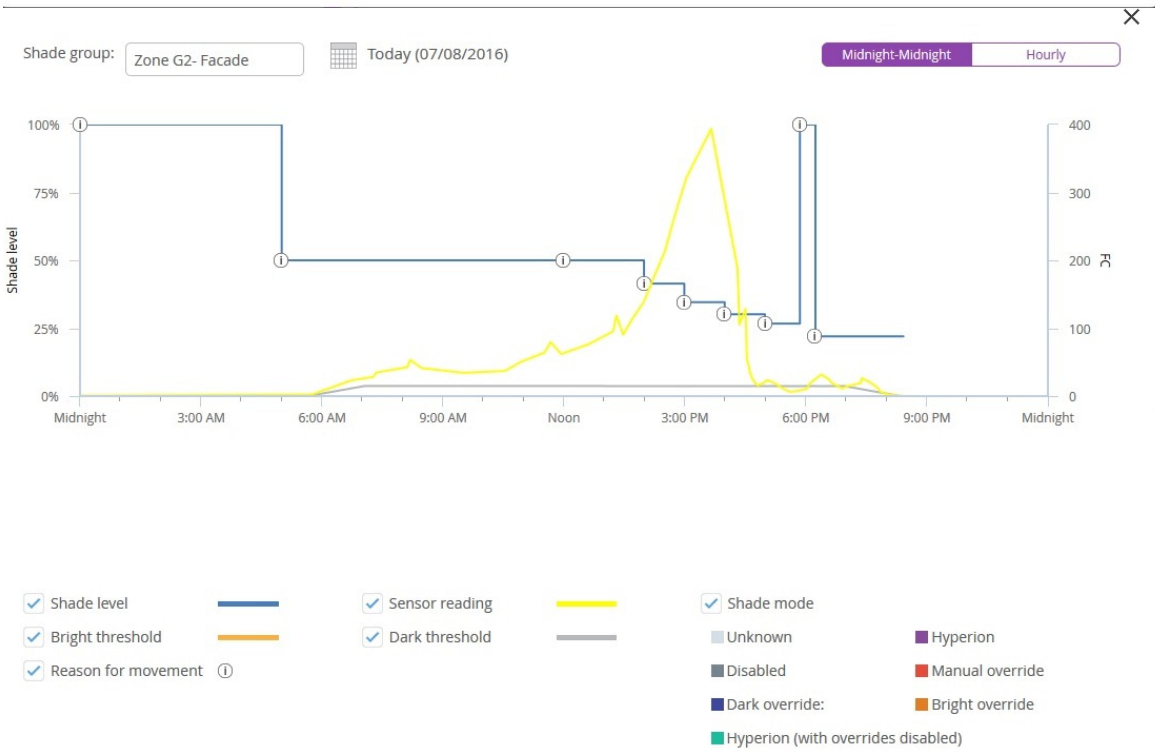


Figure 40. West-facing façade, Area G2, test floor, March 18 (above) and July 8 (below). Screen capture of vendor's interface showing shade position and window sensor signal versus time of day.
Note that the right-hand y-axis units should be multiplied by 10.

Figure 41. East-facing façade, Area G3, test floor, March 18 (above) and July 8 (below). Screen capture of vendor's interface showing shade position and window sensor signal versus time of day.
Note that the right-hand y-axis units should be multiplied by 10.

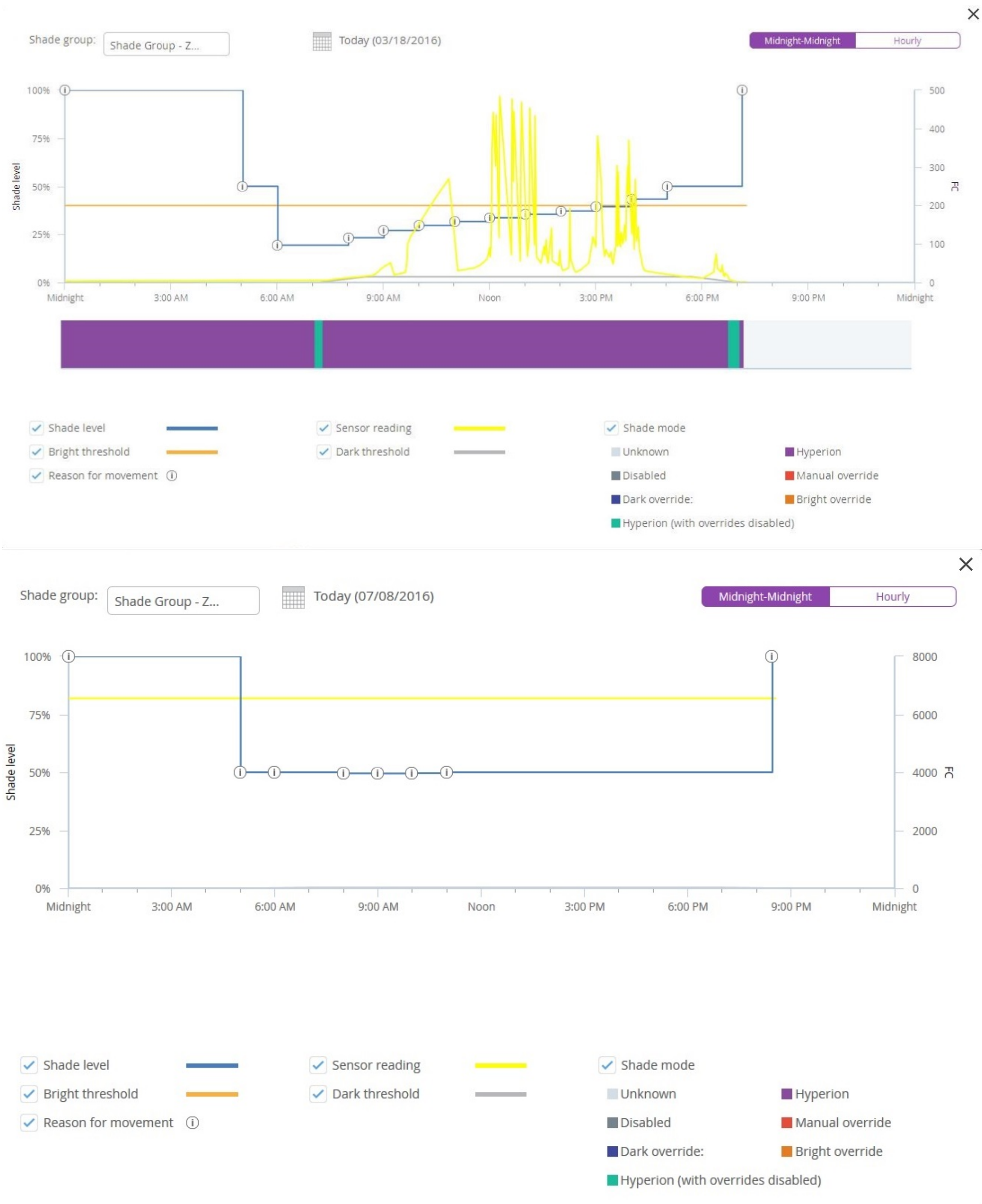


Figure 42. South-facing façade, Area G3, test floor, March 18 (above) and July 8 (below). Screen capture of vendor's interface showing shade position and window sensor signal versus time of day.
Note that the right-hand y-axis units should be multiplied by 10.

4.2.2. Thermal comfort

Cold window surface temperatures during the winter or hot surface temperatures and direct sunlight during the summer can cause thermal discomfort near windows. This study provided an opportunity to evaluate thermal comfort adjacent to windows with automated shades: occupants in the open plan areas worked within 2 ft from the window, the windows were large in area, and the reference and test floors were exposed to approximately the same outdoor environmental conditions. The primary variables in this comparison were openness of the shade fabric and how the shades were operated.

With roller shades, fabric choice is a compromise between a variety of competing issues: more view and daylight through the fabric versus glare control; more solar transmission through the fabric for passive solar heating or less to control cooling load; lighter fabric color to enhance interior brightness or darker fabric to enhance views out. Once the fabric is selected, the combination of outdoor weather conditions (primarily outdoor temperature and solar irradiance), window properties, shade properties and position, and HVAC operating conditions dictate thermal comfort near the window wall.

To summarize the context, a 3% openness factor (OF) light gray shade was used on the reference floor while a 1% OF (in Area G2 west) and 3% OF (in Area G3 east) light gray shade by a different manufacturer was used on the test floor. Both shades were operated generally to control direct sun and glare. Since control was implemented by two different manufacturers, there were differences in the way the shades were operated throughout the day. The windows were floor-to-ceiling, dual-pane, spectrally selective, low-emittance insulating glass units (SHGC=0.35, U-value=0.29 Btu/h-ft^2-°F) with thermally-broken aluminum framing. East windows faced 19° south of due east while the west windows formed a single broad curved arc.

In the area where the sensors were located, perimeter heating and cooling were supplied from a variable volume fan coil unit through a ceiling-mounted linear diffuser. Swirl diffusers at floor level provided low-velocity air from the underfloor air distribution system. The swirl diffusers were located about 6-7 ft behind the desk in the corridor between desks. The setpoint temperature of 72°F (winter) or 74°F (summer) was maintained on weekdays from 6 AM to 6 PM, but could be extended if occupants worked late. When in heating mode, the perimeter fan coil unit operated at minimum speed while the heating valve on the four-pipe system was adjusted to maintain the setpoint temperature. When in cooling mode, variable volume air was supplied at 55°F. Thermostats were located at the perimeter on the face of the building columns (facing the core). During the night on weekdays and all day on weekends and holidays, space temperatures were maintained within a 62-80°F range.

Predicted mean vote (PMV) and percentage of people dissatisfied (PPD) levels were determined on the reference and test floors at a distance of 3 ft from the window and at head height. These data are shown in Figure 43 and 44 for the west-facing G2 zone on the reference and test floors for the December 1, 2015 to June 30, 2016 period.

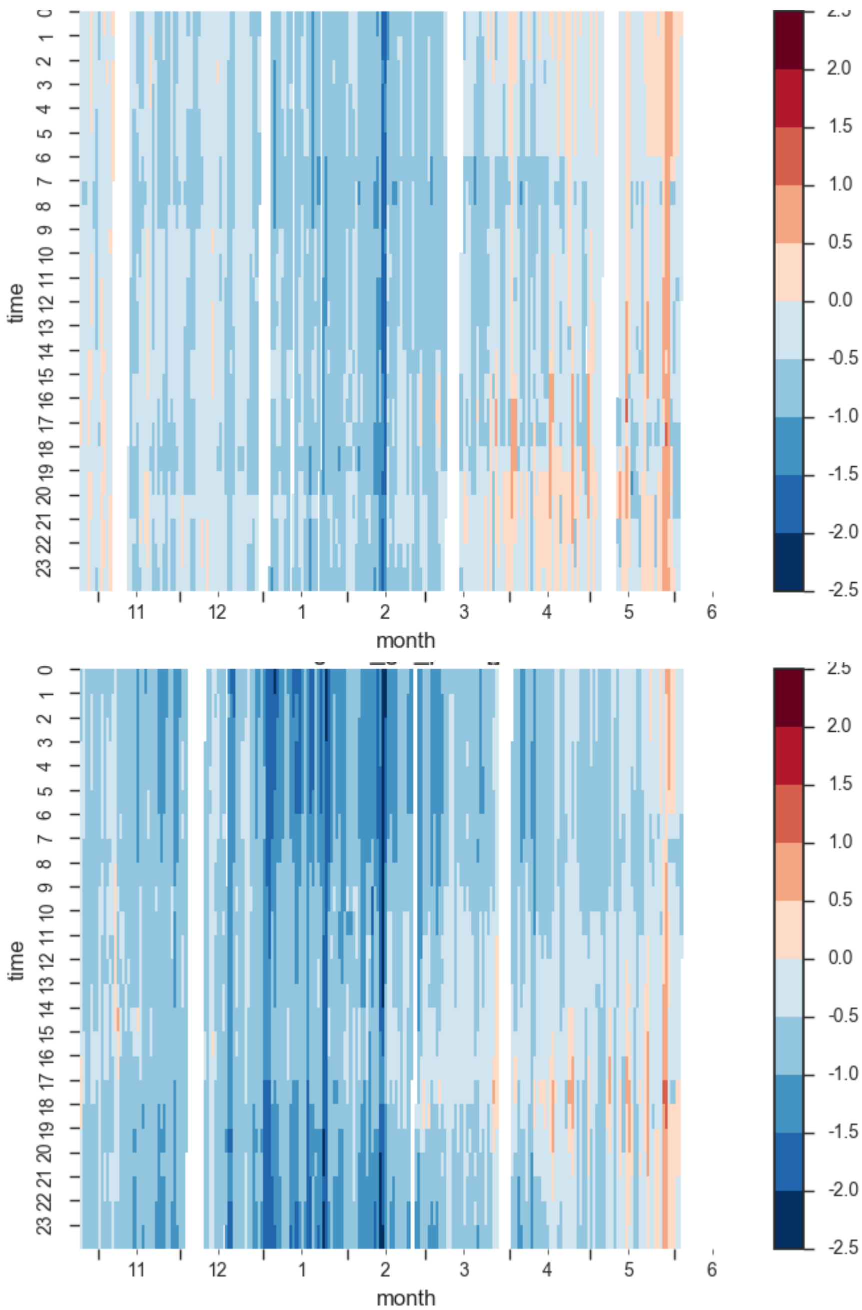


Figure 43. PMV, West, clo=0.61. Temporal plot showing hourly PMV levels from December 1 to May 30, 2016 for the west-facing G2 zone on the reference (upper plot) and test (lower plot) floors.

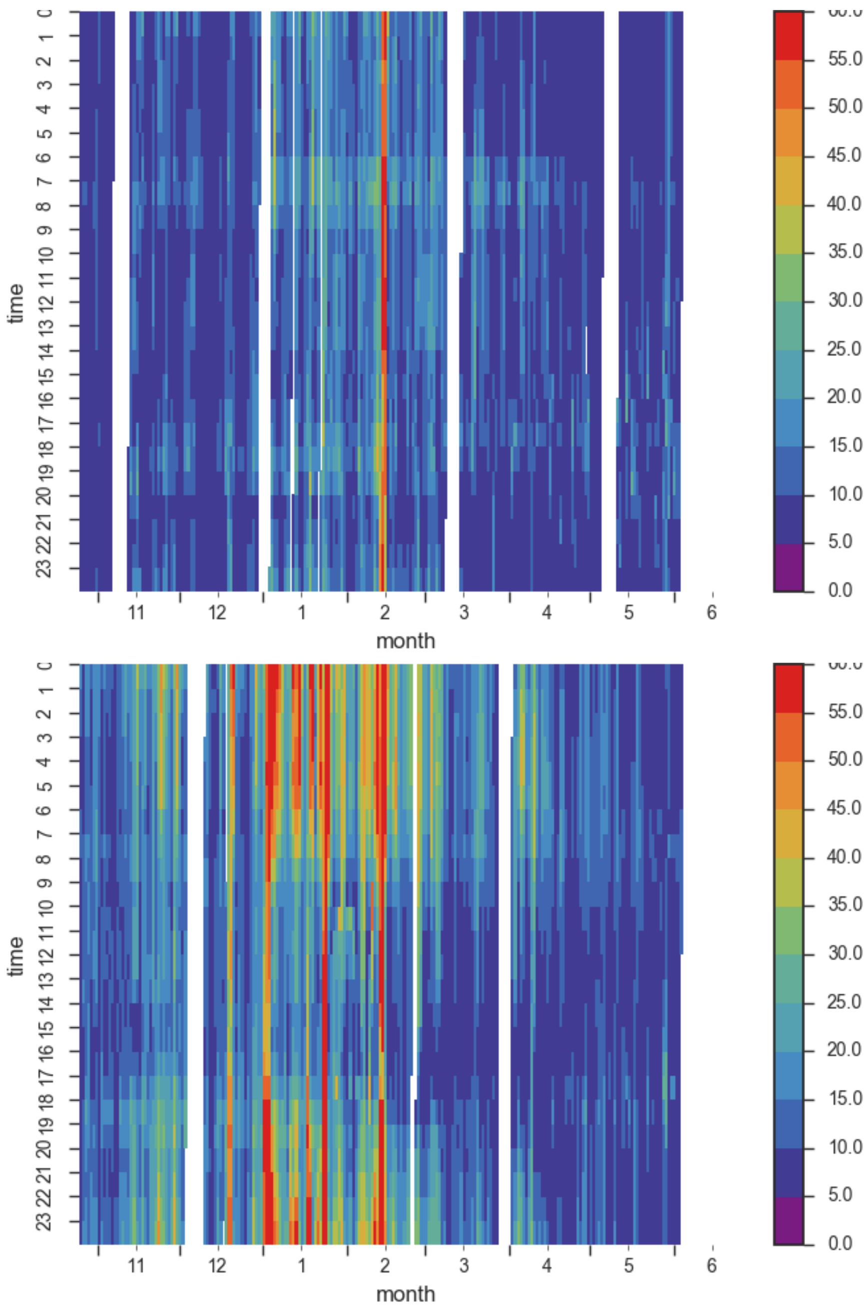


Figure 44. PPD, West, clo=0.61. Temporal plot showing hourly PPD levels from December 1 to June 30, 2016 for the west-facing G2 zone on the reference (upper plot) and test (lower plot) floors.

Calculations for PMV and PPD were conducted assuming a summer clothing level (clo=0.61). For the majority of the six-month period, PMV values were within the -0.5 to +0.5 PMV range defined as thermally acceptable by ASHRAE Standard 55.

- Reference floor areas G2 and G3 with the 3% OF fabric were comfortable for 88.4% (west) and 86.7% (east) of the assessed period when PPD levels were less than 20% (Table 27).
- Test floor areas G2 and G3 with 1% and 3% OF fabric, respectively, were comfortable for 84.6% (west) and 86.0% (east) of the time.
- Average air velocity was 0.04 ± 0.02 m/s and average relative humidity was 31 ± 7% over the 6-month monitored period.
- For the remaining periods when PPD was equal to or greater than 20%, discomfort due to slightly cool conditions (-PMV) was due to the HVAC system delivering relatively cool temperatures at moderate air velocities. MRT values were within only a degree or two from DBT values, indicating that temperature asymmetry due to cold window or shade surfaces was not a contributing factor to PPD levels greater than or equal to 20%.

If occupants were assumed to be wearing a light jacket or sweater, the clo level is raised to 1.0, reducing the frequency of thermal discomfort.

- Reference floor areas G2 and G3 with the 3% OF fabric were comfortable for 99.5% (west) and 98.2% (east) of the assessed period when PPD levels were less than 20% (Table 28).
- Test floor areas G2 and G3 with 1% and 3% OF fabric, respectively, were comfortable for 98.9% (west) and 98.7% (east) of the time.
- For the 7-16 hours over the six month period when PPD was equal to or greater than 20% and +PMV was greater than 0.5 (warm discomfort), we expected to see a potential influence of temperature asymmetry on thermal discomfort. At certain angles, sunlight can be transmitted directly through the fabric without diffusion (Figure 45-46). If incident on the occupant, this direct solar irradiance can cause thermal discomfort. With the more densely woven 1% OF fabric, however, the monitored +MRT was greater on average than the ambient +DBT by 6.4°C (Table 28) whereas with the more open 3% OF fabric, the +MRT was less than the +DBT by about 0.5°C. Proximity to the ceiling linear diffuser may have had an influence on monitored MRT readings (the DBT sensor was under the desk) or the VAV system may have just been operating more diligently with the higher loads from the 3% OF fabric. Thermal infrared time-lapsed images (Figure 47) confirm that shade surface temperatures when the shade was directly irradiated were within the 29.8-31.8°C range, which were in agreement with the +MRT values.

Two conclusions can be inferred from these data: 1) the combination of the low-emittance window and automated shading system contributed to a well-controlled thermal environment within 3 ft from the window despite the prevalence of low-angle sun for the west- and east-facing orientations, and 2) differences between the 3% and 1% OF fabrics and controlled shade positions had minimal impact on differences in thermal discomfort between the reference and test floors. Perimeter heating and cooling however most likely mitigated these impacts.

Table 27. Levels of thermal discomfort, December 1 to June 30, weekdays 7 AM to 7 PM, clo=0.61.

		PPD < 20%	PPD>=20% -PMV	-DBT (degC)	-MRT (degC)	-Vair (m/s)	+PMV	+DBT (degC)	+MRT (degC)	+Vair (m/s)
Ref G2	%time	88.4%	11.6%				0.0%			
West	hours		166.9				0			
3% OF	Avg		-1.02	22.72	21.35	0.06	na	na	na	na
	Stdev		0.19	1.09	1.00	0.05	na	na	na	na
Test G2	%time	84.6%	15.3%				0.1%			
West	hours		224.7				0.9			
1% OF	Avg		-1.05	22.16	21.63	0.05	0.91	23.78	33.44	0.09
	Stdev		0.19	0.64	0.94	0.04	0.05	0.47	0.94	0.05
Ref G3	%time	86.7%	13.3%				0.0%			
East	hours		190.4				0.0			
3% OF	Avg		-1.12	21.47	21.88	0.02	na	na	na	na
	Stdev		0.46	1.43	1.73	0.02	na	na	na	na
Test G3	%time	86.0%	14.0%				0.0%			
East	hours		203.7				0.0			
3% OF	Avg		-1.05	21.39	22.37	0.03	na	na	na	na
	Stdev		0.22	0.64	1.11	0.01	na	na	na	na

Table 28. Levels of thermal discomfort, December 1 to June 30, weekdays 7 AM to 7 PM, clo=1.0

		PPD < 20%	PPD>=20% -PMV	-DBT (degC)	-MRT (degC)	-Vair (m/s)	+PMV	+DBT (degC)	+MRT (degC)	+Vair (m/s)
Ref G2	%time	99.5%	0.0%				0.5%			
West	hours		0				7			
3% OF	Avg		na	na	na	na	0.99	26.99	26.51	0.04
	Stdev		na	na	na	na	0.06	0.98	0.97	0.02
Test G2	%time	98.9%	0.1%				1.1%			
West	hours		1.2				16.5			
1% OF	Avg		-0.94	21.98	18.10	0.23	0.96	23.84	30.21	0.06
	Stdev		0.09	0.92	1.43	0.08	0.11	0.50	1.29	0.04
Ref G3	%time	98.2%	1.1%				0.7%			
East	hours		15.6				9.6			
3% OF	Avg		-1.44	17.15	16.83	0.02	0.95	26.79	26.26	0.07
	Stdev		0.27	1.04	1.26	0.00	0.06	1.44	1.74	0.01
Test G3	%time	98.7%	0.3%				1.0%			
East	hours		4.3				15.3			
3% OF	Avg		-0.97	19.24	18.32	0.02	0.90	23.75	29.56	0.07
	Stdev		0.08	0.27	0.46	0.00	0.05	0.28	0.67	0.04

Figure 45. Photograph of test floor Area G1 with the reference shade controlled to block direct sun at a depth of 3 ft from the window at a height of 0 inches above the floor.
The control system selects the lower of the five preset heights that fulfills this control objective. The shadow lines are produced by direct sunlight transmitted through the open holes of the shade fabric. Photograph was taken on the same date and time as Figure 46.

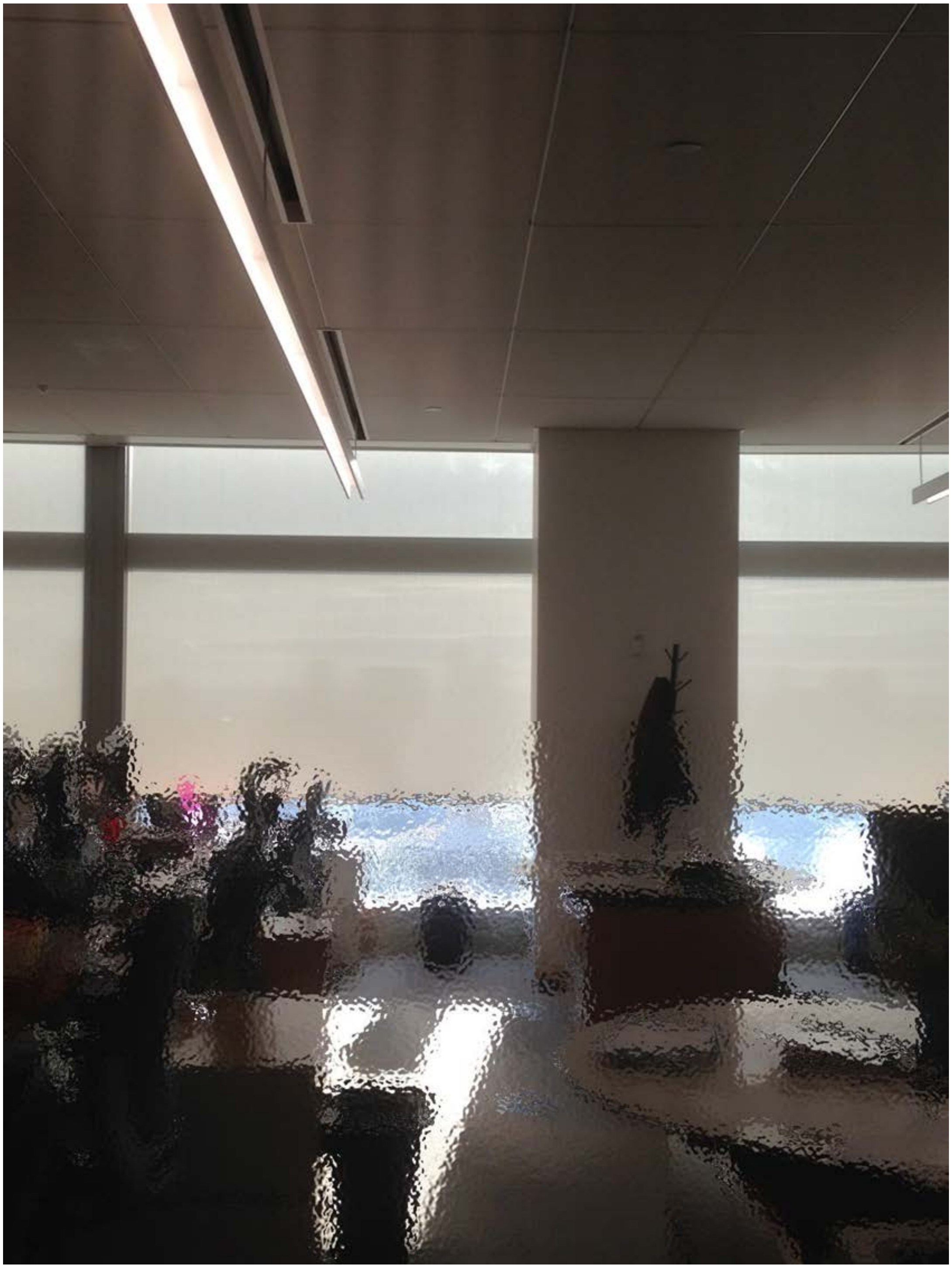


Figure 46. Photograph of test floor Area G2 with the test shade controlled to block direct sun at a depth of 14 inches from the window at a height of 29 inches above the floor.
The control system positions the shade height over a continuous range to meet this objective. Note how for low sun angles, direct sunlight at floor level is allowed to enter the space at much greater depths than the reference control system. This affects window heat gains and potentially visual and thermal comfort.

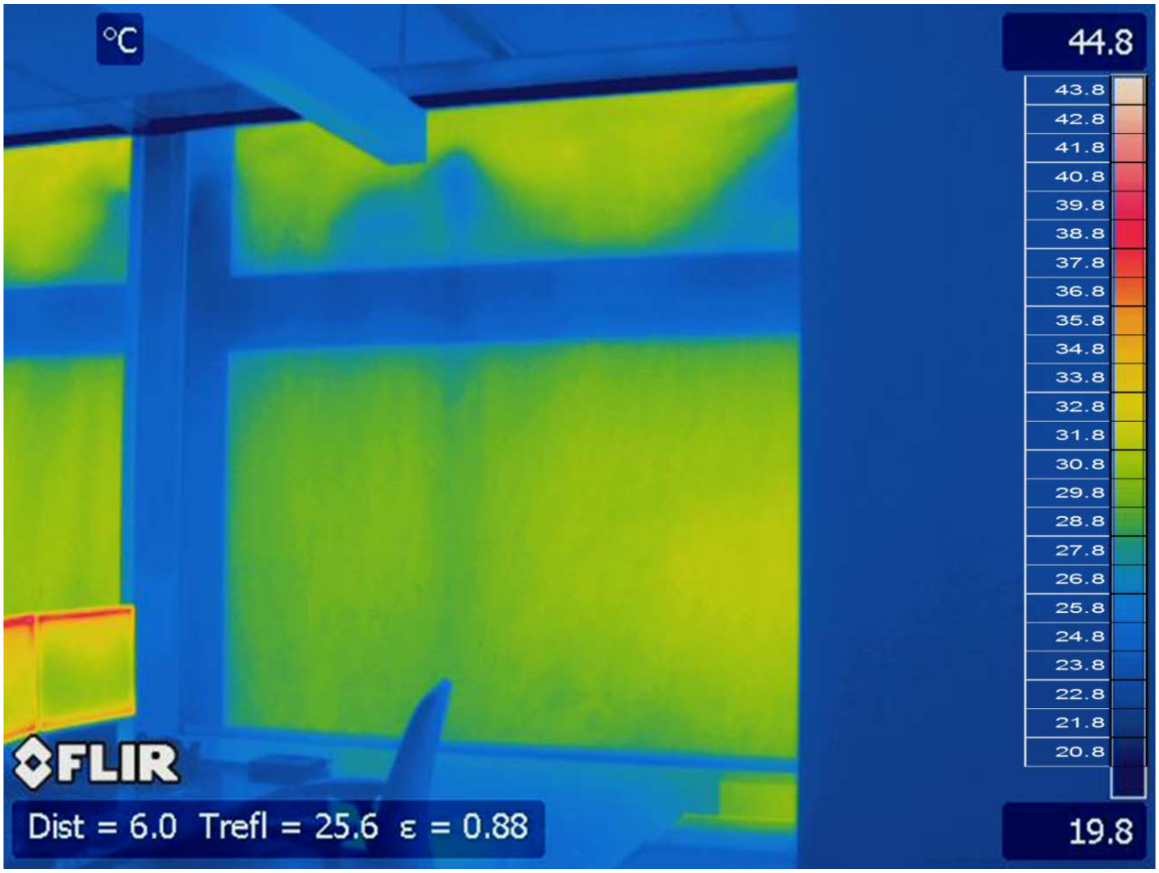


Figure 47. Thermal infrared image showing the surface temperature (°C) distribution of the west-facing window wall with the 3% openness factor roller shade fabric lowered to just above desk height. October 23, 2015, 2:09 PM, test floor, Area G1.

4.2.3. Visual comfort

Visual comfort was evaluated using field of view luminance data gathered on weekend site visits during equinox and solstice periods (data were not gathered simultaneously on both the test and reference floors due to the limited amount of instrumentation). Occupant surveys provided the long-term assessment of visual comfort on the test and reference floors (see Section 4.4).

With the measured data, daylight glare probability (DGP) class was computed for the period from 7 AM to 7 PM. The shades and electric lights were operating on the weekend schedule at the time the measurements were made. With the exception of reference Areas G1 and G4 where the shade was lowered at 6 PM on weekends instead of 8 PM on weekdays, these DGP results for the test and reference areas would be the same for weekdays. The lack of electric lights would also have changed the background luminance and therefore visual adaptation level of the occupants. Since the measurements were conducted primarily during daytime hours, these differences are expected to have a minor effect on DGP class.

For the viewpoint parallel to the window, looking toward the computer monitor at the first workstation closest to the window, visual comfort was maintained within acceptable limits over the course of the day in all areas. Both automated shade control systems were configured to address glare from this primary viewpoint and the limited data indicated that the systems operated as intended. The sky conditions were partly cloudy during the site visits with occasional clear skies, as is typical of the weather in the area. Summary data are given in Table 29, with Class A being the more desirable level of the four classes of comfort and Class D being equal to a "discomfort" rating (see Section 3.6.3f for a description of the DGP classes).

Table 29. Daylight glare probability (DGP) Class for each area and view direction on the test floor.

	Area	Date	View angle**	DGP (7 AM to 7 PM)		
				mean5%	max95%	class
West	G1 Ref, OF=3%	9-Jul	G1-desk	0.28	0.25	A (best)
		25-Oct*	G1-desk	0.29	0.28	A
		9-Jan	G1-window	0.38	0.37	B (good)
		10-Jan	G1-window	0.45	0.34	B
		19-Mar	G1-window	0.26	0.23	A
		20-Mar	G1-window	0.38	0.36	B
		10-Jul	G1-window	0.36	0.34	A
		25-Oct*	G1-window	0.39	0.35	B
	G2 Test, OF=1%	9-Jul	G2-desk	0.24	0.24	A
		9-Jan	G2-window	0.29	0.27	A
		10-Jan	G2-window	0.26	0.25	A
		19-Mar	G2-window	0.23	0.23	A
		20-Mar	G2-window	0.36	0.34	A
		10-Jul	G2-window	0.46	0.44	C (reasonable)
East	G3 Test, OF=3%	9-Jul	G3-desk	0.22	0.21	A
		25-Oct*	G3-desk	0.26	0.2	A
		9-Jan	G3-window	0.26	0.24	A
		10-Jan	G3-window	0.31	0.3	A
		19-Mar	G3-window	0.26	0.26	A
		20-Mar	G3-window	0.49	0.41	C
		10-Jul	G3-window	0.48	0.43	C
		25-Oct*	G3-window	0.34	0.26	A
	G4 Ref, OF=3%	19-Mar	G4-desk	0.24	0.23	A
		10-Jul	G4-desk	0.23	0.22	A
		9-Jan	G4-window	0.41	0.39	B
		10-Jan	G4-window	0.42	0.37	B

* Measurements on October 25 for the "window" direction of view were taken 18 ft from the window. All other measurements (on this and other days) were taken as described in Section 3.6.3f (4.5 ft from the window).
** View angle: desk (looking parallel to the window); window (looking perpendicular to the window towards the outdoor view).

The facility management team, however, relayed to the project team that there were complaints of glare, particularly along the west façade both prior to the Living Lab project and during the project itself. Comments from the occupant surveys also indicated that there were periods of glare described by individuals as "uncomfortable" and "intolerable".

To better understand the potential causes of glare, field of view luminance measurements were made looking *towards* the window from a seated position 4.5 ft from the window. This direction of view requires significantly more stringent control of the shades and would likely have required different settings for the automated control system. This is for two reasons: a) the size of the glare source (the window) is significantly larger within the field of view and therefore has more impact on discomfort than the side view of the window, and b) the orb of the sun (a very significant glare source) is within direct field of view for a larger percentage of the day. More stringent control of glare would reduce access to view and admission of daylight. Therefore, the following observations are instructive of potential changes that could be made to either the selection of the roller shade fabric or adjustments to the control settings if the owner wished to further reduce glare. Similar to the analysis conducted for the side view, analysis looking towards the window assumed that the primary task was use of a computer monitor.

In Areas G1 and G4, excessive glare occurred for views looking toward the window as indicated by data gathered during the site visits:

- the roller shades were lowered but sunlight transmitted through the 3% OF fabric and/or reflected off of the window sill caused discomfort glare (Figure 48-49); or,
- the roller shades were fully raised and the cloud layer was backlit by the sun, causing discomfort glare (Figure 50-51).

In Areas G2 and G3, excessive glare for views looking toward the window occurred as follows:

- the roller shades in the "visor" (partially lowered) position were not lowered enough to block glare from the bright sky (Figure 52-53); or
- the roller shades were lowered but sunlight transmitted through the fabric and/or reflected off of the window still caused discomfort glare (Figure 54-55).
- With the 1% OF fabric in Area G2, it is important to understand that while openness factor provides an indication of the amount of light transmitted through the material, there are other factors such as thread color, type of weave, and opacity of the thread that also contribute to whether the fabric can or cannot reduce glare from the sun. In addition, manufacturing of fabrics does introduce variability in products (e.g., tightness or looseness of weave). These factors contribute to variability in performance in the final installation.

Figure 48. Daylight glare probability (DGP) and vertical illuminance versus time of day, October 25, 2015, for Area G1 at a view position near the window, looking toward the window.
The vertical illuminance was measured at the indoor face of the window glazing. The DGP class for this day was Class B ("good"); 5% mean DGP value = 0.39; 95% maximum DGP value = 0.35.

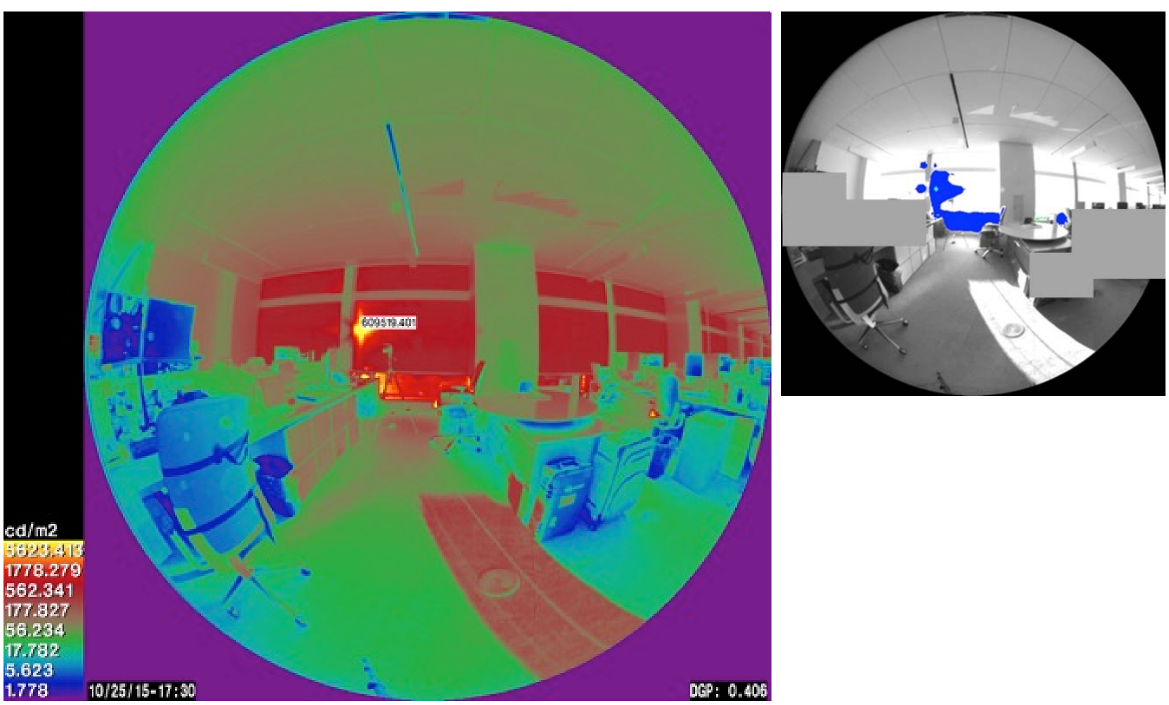


Figure 49. Falsecolor luminance map looking toward the west-facing window in Area G1 (left).
The shade is almost fully lowered at this time (preset 4). The sun and the window area below the lower edge of the shade were identified as glare sources (right). DGP=0.406 ("perceptible" glare); maximum luminance (orb of sun through the fabric) is 609,519 cd/m^2. October 25, 2015, 5:30 PM.

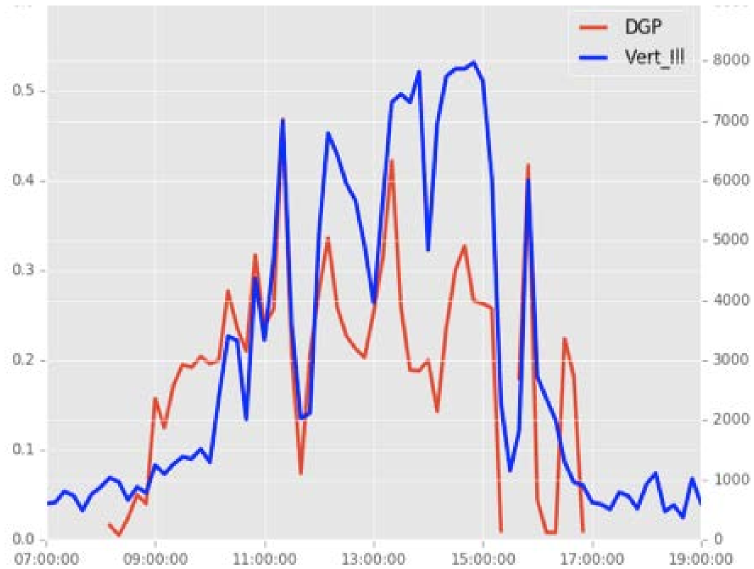


Figure 50. Daylight glare probability (DGP) and vertical illuminance versus time of day, January 10, 2016, for Area G1 at a view position near the window, looking toward the window.
The vertical illuminance was measured at the indoor face of the window glazing. The DGP class for this day was Class B ("good"); 5% mean DGP value = 0.45; 95% maximum DGP value = 0.34.

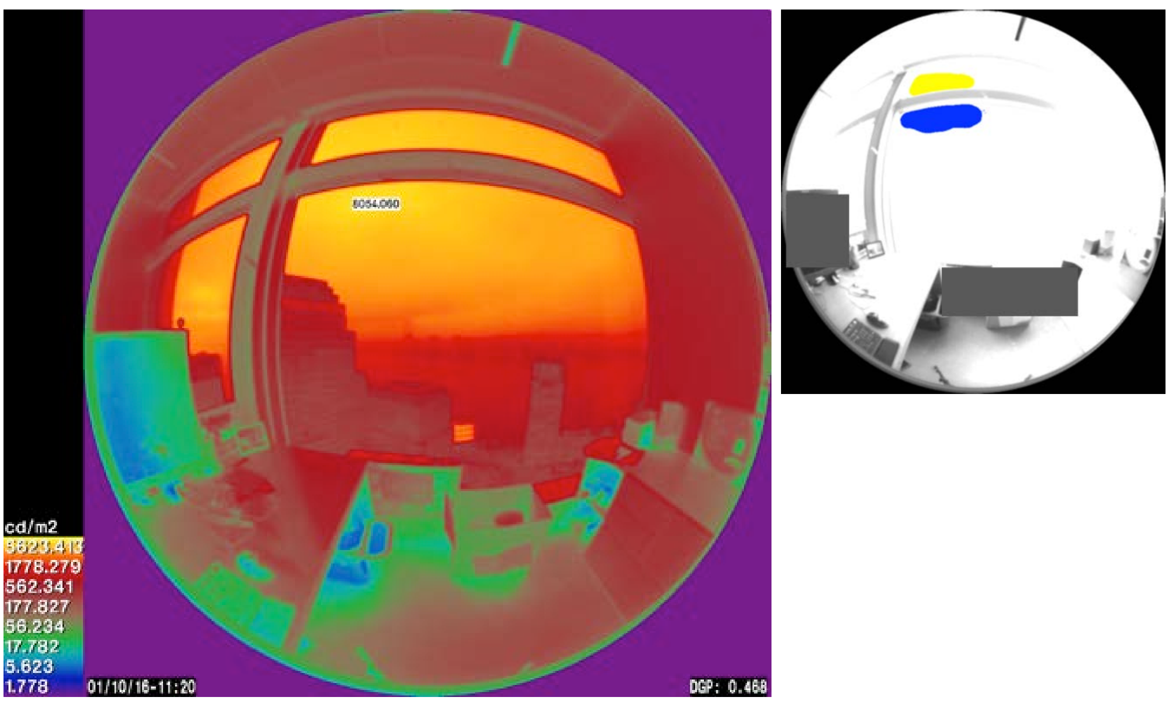


Figure 51. Falsecolor luminance map looking toward the west-facing window in Area G1 (left).
The shade is fully raised at this time (preset 0). The backlit clouds were identified as glare sources (right). DGP=0.468 ("disturbing" glare); maximum luminance (orb of sun) was 8054 cd/m^2. January 10, 2016, 11:20 AM.

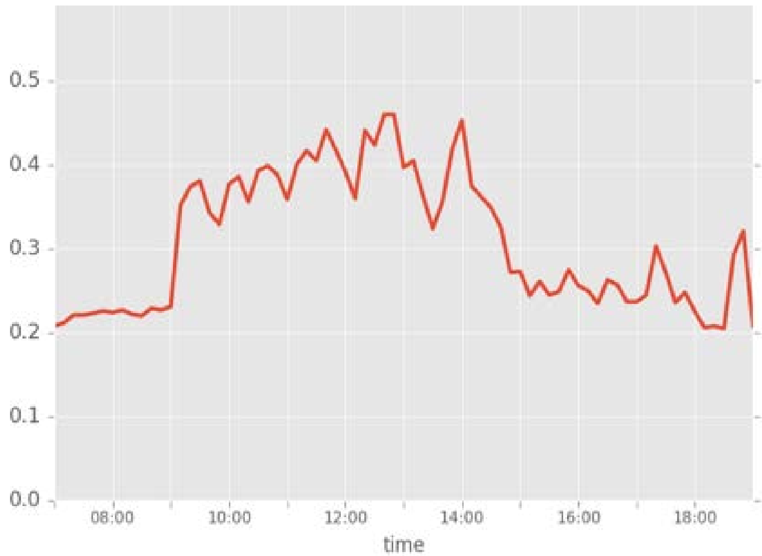
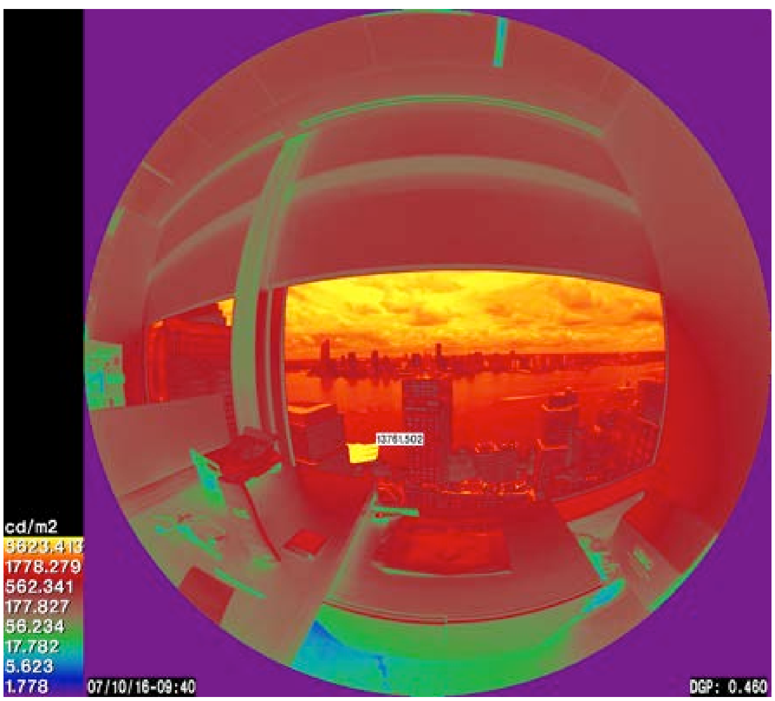


Figure 52. Daylight glare probability (DGP) versus time of day, July 10, 2016, for Area G2 at a view position near the window, looking toward the window.
The vertical illuminance data was not available for this day. The DGP class was Class C ("reasonable"); 5% mean DGP value = 0.46; 95% maximum DGP value = 0.44.



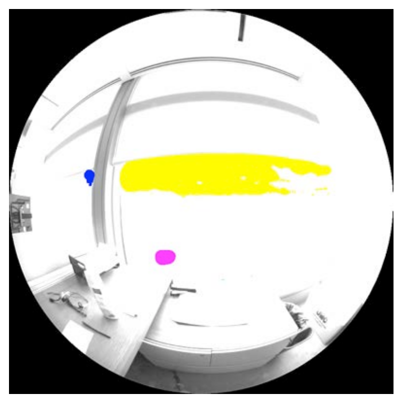


Figure 53. Falsecolor luminance map looking toward the west-facing window in Area G2 (left).
The 1% OF shades were in the "visor" position and the bright clouds below the lower edge of the shade was identified as a glare sources (right). DGP=0.46 ("disturbing" glare); maximum luminance was 13,762 cd/m^2. July 10, 2016,12:40 PM.

Figure 54. Daylight glare probability (DGP) and vertical illuminance versus time of day, March 20, 2016, for Area G3 at a view position near the window, looking toward the window.
The vertical illuminance was measured at the indoor face of the window glazing. The DGP class for this day was Class C ("reasonable"); 5% mean DGP value = 0.49; 95% maximum DGP value = 0.44.

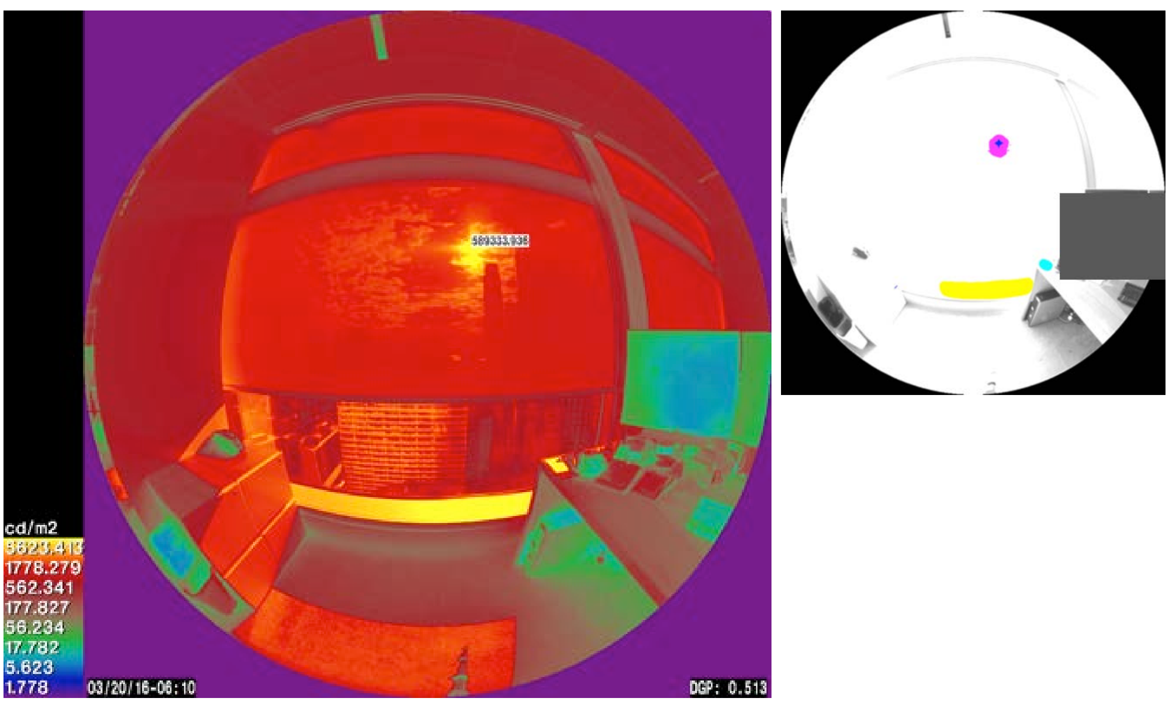


Figure 55. Falsecolor luminance map looking toward the west-facing window in Area G3 (left).
The 3% OF shades were almost fully lowered at this time. The sun and reflected glare off the window sill were identified as glare sources (right). DGP=0.513 (near "intolerable" glare); maximum luminance was 589,334 cd/m^2. March 20, 2016, 9:10 AM.

Figure 56. Photograph of shades in Area G1 on the west façade.
Area G1 has a fabric with a 3% openness factor. Brightness from the sun and sunlight reflected off of the Hudson River can be seen from this viewpoint. The 3% fabric permits partial view through to the outdoors.

Figure 57. Photograph of shades in Area G1 (left) and Area G2 (right) with the wide column dividing the two areas of the west façade.
Area G2 has the fabric with the 1% openness factor and one can see the brightness of the sun through the fabric. Notice how the table in the foreground has sunlight on its surface. The sunlight has passed directly through the holes in the fabric without scattering and diffusion, as evidenced by the sharp shadow lines of the window mullions that can be seen across the surface of the table.

For the instances when there was glare when the shades were fully raised, thresholds for control could be lowered to trigger the shades to be more responsive to glare. In the instances where the Area G2 and G3 "visor" position was insufficient for controlling sky glare, the visor height could be adjusted lower according to end user preferences.

For the instances when the shades were partially or fully lowered and there was still glare from views of the sun through the fabric, a roller shade fabric with an openness factor of less than 1% would need to be used to further reduce glare (Figure 56-57). Reducing shade fabric transmission to a level nearly equivalent to that of a blackout shade would likely be unacceptable from a qualitative point of view because daylight quality and views to the outdoors would be significantly reduced. This dialectic is somewhat perceptible in the end user comments – see Section 4.4 for outcomes from the occupant survey.

The effect of direct and/or filtered sunlight on computer screens was not investigated in this study (LBNL researchers were unable to display typical content on the computer screen).

Sunlight can reduce contrast on a screen or cause veiling reflections across the screen, making it difficult to view content clearly. To illustrate the effect, filtered sunlight is shown on floor and table surfaces in Figure 45 and 57.

4.2.4. Daylight potential

An analysis of illuminance levels in the various zones can provide some insights into the daylighting potential of the indoor environment produced by the automated shading systems. It has been argued that automated shading enables greater opportunities for daylighting by raising the shade during periods when there is no direct sun or glare. In the instances of manually-operated shades, field observations have indicated that shades will remain lowered well after the source of discomfort has passed.

Total workplane illuminance was monitored in each of the four areas on both the reference and test floors. In the case of Area G2 on the test floor, daylight dimming was not implemented. The lights were also on fairly consistently during the day over the monitored period, despite use of occupancy-based controls (see lighting energy use profile in Section 4.1.1f). So with the conservative assumption that illuminance levels from the electric lights were consistently on during the day (producing an average illuminance of 153-248 lux, see Table 8), the daylighting potential with automated shades can be estimated.

Figure 58 shows the frequency distribution of total illuminance between December 1 and June 30 for Area G2 on the test floor on weekdays from 7 AM to 7 PM. When the total illuminance was 450 lux, the contribution from daylight was about 200-300 lux. So for this west-facing zone with automated shades and a 1% OF fabric, daylight illuminance levels exceeded 200-300 lux for 47%, 38%, and 25% of the monitored period at the three zone depths of 2.5, 9.9, and 17.2 ft from the window. During these periods, the electric lights could have been dimmed significantly in response to available daylight to increase energy savings at all three depths.

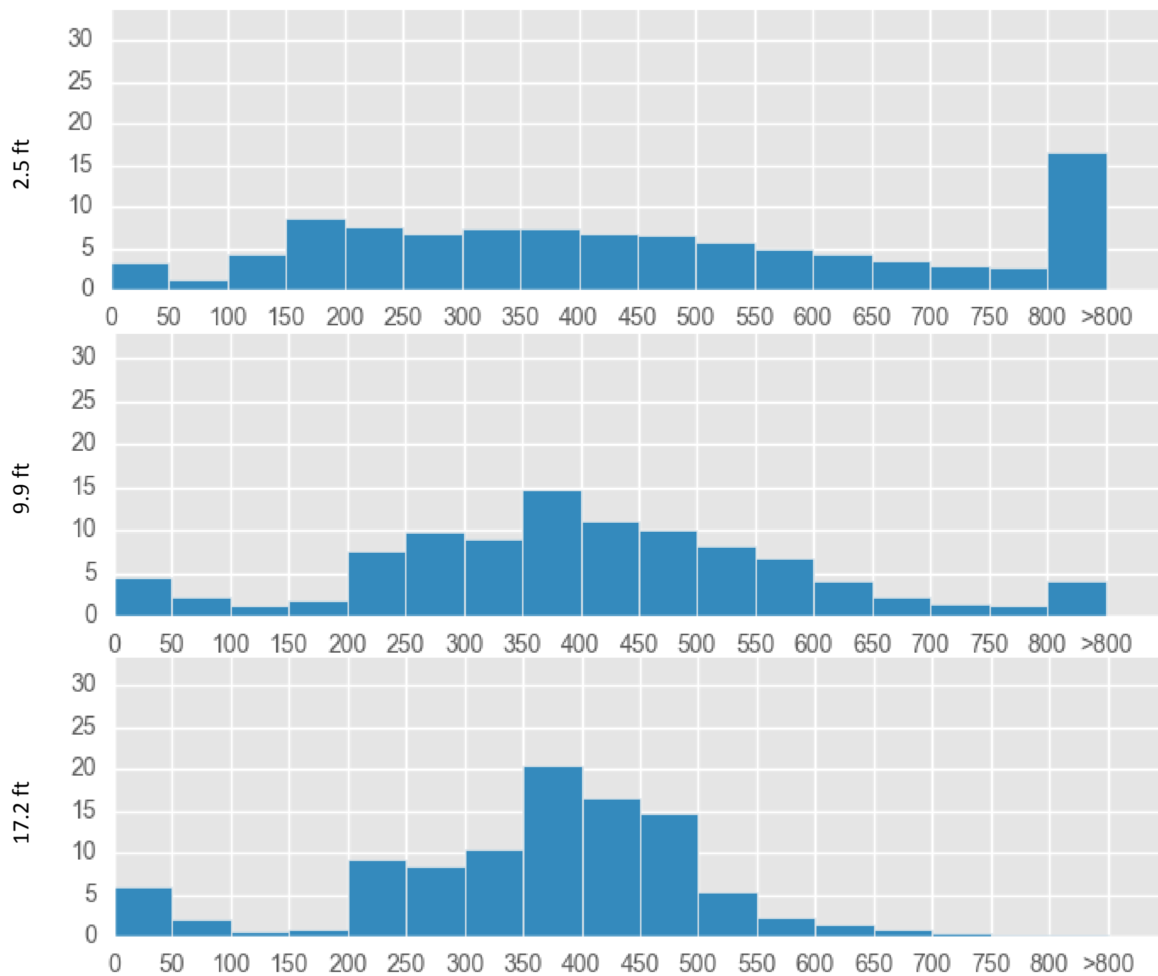


Figure 58. Zone G2 (west). Percentage of time (y-axis) that the total workplane illuminance (lux) was within the range of each binned level.
The 0-50 lux bin is represented by the first column on the x-axis. Data were binned for the period from December 1 to June 30 on weekdays Monday through Friday, 7 AM to 7 PM at depths of 2.5 ft (upper graph), 9.9 ft (middle), and 17.2 ft (lower) from the window.

4.2.5. Useful daylight index

The useful daylight index (UDI) index uses illuminance levels as a proxy metric for evaluating indoor environmental quality. If illuminance levels are excessively high near the window, then one can infer that visual and thermal discomfort and window heat gains are likely to be correspondingly high. In this study, since direct sun was controlled by the automated shade, an assessment can be made of the frequency of excess illuminance and therefore level of discomfort and solar heat gains due to either bright sky conditions from an unshaded window or from direct sunlight transmitted through the roller shade fabric. UDI sets this limit for daylight to 2000 lux [Nabil and Mardaljevic, 2006].

Figure 59 shows the frequency distribution of total illuminance binned in 250 lux increments up to 2500 lux for the period between December 1 and June 30 on weekdays from 7 AM to 7 PM.

This distribution includes the contribution from the electric lights, therefore the lower end of the frequency distribution reflects the contributions of electric lighting to the setpoint illuminance on the two floors during periods of low light (early morning/ late evening hours). For the reference floor with a sensor[4] setpoint of 350-500 lux, there was a high frequency of light levels within the 250-500 lux bin while for the test floor with a sensor setpoint of 100-300 lux, there was a high frequency within the 0-250 lux bin.

Notice that total illuminance levels were well controlled, with the majority of illuminance falling within the range of 250-2000 lux for 81% of the period on the test floor and 97% of the period on the reference floor (the difference was due to the difference in sensor setpoint illuminance between floors). A tally was made of the number of minutes when illuminance levels at 2.5 ft from the window were excessively high (Table 30). Over the 7-month period, total illuminance exceeded the 2000 lux limit by no more than 1256 minutes (21 hours) or 1% of the monitored period in all areas. For the remainder of the time (2-18%), total illuminance levels fell within the 0-250 lux range.

One could argue from this data that the automated shades contributed to a well-controlled daylit environment that met qualitative measures for comfort and adequate daylighting.

Table 30. Minutes that total workplane illuminance at 2.5 ft from window was greater than defined maximum illuminance*

Max illuminance (lux):		>2000	>3000	>4000
Reference	G1	358	39	29
	G2	69	4	2
	G3	216	46	19
	G4	1256	16	0
Test	G2	358	87	50
	G3	1150	0	0
	G4	117	2	0

*Note: Quadrant level performance is not comparable to other quadrants because the quadrants differed in window orientation, floor layout, etc.

[4] Workplane and sensor setpoint levels differed due to positional differences between the two locations. The sensors were located 2 ft above the desk and sensor illuminance levels were on average 22 lux lower than the workplane illuminance level due to relative position to the light fixtures. The setpoint levels varied by sensor location.

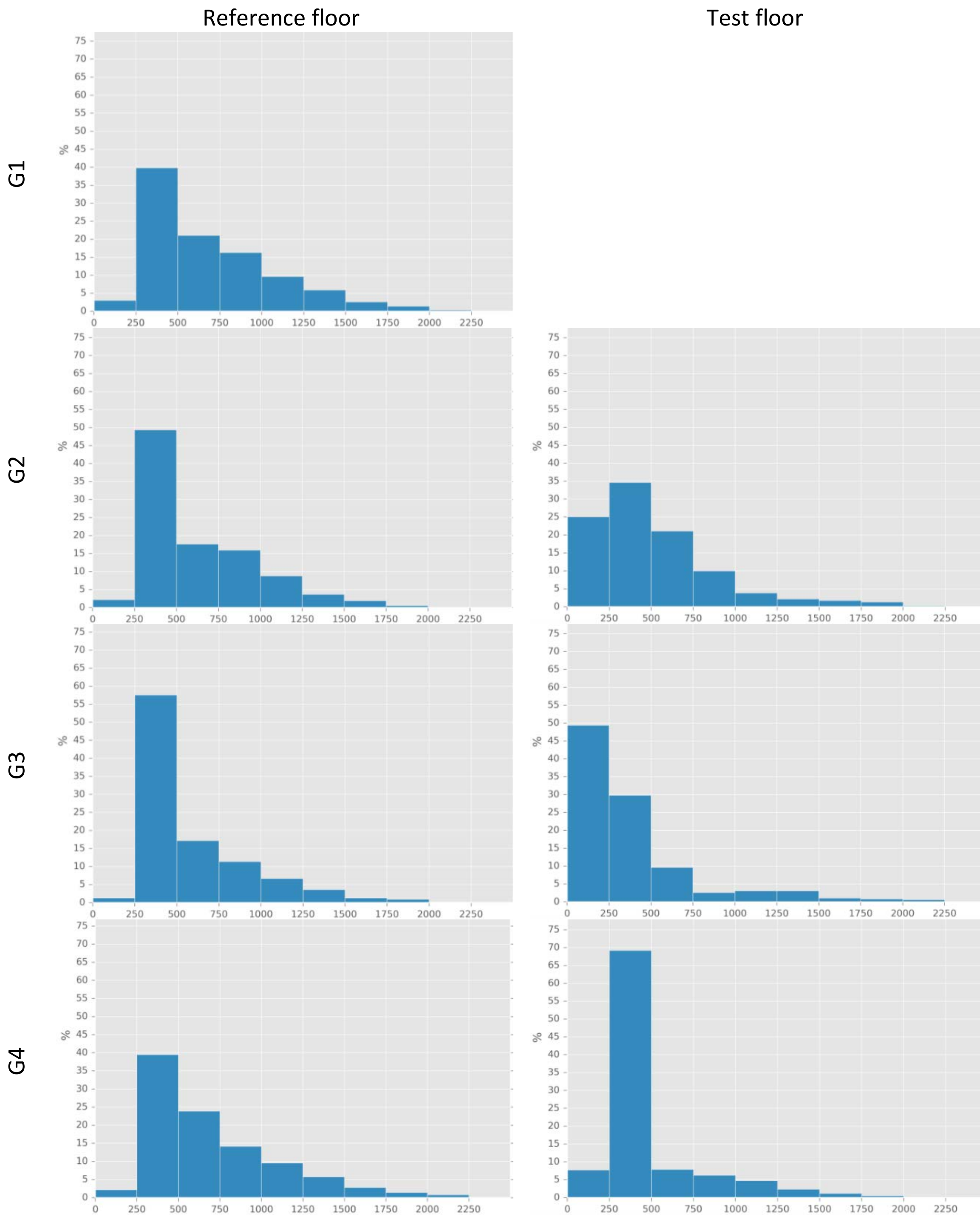


Figure 59. Percentage of time that the total workplane illuminance was within the range of each binned level.
The 0-250 lux bin is represented by the first column on the x-axis. Data were binned for the period from December 1 to June 30 on weekdays Monday through Friday, 7 AM to 7 PM at depths of 2.5 ft from the window.

4.3. Integrated Systems Energy use and Peak Demand Savings

Direct monitoring HVAC energy use was not conducted in this study because the four Living Lab test areas were not thermally isolated from each other. As a result, incremental differences in energy use could not be measured accurately. Instead, we have used data from other simulations, field studies, and calculations to delimit the savings potential from the retrofit shading and lighting technologies as follows:

Energy savings specifically relevant to the LL building:

- Cooling energy use reductions due to reduction in heat gains from the LED lighting system were estimated for the LL test floor (Section 4.3.1);
- Total energy use reductions due to lighting and cooling were estimated for the LL test floor (Section 4.3.2);
- Peak electric demand reductions due to reduced heat gains from the lights and reduced lighting energy use were estimated for the LL test floor (Section 4.3.3);
- DOE-2 simulations previously conducted by Viridian for the original, new LL building were used to estimate the incremental benefit of each component measure (automated shading, fluorescent dimmable lighting) on whole building annual energy cost (Section 4.3.4).

Energy savings related to automated shades and dimmable fluorescent lighting from other related studies:

- Field measurements were made in the LBNL Advanced Windows Testbed to determine differences in daily cooling load due to manually-operated versus automated roller shades in a south-facing perimeter office zone – results are indicative of savings potential for a sunny, temperate climate (Section 4.3.5);
- Parametric DOE-2 simulations of a prototypical commercial office building were made to estimate perimeter zone energy use reductions due to automated shades and dimmable fluorescent lighting compared to unshaded windows of various vintages in a variety of US climates (Section 4.3.6).

A more accurate assessment, similar to that undertaken for a prior post-occupancy study involving monitored data coupled with detailed Radiance and EnergyPlus simulations [Lee et al. 2013], would be needed to estimate actual HVAC energy use savings in the LL building.

4.3.1. Cooling energy use reductions due to reduced electric lighting heat gains on the LL test floor

Cooling energy use reductions were estimated using a simple method of converting lighting heat gains to energy use using an assumed coefficient of performance (COP) for the central cooling plant and distribution systems:

- The incremental difference in lighting energy use and peak demand for all four areas G1-G4 on the floor was used to estimate differences in annual cooling energy use and peak cooling demand.
- With pendant direct/indirect fixtures and conventional overhead air-delivery systems, 100% of the lighting energy (that is not transmitted through the window to the

outdoors) was assumed to be converted to room heat gains. For peak cooling energy use, the heat gains computed for the summer afternoon hours of 2, 3, and 4 PM were assumed to be realized as instantaneous heat gains within that hour.

- With UFAD systems such as that in the LL building however, air is delivered from the floor plenum and waste heat from occupants and lighting equipment is convected upward and removed at ceiling level through the return plenum slots directly above the light fixtures. Moreover, about half of the light is directed upwards toward the ceiling plane and on average, wall and desk surface reflectances are high, reducing absorbed radiation from the lights on lower room surfaces. HVAC loads due to electric lighting heat gains in this scenario are likely to be less than with conventional VAV systems because the heat gains may minimally affect the ambient air temperature detected by the thermostat at occupant/ floor level. For this scenario, an 80% light-to-heat gain (LHG) efficiency was assumed for both the reference and test floors.
- The COP can vary depending on the vintage of the HVAC system. For older buildings, the COP is likely to be low. For newer buildings with advanced HVAC systems, like that of the LL building, the COP is likely to be high. A range of COP from 2.0 to 4.0 was assumed for the conversion of heat gains to energy use (i.e., cooling energy use = heat gains/ COP).
- The COP also varies seasonally and over time of day depending on part-load operating conditions. The COP was assumed to be fixed over the course of the year for both energy use and peak demand saving estimates.
- The floor area of the test floor was multiplied by the 43 stories to arrive at a total cooling energy use and peak cooling demand reduction estimate for the whole LL building. Differences in occupancy schedules and daylight availability between the test floor and all the other floors were not accounted for in the estimate of lighting energy savings.

Reductions in annual HVAC cooling energy use intensity as a result of reduced electric lighting heat gains were estimated to be as follows:

- The reference baseline lighting energy use for all four G1-G4 perimeter zones was 4.26 kWh/ft^2-yr, the test case lighting energy use was 0.91 kWh/ft^2-yr, and the annual lighting energy savings was 3.35kWh/ft^2-yr. These values were based on actual monitored lighting energy use at the circuit level.
- For a light-to-heat gain (LHG) efficiency of 80-100% and COP=2-4, annual cooling energy use intensity reductions for the floor ranged from 0.67 to 1.67 kWh/ft^2-yr (Table 31). This range in performance is illustrated in Figure 60.
- Whole building cooling load reductions ranged from 608,365 to 1,520,912 kWh/yr. The “whole building” floor area was defined as the G1-G4 perimeter zone area multiplied by 43 stories. The G1-G4 perimeter zone area on each floor was 21,125 ft^2 (53%) of the total 39,980 ft^2 floor area per floor.

Table 31. Reduction in annual cooling energy use intensity (kWh/ft^2-yr) and whole building cooling energy use (kWh/yr) due to reduced lighting heat gains.

LHG eff.	COP	Areas G1-G4 (kWh/ft^2-yr)	Areas G1-G4 on 43 floors* (kWh/yr)
1.0	2	1.67	1,520,912
1.0	3	1.12	1,013,942
1.0	4	0.84	760,456
0.8	2	1.34	1,216,730
0.8	3	0.89	811,153
0.8	4	0.67	608,365

*Whole building perimeter zone area affected was 21,125 ft^2/ floor for 43 floors.

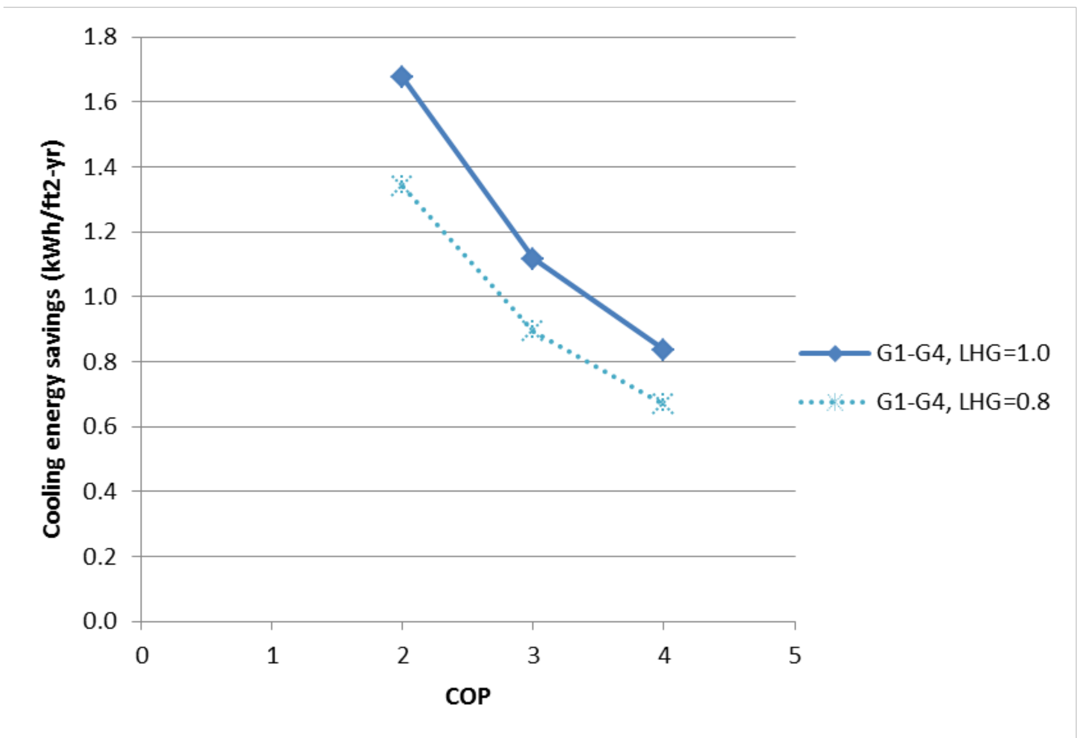


Figure 60. Annual cooling energy use reductions (kWh/ft^2-yr) due to reduction in heat gains from the electric lighting.
Data given for all perimeter zones G1-G4 assuming a range of coefficient of performance for the HVAC system and a light-to-heat gain ratio of 0.80 and 1.0. Data are given for the difference in lighting heat gains between the reference and test floor Areas G1-G4.

4.3.2. Total annual energy use and cost savings due to automated shading and lighting

Total annual energy use savings were defined by a) savings due to lighting energy use between all four G1-G4 perimeter zones on the reference and test floors, and b) reductions in cooling energy use due to reduced heat gain from the lighting system (from Section 4.3.1). Lighting energy use was determined from circuit-level metered data on the reference and test floors. Cooling energy use savings due to the difference in operations between the two automated shading systems (e.g., Area G2 and G3) were not monitored and were therefore not included in the following savings.

The economic analysis for the LL building was separated into two parts (see Section 5.3.1 for cost estimate summary):

- Cost of replacing the existing fluorescent lighting with LED lighting – we assumed that the existing fluorescent fixtures would be replaced in situ with new LED fixtures with factory-installed dimmable drivers within the housing. A range is given because costs vary with existing conditions and the solution to be installed. The lower cost is given as an estimate of cost when the market is fully mature.
- Cost of advanced lighting controls – the added incremental cost of controls includes the additional sensors, electronics, user interface and software needed to implement the various lighting control strategies, diagnostics and monitoring functions. Since both the reference and test floors had automated shades (with different shade fabric and controls), we assumed that there was no added cost for the automated shades in test Areas G2 and G3. If the incremental cost of automating the shades were to be included, costs would include motorization (which could be reduced by coupling shades together for a reduced number of motors), sensors, and controls.

Using monitored data from Sections 4.3.1 and 4.1.1e-h, total annual energy savings in the LL building were as follows:

- Whole building energy use intensity was reduced by 4.02-5.02 kWh/ft^2-yr assuming a range of LHG efficiencies and COP (Table 32).
- Whole building annual energy use reductions were 3.65-4.56 MWh/yr or a cost savings of $730-913K/yr, assuming an average time-of-use electricity rate of $0.20/kWh.
- If the total installed cost of both the LED fixtures and controls was $3/ft^2, then the simple payback would be 3.0-3.7 years. If $10/ft^2, then the simple payback would be 10.0-12.4 years (Table 33).

A cost analysis assuming an ASHRAE 90.1-1999 reference baseline yielded shorter paybacks:

- The ASHRAE 90.1-1999 baseline assumed an installed lighting power density of 1.3 W/ft^2, 18-hour schedule of operation on weekdays, and no occupancy on weekends.
- The ASHRAE baseline lighting energy use was 5.85 kWh/ft^2-yr. The total G1-G4 test case lighting energy use was 0.91 kWh/ft^2-yr. Lighting energy savings was 4.94 kWh/ft^2-yr. Using the same methods as Section 4.3.2 to determine cooling savings, whole building energy use intensity was reduced by 5.92-7.40 kWh/ft^2-yr assuming a range of LHG efficiencies and COP.
- If the total installed cost of both the LED fixtures and controls was $3/ft^2, the simple payback would be 2.0-2.5 years. If $10/ft^2, then the simple payback would be 6.8-8.4 years (Table 33).

The simple payback for the LED fixtures was computed separately from the payback for the controls to better understand the cost-effectiveness of advanced controls. This estimate was accomplished by using the weekday incremental savings given in Sections 4.1.1e to 4.1.1h. This analysis found that 41-59% (51% average) was due to the change from T5 to LED fixtures, 27-

51% was due to setpoint tuning, and 8-14% was due to occupancy and daylighting compared to the reference condition with no low-resolution occupancy controls. Assuming that there was little to no savings between the test and reference floors on weekends, 51% of the total annual savings was attributed to the LED source upgrade and the remaining 49% savings was attributed to the advanced lighting and shading controls. This 51%-49% split was applied to the reference baseline with an installed LPD=1.04 W/ft^2, 18-hour schedule, and no low-resolution occupancy controls:

- If the installed replacement cost of the LED fixtures was $2/ft^2, then the payback would be 3.5-4.3 years (Table 34). If the installed cost was $6/ft^2, then the payback would be 10.4-13.0 years.
- If the incremental installed cost for high-resolution control of the LED fixtures was $1/ft^2, then the payback would be 1.8-2.3 years (Table 34). If the installed cost was $4/ft^2, then the payback would be 7.2-9.0 years.

Table 32. Reduction in annual cooling and lighting energy use intensity (kWh/ft^2-yr), whole building energy use (kWh/yr), and electricity cost ($/yr) due to automated shading and lighting controls.

LHG eff.	COP	Whole building energy savings (G1-G4) (kWh/ft^2-yr)	(kWh/yr)	($/yr)*
1.0	2	5.02	4,562,737	912,547
1.0	3	4.46	4,055,766	811,153
1.0	4	4.19	3,802,281	760,456
0.8	2	4.69	4,258,554	851,711
0.8	3	4.24	3,852,978	770,596
0.8	4	4.02	3,650,189	730,038

Perimeter zone area affected was 21,125 ft^2/ floor for 43 floors.
* $0.20/kWh average utility rate.

Table 33. Annual energy cost savings ($/ft^2-yr) and simple payback (years) due to the total cost ($/ft^2) of LED source and lighting controls. Reference: actual monitored energy use or ASHRAE 90.1-1999.

LHG eff.	COP	Actual savings ($/ft^2-yr)	Payback (yrs), total installed cost of: $3/ft^2	$10/ft^2	ASHRAE 90.1 savings ($/ft^2-yr)	Payback (yrs) , total installed cost of: $3/ft^2	$10/ft^2
1.0	2	$1.00	3.0	10.0	$1.48	2.0	6.8
1.0	3	$0.89	3.4	11.2	$1.32	2.3	7.6
1.0	4	$0.84	3.6	11.9	$1.23	2.4	8.1
0.8	2	$0.94	3.2	10.7	$1.38	2.2	7.2
0.8	3	$0.85	3.5	11.8	$1.25	2.4	8.0
0.8	4	$0.80	3.7	12.4	$1.18	2.5	8.4

Table 34. Annual energy cost savings ($\$/ft^2$-yr) and simple payback (years) due to the incremental cost ($\$/ft^2$) of LED source and lighting controls. Reference: Installed LPD=1.04 W/ft^2, 18-hour schedule.

LHG eff.	COP	LED Source savings	Payback (yrs) for incremental cost of:		Control savings	Payback (yrs) for incremental cost of:	
		($\$/ft^2$-yr)	$\$2/ft^2$	$\$6/ft^2$	($\$/ft^2$-yr)	$\$1/ft^2$	$\$4/ft^2$
1.0	2	$0.58	3.5	10.4	$0.55	1.8	7.2
1.0	3	$0.51	3.9	11.7	$0.49	2.0	8.1
1.0	4	$0.48	4.2	12.5	$0.46	2.2	8.7
0.8	2	$0.54	3.7	11.2	$0.52	1.9	7.7
0.8	3	$0.49	4.1	12.3	$0.47	2.1	8.6
0.8	4	$0.46	4.3	13.0	$0.44	2.3	9.0

Table 35. Annual energy cost savings ($\$/ft^2$-yr) and simple payback (years) due to the incremental cost ($\$/ft^2$) of LED source and lighting controls. Baseline: ASHRAE 90.1-1999.

LHG eff.	COP	LED Source savings	Payback (yrs) for incremental cost of:		Control savings	Payback (yrs) for incremental cost of:	
		($\$/ft^2$-yr)	$\$2/ft^2$	$\$6/ft^2$	($\$/ft^2$-yr)	$\$1/ft^2$	$\$4/ft^2$
1.0	2	$0.76	2.6	7.9	$0.73	1.4	5.5
1.0	3	$0.67	3.0	8.9	$0.65	1.6	6.2
1.0	4	$0.63	3.2	9.5	$0.60	1.7	6.6
0.8	2	$0.70	2.8	8.5	$0.68	1.5	5.9
0.8	3	$0.64	3.1	9.4	$0.61	1.6	6.5
0.8	4	$0.60	3.3	9.9	$0.58	1.7	6.9

4.3.3. Peak electric demand reductions on the LL test floor

Using the method described in Section 4.3.1 above, the average peak cooling electric demand reduction due to heat gains from the lighting system was estimated for the summer afternoon hours of 2, 3, and 4 PM. When lighting demand is added to this value, we arrive at the total peak electric demand reduction (excluding cooling demand reductions from the automated shades):

- The peak electric demand reduction due to reduced heat gains from all lighting systems on the test floor (G1-G4) compared to the reference floor ranged from 0.15-0.32 W/ft^2 for a light-to-heat gain (LHG) efficiency of 100% and a COP of 2-4. Values ranged from 0.12-0.25 W/ft^2 for a LHG efficiency of 80% and a COP of 2-4. See Table 36.
- Total whole building peak electric demand reductions due to reduced lighting energy demand and reduced cooling energy use were 658-863 kW for an LHG efficiency of 100% and COP of 2-4 for summer hours between 2-5 PM in the afternoon. See Table 37.

Table 36. Average cooling energy use intensity reduction (W/ft^2-floor) during peak afternoon periods, March 1 to June 30, 2016

LHG eff.	COP	2-3 PM	3-4 PM	4-5 PM
1.0	2	0.30	0.31	0.32
1.0	3	0.20	0.20	0.21
1.0	4	0.15	0.15	0.16
0.8	2	0.24	0.24	0.25
0.8	3	0.16	0.16	0.17
0.8	4	0.12	0.12	0.13

Derived from lighting peak energy use data from Sections 411e-f.

Table 37. Average total electricity use reduction (kW/building) during peak afternoon periods, March 1 to June 30, 2016

LHG eff.	COP	2-3 PM	3-4 PM	4-5 PM
1.0	2	822	834	863
1.0	3	731	741	767
1.0	4	685	695	719
0.8	2	768	778	806
0.8	3	695	704	729
0.8	4	658	667	691

Derived from lighting peak energy use data from Sections 411e-f.
Perimeter zone area affected was 21,125 ft^2/ floor for 43 floors.

4.3.4. Original DOE-2 simulations for the new LL building

The estimates in Section 4.3.2 do not include reductions in cooling energy use or peak demand due to use of the automated shades.

During the construction and value engineering phase of the LL building, the building owners commissioned DOE-2 simulation studies to evaluate the incremental cost benefit of each energy conservation measure relative to the ASHRAE 90.1-1999 baseline. The studies were conducted by Viridian Energy & Environmental LLC (now Vidaris, Inc.). For each measure, the design case with all proposed measures was modeled first then the measure was removed and the model run again to arrive at the difference in energy use due to the measure (shading and daylight modeling assumptions for the simulations were not detailed in the report).

Whole building energy cost savings due to each of the measures were as follows, where the total annual energy cost using the local time-of-use rate schedule was a nominal $10,000,000 per year for the 2,140,000 ft^2 facility:

- Reduction in lighting power density from 1.3 W/ft^2 to 1.04 W/ft^2 saved $960,000 per year (9.6%);

- Daylight dimming saved $230,000 per year (2.3%) resulting in a simple payback of 11.3 years;
- Automated interior shades resulted in savings of $50,000 per year (0.5%; payback was not determined);
- Between all lighting, window, and HVAC measures, total whole building annual energy cost was reduced by 28%.

Changes in energy cost were the same if the baseline was ASHRAE 90.1-2004 or ASHRAE 90.1-2007. It is unclear from the report what the assumptions were for the interior shades – the low cost savings from the automated shades may be due to the assumptions made about the solar-optical properties of the shades or how the UFAD and VAV system parsed the perimeter loads or how peak cooling energy costs were minimized by thermal energy storage/ ice production during the night.

There is a potential concern that heating energy use would be increased with the reduced lighting and window loads. In the Viridian study, however, the authors commented that the LL building had high internal loads due to heavy computer use and required cooling year-round. The net benefit of a lower lighting density on cooling is much greater than the increase in heating that it occasionally causes.

In the end, the owners made their original investment decision to use automated shading and dimmable lighting technologies in the original building based on a combination of energy cost payback, qualitative factors related to the workplace environment, and LEED certification.

4.3.5. Prior field measured data for a prototypical office zone

A three-year field study was conducted in the LBNL Advanced Windows Testbed facility, Berkeley, California through a California Energy Commission (CEC) supported research program [Lee et al. 2009]. The testbed facility consists of three side-by-side, south-facing test rooms that were identically configured. It was designed to enable accurate measurement of between-room HVAC loads, given near adiabatic isothermal conditions surrounding each test cell and a calibration process that accounts for construction and operational differences between test rooms.

The field study concluded that the automated interior roller shades:

- reduced daily lighting energy use (6 AM to 6 PM) by 39%, and
- reduced daily window cooling load reductions by 3% and peak cooling load savings by 7%
- compared to a manually-operated roller shade with the same lighting controls as the test case.

The “manually-operated” shade was the same roller shade positioned to a static intermediate height (2.5 ft above the floor) throughout the day. The automated shade was controlled to prevent direct sun penetration greater than 3 ft from the window and to maintain daylight levels to within 570-670 lux at the workplane. The shade was made of a light grey basketweave fabric with a 3% openness factor. The window was a dual-pane low-emittance window (Tv=0.62, SHGC=0.40, U-value=1.7 W/m^2-°C, 0.30 Btu/h-ft^2-°F) with a window-to-wall-ratio (WWR) of 0.59, similar to that of the LL building.

Cooling load reductions due to the indoor shade were small because the "manually-operated" shade was already lowered to block direct sun, meeting minimal thermal and visual comfort requirements. If daily cooling load reductions were on average 3% between an automated and manually-operated shade (assuming the manual shade would be lowered), then the cooling load reductions between two different modes of automated control with two different openness fabrics, as in the LL building, are also likely to be small. With low-e double glazed windows, indoor shading systems can partially reject solar energy by reflecting it back towards the outdoors. Use of a high solar reflectance shade and lowering the shade reliably during sunny conditions would lower both total and peak cooling demand.

4.3.6. DOE-2 parametric analysis for automated shading and dimmable fluorescent lighting

In prior studies, parametric DOE-2 simulation studies were conducted to evaluate the annual energy savings potential of, among other systems, automated indoor roller shades and daylighting controls [Lee et al. 2004]. The shade was lowered to completely cover the window every hour if threshold limits for solar transmission and glare were exceeded and raised every hour if the limits were not exceeded. Daylighting controls were implemented with dimmable fluorescent lighting. Simulations were conducted for a 15-ft deep perimeter office zone with a variety of window types and window-to-wall ratios (WWR). The study may be useful for understanding the relative benefit of automated shading and daylighting controls combined with windows that ranged from single-pane clear to quadruple-pane low-e. For example, for a WWR of 0.30 and a double-pane, low-e tinted window, south zone annual primary (source) energy use was reduced from 157 to 125 kBtu/ft^2-yr[5] or 20% in Chicago if automated shades and daylighting controls were added. If the WWR was 0.60, then energy use was reduced from 208 to 158 kBtu/ft^2-yr or 24%. Other climates were modeled for ASHRAE 90.1-1999 and Title-24-2005 compliant conditions.

4.4. Occupant Response

4.4.1. Occupant service requests

Occupants on the test floor issued service requests via phone call or as an electronic entry into the main system between July 2015 to June 2016. The log of service requests included the date and time the request was generated, desk location, detailed comments, and the follow up response by the facilities management team. Thirty-two service requests were made by 20 people over this period, where 26 requests were made by phone call.

The following requests were made to override the position of the automated roller shades:

- Three people made five requests to raise the shades because it was a cloudy, rainy, or foggy day. The requests were made in Area G2 by occupants seated next to the window between December and February.

[5] Derived from Figure 7 (upper graph) on page 22 for "low-e tint" on the x-axis and total energy use intensity for the "ns ndlc" versus "sh dlc" cases of the report: http://eetd.lbl.gov/sites/all/files/publications/lbnl-54966.pdf

- Eleven requests were made by six people in Areas G2 and G3 to lower the shades because it was too bright, all within an eight day period in November. Seven of these requests were made by three people in Area G3 within 3 ft of the south windows. These occupants faced the windows and presented the worst case situation on the test floor given prolonged, direct views of the sun. The remaining four requests were made by three people in Area G2 against the west windows and one near the corridor.

There were no requests made about the reference automated shades in Areas G1 and G4, presumably because these existing shades had been tuned based on occupant feedback when installed several years ago.

The following requests were made to adjust or repair the electric lighting:

- Five requests were made by four people in Area G4 because the light level on the desks was too dim.
- Five requests were made by four people to lower light levels because the light fixture above the desk was too bright or produced too much glare. Three of these requests were made in Area G3. One involved replacement of the light.
- Three requests were made by two people in Area G3 to raise the light level of the atypical light fixtures (type FC-1) because they were too dim. One of these lights was replaced.
- Five requests were made by four people to fix the lighting either because the controls were not working as intended (lights were off but needed to be turned on) or the fixture was not working. Two lights were replaced.

4.4.2. Occupant surveys

Occupants on the reference and test floors were issued electronic surveys (Appendix D) in mid-June 2016, six months (solstice-to-solstice period) after the shading and lighting systems had been commissioned, and given two weeks to voluntarily complete the survey. Two reminder emails were sent to the employees. No incentives were provided to encourage completion of the survey (e.g., donuts and coffee).

A total of 20 responses (“n”) were received from the reference floor and 58 were received from the test floor. A breakdown of the number of responses in each of the open plan areas is given in Table 38. Each floor had about 260 desk locations. The number of responses per area overall was low so results are indicative of potential trends between the two floors.

Table 38. Number of survey responses from open-plan areas

Area	Floor	
	Reference	Test
G1	4	4
G2	8	13
G3	6	30
G4	2	11
Total responses per floor	20	58

Responses were sorted and analyzed based on location in the G1-G4 areas. Responses could not be filtered based on precise location within each of the four areas due to privacy concerns. Therefore, occupants seated on the borderline between areas were not excluded from the analysis even though their field of view (on the test floor) may have included windows from the adjacent areas or light from the adjacent area's fixtures.

Employees occupying the floors were the same people for the most part before and after the test period. The tasks that they performed remained the same (i.e., computer, reading, writing). In the last week of January 2016, 34% of the total number of occupants on the test floor were moved from a floor near the ground floor (where daylight/ sunlight was largely obstructed by nearby buildings) up to the test floor and an additional 11% of the existing occupants were moved to a different location on the test floor. On the reference floor, 2% of the occupants were moved to a different floor and were not replaced. When the survey was issued, all the occupants had been in their final location for no less than five months and had experienced both winter and summer solar conditions. The occupants moving up from the lower floor would have had a significant increase in access to daylight and views. The survey requested that occupants provide responses based on their experiences between February 1, 2016 and mid-June 2016.

Occupants on the test floor in Area G2 were found to have significantly lower sensitivity to "darkness" (p=0.02) and significantly greater sensitivity to "glare" (p=0.03), but in all other aspects, occupant preferences and sensitivity regarding environmental conditions were, on the whole, comparable between the two floors. A summary of responses is given in Appendix D.

4.4.2a – Lighting

The three main differences between the test versus reference floor lighting systems were greater granularity or resolution of control, lower light levels, and LED versus fluorescent light source and fixture distribution. Overall, occupants indicated a preference for greater light levels than that provided on the test floor and were annoyed by having to trigger the electric lights to turn on by waving or standing up and walking near the occupancy sensors. Occupants experienced glare from the fixtures on both the reference and test floors. Responses related to the lighting systems were as follows:

Area G1 (n=4 and 4 for reference and test floors, respectively)

- Occupants on the test floor indicated that glare from the LED lights was "perceptible", making it slightly difficult to read or see the computer monitor, and that the lighting level was close to "too dark".
- On the reference floor, glare was at a similar level to that of the LEDs, with no effect on the computer monitor, while light levels were perceived as slightly above the "just right" level (towards brighter levels). Occupant perceptions of bright and dark light levels were consistent with the measured illuminance levels – reference floor total light levels were twice that of the test floor (average 46-696 lux versus 263-291 lux, see Table 11).
- On both floors, occupants were neutral on their opinion (neither agreed nor disagreed) on whether the ceiling was pleasantly lit (neutral to slightly agreed). They did not find the lights not all dimmed to the same level (as related to granular control) to be distracting. They were also neutral (neither agreed nor disagreed) in their satisfaction with the overall operation of the electric lights (slightly above neutral for the reference floor and slightly below for the test floor).

- Written comments for the test floor indicated annoyance with the occupancy sensors (at night, occupant needed to stand up or walk around to trigger lights on for a short period) and dissatisfaction with low overhead light levels during the day.

Area G2 (n=8 reference, n=13 test floor)

- Occupants found the light level to be just right on both the test and reference floor areas. Glare from the lights (in both areas) was just above "acceptable" and had a neutral to slight effect on difficulty in reading the computer screen.
- Occupants on both floors found the lighting to be comfortable, and not too dark. Occupants on the test floor were neutral regarding whether the ceiling was pleasantly lit, whereas on the reference floor, they slightly agreed. Occupants were neutral in their satisfaction with the overall operation of the electric lights (middle of the range between "strongly disagree" and "strongly agree").
- Comments on the test floor expressed dissatisfaction with the frequent distraction of the occupancy sensor. Contrary to the average response to the survey questions, there were comments on too dark light levels when working late at night, and dissatisfaction with the harsh bright lines of light across the ceiling.

Area G3 (n=6 reference, n=30 test area)

- Occupants on the test floor indicated that glare from the LED lights was "perceptible", making it slightly difficult to read or see the computer monitor, and that the lighting level was just below "just right" (towards the dark end of the scale).
- On the reference floor, glare was at an "acceptable" level (greater level of glare than the test floor), which made it difficult to read or see the computer monitor.
- On both floors, occupants were slightly above neutral/ agreed (between "strongly disagree" and "strongly agree") on whether the dimming of the lights was pleasant, whether the electric lighting was comfortable, and whether the ceiling was pleasantly lit.
- Occupants on the test floor agreed slightly that they were satisfied with the overall operation of the electric lights while on the reference floor, they agreed that they were satisfied.
- Comments on the test floor lighting were about the light level being too low and on the occupancy sensors turning off the lights when the space was occupied.

Area G4 (n=2 reference, n=11 test area)

- On the test floor, occupants found light levels a little above "just right" (towards too bright), the light distribution in general and on the ceiling to be slightly above "just right" (towards "well distributed"), and that the level of glare from the lights was perceptible but had little effect on seeing the computer monitor. Occupants were just above neutral (towards "agree") regarding whether they were satisfied with the overall operation of the electric lights.
- On the reference floor, trends were similar to the other reference areas. The light level was slightly above "just right" (towards the bright end of the scale), the level of glare was acceptable (greater than "perceptible"), which made it difficult to read or see the computer monitor. The lighting was comfortable ("agree") but the level of satisfaction with the overall operation of the electric lights was neutral.

- Comments on the test floor expressed annoyance with the occupancy sensors (i.e., turning the lights off in the evening; difficulty in triggering the lights on again). One wanted task lighting.

4.4.2b – Automated shading

The key differences between the automated shading systems were the control logic and the density of the shade fabric. More relevant is the overall occupant satisfaction with each automated shading system. Occupants were generally neutral (neither agreed nor disagreed) about whether they were satisfied with the reference and test shades. Glare was perceived as higher in the G2 test area with the more densely woven fabric compared to the G2 reference area; accordingly, there were many more comments about glare in the G2 and G3 test areas than the reference areas. This may be due to the test area shading system being new, whereas the reference shade had been in place for years. Responses related to the automated shading systems were as follows (same number of responses per area as the lighting system above):

Area G1 (west façade) – same reference shading system on both floors

- The reference and test floors (n=4) had the same automated shading system so differences in occupant response were due either to the physical layout of the spaces or variability in the population responding to the survey. In Area G1 on the test floor, the majority of the occupants in the open plan area were seated inboard of the private windowed offices so there were significant differences in occupants' experiences with the automated shades. The occupants in the private offices, for example, could override the position of the automated shades, whereas those in the open plan areas could not (unless they issued a service request).
- On both the reference and test floors, glare from the windows was "acceptable" (slightly greater than "perceptible" but lower than "uncomfortable"). On the test floor, occupants slightly agreed in their response to "bright light (from either the electric lights or the windows) made it difficult to read or see my computer monitor"; on the reference floor, they slightly disagreed.
- Occupants disagreed that the shades were too noisy and that the operation of the shades was distracting. They agreed that the automated shades allowed them to better focus on their work.
- On the test floor, occupants slightly agreed that the transparency of the shades allowed them to see outside; on the reference floor, occupants slightly disagreed.
- On both floors, occupants were slightly above neutral (towards "agree") in their response to "I am satisfied with the overall operation of the shades".
- Comments on the reference floor were concerned on the amount of shade movement, sometimes within a few minutes of each other, and the desire for views outside at night.

Area G4 (north façade) – same reference shading system on both floors

- Glare from the windows was acceptable on the test floor (n=11) but slightly uncomfortable on the reference floor (n=2), making it difficult to read or see the computer screen.
- The operation of the shades was not distracting on the reference floor but was slightly distracting on the test floor.

- The reference floor agreed that the transparency of the shades allowed them to see outside, while the reference floor was slightly below neutral (towards “disagree”).
- On the test floor, occupants were slightly below neutral (towards “disagree”) in their response to “I am satisfied with the overall operation of the shades”. On the reference floor, they were neutral.
- Comments were made about glare. One expressed preference for outdoor view despite glare. Another mentioned glare even on cloudy days; this occupant used a computer monitor while facing the window. The control system had been commissioned for views parallel to the window – adjustments to the control system could be made for this particular case. One occupant noted that conditions were acceptable except in the evening when low sun shined in their eyes. Another indicated borderline intolerable glare when the shades were raised since it caused eye strain when using the computer monitor.
- Comments were made about the operation of the shades. One commented that the movement was unexpected, distracting, and seemingly unnecessary. Another commented that some shades were noisy but that most were nearly silent and not noticeable.

Area G2 (west façade) – 3% OF reference shade on reference floor, 1% OF test shade on test floor

- Results indicate differences in trends between the 3% OF reference shading system on the reference floor (n=8) and the 1% OF test shading system on the test floor (n=13).
- There was a statistically significant difference in occupants’ rated level of glare from the windows (p=0.03). The reference system had a perceptible level of glare while the test system had an “acceptable” (greater) level of glare.
- There was a statistically significant difference in response on whether the transparency of the shades allowed occupants to see outside (p=0.02): “disagree” for the test floor with the 1% openness factor for the shade (more densely woven) and a little above neutral (toward “agree”) for the reference floor with the 3% fabric.
- Occupants were neutral (test floor) or disagreed slightly (reference floor) on whether they were satisfied with the overall operation of the shades.
- Comments regarding the test shading system included one indicating appreciation for the view at sunset but objected to the glare. Another indicated that the shades were lowered below eye level making it impossible to have an unobstructed view. Another noted that the shades worked improperly, raising when there was direct sun on their workstation. One commented that the shades used to work but seemed to stop working after a period of time (this could be when the sensor malfunctioned).
- Comments regarding the reference shade system included a comment regarding how they provided little benefit when partially or fully closed.

Area G3 (east façade) – 3% OF reference shade on reference floor, 3% OF test shade on test floor

- Results indicate differences in trends between the reference shading system on the reference floor (n=6) and the test shading system on the test floor (n=30).
- The level of glare from the windows was rated to be the same between the reference and test floors.

- Occupants agreed (reference) or slightly agreed (test floor) that the bright light (from windows and/or lights) made it difficult to read or see their computer monitors.
- Occupants slightly agreed (reference) or slightly disagreed (test floor) that they were satisfied with the overall operation of the shades.
- Comments regarding the reference shade included one referring to noisy shades that should be serviced (also noting that the facility managers had been responsive to requests for repairs). Another commented that the shades lowered at 8 PM created a distracting, claustrophobic, unpleasant work place.
- There were many comments on the test shades and were primarily about intolerable glare from reflections off of nearby buildings. The G3 test area had direct views of nearby high-rise buildings. Another comment indicated erratic operation of the shades.

5. LESSONS LEARNED

5.1. Design, bid, and procurement phases

5.1.1. Background: Deployment in the Living Lab

Technologies deployed in the Living Lab were selected based on a combination of technological innovation and preferences stated by the owners.

Functional performance specifications were created for distribution to vendors of light fixtures, advanced lighting control systems, window shading systems, and daylight-redirecting systems. These were essentially guidelines that contained a variety of options for potential bidders to choose from when developing their initial proposals. In some cases, functional attributes were listed as “tiers” to suggest a ranking of options. For example, the owners and project team preferred that lighting control systems be installed with maximum granularity but a less stringent tier option allowed vendors to submit proposals for systems at reduced levels of granularity. Vendors who were able to meet the requirements of the higher level tiers were given more weight than vendors who could not.

The specifications and a request for information (RFI) were publicized nationally through multiple communication channels and were sent directly to a list of potential participants identified by the project team and owners. The project team evaluated all of the submitted vendor proposals to determine if they met the minimum requirements based on the specifications and RFIs. Some proposals were eliminated from consideration. Based on technical input provided by the project team, the owners then made preliminary selections for each area of their respective test floors. Some of their decisions were based on aesthetics or broader business concerns, such as vendor reputation. The selected vendors were then invited to submit more detailed proposals following site inspection tours of the test floors and related facilities at both the LL and BA sites.

In this second round, vendors were asked to provide more comprehensive proposals for final consideration, including pricing for all required components in each test area per building site. This allowed the project team to determine the best combination of lighting, shading, and daylighting technologies in each test area.

Rounds 1 and 2 involved solicitation of proposals for equipment only. Once detailed proposals were received from the equipment vendors, each owner solicited bids for installation of the equipment by electrical contractors. The owners managed this process themselves, largely because of their existing relationships with local electrical contractors. The BA project team solicited a single-source bid price from the electrical contractor who installed the original fixtures and controls in the building (and who still had a Master Services Agreement for ongoing work in the building). The LL project team, on the other hand, solicited competitive bids from four different electrical contractors.

The LL team used this competitive bid process to substantially reduce installation cost. Initially, the highest bid for labor cost for the entire project floor was significantly over the allocated budget. Ultimately, the selected bidder's labor cost for the entire floor was significantly reduced through detailed discussions between the LL project team and bidding contractors to clarify and normalize the estimates between bidders (e.g., assumptions on how work would be staged). The BA project team also received a quote that was substantially greater than the original budget, although in this case, the BA team was unable to reduce the cost of the bid because it was non-competitive. Instead, the scope of work was reduced:

- The project team recommended deploying equipment in only two of the three areas delineated on the project floor.
- One of the lighting controls vendors tentatively selected for deployment had just introduced a fully wireless version of their system. This eliminated the need for the contractor to access the plenum to run additional control wires, thereby reducing installation cost.
- In the other area, it was proposed that the existing DALI ballasts in the perimeter private offices be left unmodified. Additionally, DALI dimmable ballasts were introduced in the open office areas at a lower granularity than previously proposed (one 2-lamp ballast per 10 ft fixture housing section as opposed to ballasts for each individual lamp). This decision alone resulted in approximately a 50% reduction of required ballasts, thus reducing both system and installation costs. Although this approach did not conform to the comprehensive equipment change originally desired, it represented a viable alternative for an owner whose predominant concern was cost containment.

The BA owner decided to proceed with the project, pending final installation and labor cost estimates. The project team worked with the BA owner to finalize many details of the installation and there were a series of indications that they intended to move forward. Unfortunately, at this time the BA organization initiated a major restructuring of their real estate management division and the project was halted.

5.1.2. Lessons learned from the Living Lab

At the commencement of the RFI/bid process for both equipment as well as installing contractors, the project team indicated to the owners that this project would be more complicated than a typical new construction or retrofit project. This was partly due to the fact that this was a research and demonstration project involving atypical requirements (such as independent energy monitoring and verification, specific calibration procedures, equipment analysis requirements, etc.). In addition, each owner subdivided their project floor into 3-4 separate areas, each with different equipment. This multiplied the complexity of the installation as compared to a typical project.

Although some aspects of the project were considerably more complex than an owner would typically experience, the bid and procurement process did yield some significant lessons about ways for an owner to reduce cost. These are detailed for the advanced lighting control systems in the following sections. Similar lessons learned are applicable to the advanced shading control systems.

Consider how on-site labor will be scheduled

As previously mentioned, the LL project team had discussions with multiple bidding electrical contractors about how to stage the installation work. Obviously, the LL building would remain occupied and fully functional during the installation phase. With this in mind, the project team identified three viable options for staging the installation work:

Night/weekend installation – Space remains occupied during daytime hours. Installation occurs at night and/or on weekends. This would trigger premium overtime labor rates, driving up costs. Impacts on employees, however, would be minimized.

Vacate entire floor – Space is completely vacated for the duration of the installation process. Installation work would occur during the day, eliminating the need to pay for premium labor rates for night/weekend labor. Occupants would need to be temporarily relocated or asked to telecommute during the period of renovation.

Vacate one quadrant at a time – Space is partially vacated (for example, one quadrant of an office floor at a time). Installation work would occur during the day for each area until installation and commissioning is complete. The next portion of space could then be vacated and installation could continue throughout the floor in this manner until complete. Assuming close to full occupancy, this approach would also require temporary relocation of occupants. Noise and construction dust would need to be controlled to minimize impact on working occupants.

The selected electrical contractor concluded that the third option (partially vacating the floor and installing one quadrant at a time) would be the lowest cost option. The owner decided in the end to go with night/ weekend installations. The right choice will depend on the specific building application and local labor rates.

The owners should consider the various options for the retrofit project upfront – including installation staging options, which are somewhat independent from the equipment itself.

Determine how you will stage the equipment

Other aspects of the work were also discussed with the bidders. For example, it was determined that the electrical contractor would remove and protect the existing light fixtures. However, the LL team would assume responsibility for removing them from the project floor (for storage for possible reuse, or to discard). By using their own staff to remove existing fixtures from the project floor, instead of the electrical contractors performing that function at high labor rates, this represented a significant savings in the overall installation cost. Still, since the mercury in fluorescent lamps is considered to be a hazardous waste, coordination on the handling and disposal between work groups had to be conducted carefully.

Commit to a scope of work

The iterative process of refining the scope of work to reduce the total cost of the project during the bid negotiation process requires time, patience, and due diligence by all parties; the owner, owner's consultants, vendors, and contractors. This process can cause owners to dismiss the project given the complexity of options or cause vendors and installers to increase prices to cover their cost of pricing out too many changes and modifications to the original scope.

Evaluating options and cost trade-offs is probably one of the single most significant barriers to widespread adoption of new technologies. Having some generic guidance on the relative costs for options, such as fixture replacement versus gutting an existing fixture and installing the controls on site, would significantly lessen the time and expense required by the owner to research various options.

Anticipate the need for licensed engineering support for retrofit projects during the design and procurement process

It is tempting to think that a retrofit project is simple – and that any facility manager or owner can solicit proposals from vendors for an energy efficiency upgrade. However, there are certain complex considerations that must be taken into account in any project. For example:

Codes – In some cases, retrofits trigger the need to bring an entire space up to current code requirements. That may impact (among other things):

- Lighting power density (and therefore power distribution to any affected equipment)
- Lighting controls (certain codes such as California Title 24 have very complex lighting controls requirements even for most retrofitted spaces)
- Daylighting zones (required by many recent codes)

Emergency lighting – Virtually all regularly occupied spaces require lighting for emergency egress. This can have an impact on retrofit projects because of the following:

- Unlike other aspects of normal operation of a lighting and control system, EM (emergency egress) lighting is a "life safety" issue. Most spaces require some form of EM lighting.
- When EM lighting is achieved by using standard fixtures – but supplied with a source of emergency power – it is typical that approximately 10% of the fixtures will be designated as EM. Because of this small percentage, many owners and vendors don't think about EM lighting when planning for the typical equipment they'll need to retrofit the space.
- Different locales have different requirements for EM lighting. For example, in NYC, you're not allowed to turn EM fixtures full OFF. However, in California, you are actually required to turn EM fixtures full OFF under normal conditions. Someone must take responsibility for verifying what the requirements are based on the project location, and

vendor representatives often do not have the technical background to provide this level of detail.

- Different lighting control systems have different methods of providing EM lighting. These are often based on the different topologies used by each vendor, making the design and code verification process even more complex when different systems are being considered.

In most locations, a licensed professional (typically an electrical engineer) is required to "sign off" on issues like adherence to codes and provision for EM lighting – even for "retrofit" projects. Vendors may be able to provide guidance, but they do so reluctantly because they know that there are legal consequences involved. Needless to say, vendors can provide information on products they make that can help to satisfy EM lighting requirements (such as phase-loss sensor modules, bypass relays or other compliant devices, etc.).

Define the desired level of granularity/ zoning

Initially, the project team designed RFIs and RFQs based on a desire for "maximum granularity" of zoning. This maximum granularity would help the project team to parse data about things like daylight harvesting. During the process of soliciting RFIs and RFQs, it became apparent that "maximum granularity" meant different things in different lighting control systems.

As an example, one control system allows any fixture in a space to respond differently to input from the same photosensor, or any other photosensor for that matter. In another system, every single control zone must have its own photosensor. To match the operation of the first system, every single fixture in an area using the second system would require one photosensor for every single fixture. This zoning requirement therefore impacts the project cost as well as complexity of installation, commissioning and operation for some systems.

Because of the variety among control systems in how they deal with "zoning", it's important for an owner to carefully define their needs in advance.

Decide whether to retrofit old fixtures with advanced controls or replace with new LED fixtures

In new construction projects, light fixtures can be supplied with all required control components pre-installed. This allows the fixture vendor to install any required components in the most efficient manner, on the ground, in a factory environment. In a retrofit project, the electrical contractor essentially has to do "surgery" on existing fixtures in-situ while standing on a ladder.

If a decision is made to provide new fixtures as well as lighting controls for a retrofit project, then just as in new construction projects, the fixtures can be supplied with all required components pre-installed (on-board controllers, sensors, drivers sold on an OEM basis are shipped to the fixture manufacturer). This may produce a substantial decrease in per-fixture labor cost for installation, though this will increase the capital cost of the new fixtures.

With wired control systems, it is likely that low-voltage control wires will still have to be run through the plenum – even to new fixtures. However, if a wireless control system is used with new fixtures, then existing fixtures can simply be swapped with new fixtures – and the electrical contractor should only have to disconnect and reconnect the line-voltage power wires (black, white and ground). In theory, this should be the lowest-cost option for a retrofit project (if new fixtures and a new wireless control system are installed).

Assess the state of the existing electrical closets/ lighting power distribution panels

Some advanced lighting control systems require that lighting branch circuits be distributed from proprietary panels. Others do not. In addition, some existing spaces may already have lighting control systems for some or all of the existing light fixtures. For example, both the BA and LL sites have existing dimmable lighting control systems for the perimeter area next to the window while the remaining core lighting is switched.

Both project spaces also have emergency power distribution panels that supply select lighting circuits. This is a common method of providing EM power for emergency egress lighting.

When retrofitting a new lighting control system in an existing space, it may be necessary to eliminate or bypass one or more existing distribution panels, or to replace them with those from a new system. In certain cases, it is possible to leave all existing distribution panels in place. In any case, it is important for a qualified person to determine whether panels have to be eliminated, bypassed, replaced, or can be left in place. This determination may have a significant impact on cost as well as complexity of installation.

Decide whether default control profiles/system setup/behavior is acceptable for your project

During the initial stages of the bidding process, some vendors supplied information and costs based on "default" equipment and system behavior – irrespective of the project team's detailed performance specifications. Ongoing communication was required with some of these vendors to obtain Bills of Material and pricing based on the specific project requirements.

It is clear that most vendors have "default" expectations regarding the use of their systems – and the equipment required. Providing information, Bills of Materials and pricing for "non-standard" equipment and behavior obviously requires extra time and effort on the part of the vendor.

A possible solution for part of this problem is to standardize methods for specifying granularity (of control zones, occupancy sensors, photosensors, switches, etc.) as well as for system behavior (standardized control profiles, etc.).

Conclusion

Considering the complexity of the issues involved in a lighting fixture and/or control system retrofit, it is preferable for an owner to retain a qualified consultant(s) to provide appropriate guidance. Besides the potential legal ramifications (as described above), relying on vendors to suggest appropriate equipment and installation options may not always result in the lowest cost, shortest payback period, or even the greatest energy reduction.

5.2. Installation phase

Upon completion of the procurement phase, the following steps were taken to install the technologies in the Living Lab:

- Obtained final sign-off of the submittals, including the drawings showing location of all equipment, cut sheets, zoning diagrams, and desired settings for the control systems
- Issued the purchase order (PO) and ordered the final materials
- Where new LED replacement fixtures were used, the lighting controls manufacturers shipped on-board controllers and/or sensors (sold on an OEM basis) directly to the fixture manufacturers for factory installation by the fixture manufacturers (LED drivers were supplied by the fixture vendors regardless of whether they were incorporated into the fixture housings or remotely-mounted in the plenum)
- Received shipments of equipment (fixtures and control system components) at the job site and verified that the material is correct
- Obtained the City permit to conduct construction in the building, where the drawings were stamped by a licensed electrical engineer regarding code and safety requirements of the final design
- Covered all office work surfaces each night and/or on Saturdays prior to installation (and removed plastic covering plus cleaned any debris from the space each night/on Saturdays)
- Accessed the ceiling plenum by temporarily removing specific ceiling tiles
- Turned off lighting branch circuits
- Installed the fixtures, including (in some cases) remotely-mounted LED drivers and/or controllers
- Installed wireless or wired sensors and switches
- Tested the fixtures by turning on branch circuits
- Corrected any wiring or other installation problems
- Ran low-voltage wiring from fixtures to control panels in electrical closets, as required (e.g., with DALI systems)
- Linked servers with other control system components (such as wireless gateways) by running Ethernet cable from the finished office space to the electrical closets
- Installed servers and other central control system components in electrical closets
- Connected servers in electrical closets to the owner's BMS (building management system) network for access to the system software
- Verified that control system wiring was correct
- Commissioned control systems (including zoning, photosensor calibration, programming of all settings, establishing schedules, etc.)
- Evaluated normal operation of each control system, especially daylight harvesting operation and target light levels

5.2.1. Lessons learned to reduce cost

Construction permits

There is a common belief that retrofit projects involving light fixtures and control systems can be installed without the need to get appropriate building permits. Retrofit projects involving light fixtures and control systems usually impact the emergency lighting. Therefore, typically a licensed electrical engineer will need to provide official documentation, and appropriate building permits will need to be secured prior to installation. Most current codes also stipulate a threshold, typically expressed in percentage of luminaires in a given space that are replaced, beyond which the entire lighting system must be upgraded to meet the current energy code, not just the portions intended for replacement. Significant gray areas exist with regard to code compliance in those situations in which portions of the system are replaced or modified. For instance, if fixtures remain in place and new controls are installed to drive them, or if fixture housings are left in place and some or all of the internal componentry is replaced.

Drawings

On new construction projects it is a standard requirement for all drawings related to every aspect of construction to be available on-site at all times. In "retrofit" projects, it is not always typical to have full sets of drawing on-site documenting all of the electrical equipment as well as all wiring connections. When installing a new lighting control system, whether fixtures are new, refurbished or existing, it is imperative to have a full set of drawings on-site showing all details of the equipment, including documentation showing every wiring connection.

An owner may be tempted to allow the control system vendor to provide much of the documentation. This can result in costly mistakes because there is no recourse if the vendor-supplied documentation is incomplete and/or has not been officially approved by the owner and the design team. Therefore, drawings for on-site reference – whether in paper or electronic form – should be those created by the electrical engineer. The control system vendor may incorporate vendor-supplied information and documentation, but that information should be incorporated into "official" documentation.

In addition to drawings showing every aspect of the equipment to be installed, it may be desirable to provide photographs or even short videos of fixture or control system installation. In some cases documenting the first several installations of each equipment type (fixtures, control components, etc.) might help crews in future phases avoid mistakes. In general, any support that vendors can provide to demonstrate how equipment should be installed and wired is beneficial to help reduce mistakes in the field and minimize scheduling delays.

On-board control equipment

Whenever possible, it is preferable to incorporate controllers or any other required equipment in the fixture housings, rather than within the ceiling plenum. Ideally the housing would also include photosensors, occupancy sensors, bypass relays or any other equipment required for the normal operation of the lighting control system. In addition, it is preferable if LED drivers are mounted within the fixture housing if possible. Feedback during the installation suggested that the test floor Area G4 had the least learning curve due to factory-installed hardware included with the fixtures. Logistically, the owner directly procured the equipment then coordinated shipment of the material to the site or to the fixture manufacturer.

Not all fixtures will have adequate space in the housings for these components. If not, then certain components may need to be remotely mounted in the plenum, which typically adds cost and complexity to the installation. Also, not all electrical contractors are experienced with wiring controllers, digital LED drivers, bypass relays, analog and digital sensors, and other components of advanced lighting systems. Therefore, remotely mounting some or all of these components in the plenum increases the risk of incorrect wiring, which may damage or destroy certain components. Therefore, when considering possible new fixtures or retrofit kits, it may be preferable to consider those with adequate space for accommodating all necessary components in the fixture housing. In that situation, the fixture vendor(s) would purchase controllers, bypass relays and/or other required components from the control system vendors on an OEM basis, and factory-install those components. This reduces wiring problems on the job site.

Wire colors

As previously mentioned, some electrical contractors do not have experience installing fixtures with 0-10V dimming ballasts or drivers, digital (e.g., DALI) dimming ballasts or drivers, advanced lighting control systems, or unusual methods of providing EM lighting or transfer to EM power sources. Therefore, in addition to providing drawings showing all wiring connections, it is imperative that vendors fabricate all fixtures using industry-standard wire colors. For example, 0-10V dimming signals should be carried over violet and gray wires, DALI signals should be carried over two violet wires (or, preferably, a violet wire and a separate violet wire with a white stripe). This is especially important if any fixtures are used that cannot incorporate all required components within the fixture housing. For example, if a fixture is chosen that has enough room for an integral 0-10V dimming driver, but not enough room for a controller, the controller must be remotely mounted in the plenum above the fixture. The electricians in the field must connect the controller in the plenum to the 0-10V dimming driver in the fixture. The controller supplied by the lighting control system vendor will definitely have the correct (industry-standard) wire colors. If for any reason the fixture vendor fabricates the fixtures with 0-10V dimming drivers using non-standard wire colors in a cord set, the electricians may not be certain about how to correctly wire them together.

Installation diagrams

Most fixtures include a wide variety of options, including mounting details, optics, optical control media, light source color, wattages, lengths, EM batteries, etc. Light fixture vendors often provide standard catalog pages in their documentation, sometimes even in official submittals. If a standard page showing a list of possible options is the only documentation available on-site, the installing electricians may not have enough detailed information to efficiently and correctly install the fixtures. It is imperative that the fixture vendors supply project-specific information about mounting details, wiring connections, etc., including detailed instructions for mounting the specific fixtures supplied to the job site.

EM (emergency) lighting

In commercial office (and other) spaces, a small percentage of the light fixtures are typically identified to deliver emergency (EM) lighting. This is typically achieved either by using on-board batteries (with EM ballasts or drivers), or by powering those fixtures from an emergency power source (such as an emergency generator). When using an advanced lighting control system, fixtures are typically nodes on a digital wired or wireless network for transmission of control signals or other information. Integration of EM fixtures into the lighting plan may require more complex methods of local transfer. For example, besides providing EM power to the designated fixtures, applicable codes may also required that bypass relays cut out any signals on digital networks also connected to those fixtures. Some electrical contractors do not have experience in installing such equipment. Therefore, it is essential that complete documentation be provided explaining how EM fixtures or other equipment are to be connected.

Luminaire quality control

New LED luminaires and LED retrofit kits often incorporate one or more “boards” (LED matrices), each containing multiple LED dies. There are a wide variety of boards available based on factors such as size, shape, number of LED dies, color and light output of LED dies, forward voltage, drive current and many other factors. When these boards are used in a new LED luminaire or retrofit kit, the fixture manufacturer must mount and then connect the boards to the LED driver using secondary wiring. Legacy light sources (e.g., incandescent, fluorescent, HID, etc.) rely on a relatively small variety of bases (sockets) for mounting and providing electricity to the lamp. Once the fixture manufacturer installs and wires the base, a lamp is virtually guaranteed to work properly when installed in the fixture.

Some standardization exists in the LED industry due to the development of standard “modules” (such as “twist-and-lock” puck-shaped modules for recessed downlights). However, many new LED luminaires and retrofit kits still use a luminaire-specific pattern of “boards” that must all be wired back to the driver. Designers should incorporate language in the lighting specifications that require all fixtures to be factory-tested. This will insure that secondary wiring is properly powering the LED boards. In addition, typical control functions such as dimming 0-10V drivers or even DALI drivers can be factory-tested. This may help to reduce installation problems in the field. Alternatively, the electrical contractor can perform similar checks prior to installation. However, field checking is almost certainly a more costly option due to the high labor costs of electrical contractors.

Obstructions in the plenum

In a new construction project, ductwork and other obstructions can be routed to avoid conflicts with things like light fixtures and junction boxes as part of the design process before construction begins. In a retrofit project, it is possible that existing ductwork, other equipment or the structure itself may affect the mounting conditions for certain fixtures, junction boxes, etc. “As-built” drawings may or may not describe all conditions that have a potential impact on those locations or mounting conditions, so it may be desirable for the project team, including the installation contractors, to survey the plenum to assess the viability of installing new equipment. Some manufacturers produce fixtures and other equipment with “low recess height” specifically for the most constricted conditions.

Fixture mounting heights and locations

If project-specific drawings (such as lighting plans) are not available on-site during installation, the installing contractors may assume that new fixtures should simply be swapped 1-for-1 with existing fixture, using the same locations. In projects with pendant-mounted fixtures, they may also assume that new fixtures should be mounted at the same height AFF (above finished floor). However, the designer may have changed the layout and/or other details such as the mounting height of pendant fixtures in an attempt to reduce the number of fixtures, or to reduce the energy use, or simply because the new or retrofitted fixtures have advanced optical properties that allow for greater spacing or different mounting heights. It is essential that drawings showing all project conditions are available on-site to reduce such installation errors.

Inventories of fixtures and control equipment

On a typical lighting retrofit project incorporating an advanced control system, separate shipments to the job site will come from the fixture vendor(s) as well as the control system vendor. It is essential that a designated party (typically the installation contractor) be responsible for checking the shipments to insure that all required equipment is on-site in advance of the start of installation. It is possible that certain equipment can be installed while waiting for other equipment to arrive. For example, typically fixtures can be installed and even wired and energized to provide light in occupied spaces, before the control system is commissioned. However, none of the functions of the control system will operate until all of the control system equipment is on-site, installed and properly commissioned and programmed. Because of the complexity of such an installation, it is imperative that a designated party take responsibility for checking shipments against the specifications and drawings.

Linear rows of fixtures

Predominantly, open office spaces use individual recessed fixtures, each of which must be powered, switched and controlled. Increasingly, continuous rows of fixtures are being used for open office lighting. These are typically pendant-mounted, but continuous rows of recessed fixtures are also a viable option for office lighting. Continuous rows of fixtures – whether pendant or recessed – present unique conditions that require special attention when they are combined with advanced lighting controls. First, row configurations must be very clearly designed and documented. It may be tempting to specify that rows be comprised of the required number of modules, all of certain length, based on the plans. What if different length modules are required to complete specific rows? If the fixtures are pendant mounted, can the existing stems or cable mounting be used for the new fixtures? Probably not. If new mounting locations or hardware are required for the new fixtures, they must clearly be documented.

If continuous rows of new fixtures are used throughout the space, whether they are pendant or recessed, some segments of certain rows will undoubtedly have to be designated as EM to provide emergency lighting. Those segments may require separate emergency feeds and/or other equipment (such as on-board bypass relays, etc.). Typically a licensed electrical engineer must confirm the impact of EM requirements, such as whether the new fixtures (which presumably have different output than the existing) in existing locations will provide sufficient EM lighting.

From the viewpoint of normal control system behavior, control profiles for continuous fixture rows may be slightly different than for individual recessed fixtures. For example, if the rows are mounted perpendicular to the window wall, but you're trying to implement daylight harvesting using photosensors, will different portions of each row need to be dimmed to different levels because they are in different "daylight zones"? If so, it may be necessary to insure that LED drivers and/or controllers are installed in short segment lengths to enable the specifier to decide.

Control wiring

Many advanced lighting control systems rely on low-voltage wiring to provide dimming or other control signals to the light sources (LED drivers and boards, fluorescent ballasts and lamps, etc.). A "controller" of some type must be provided to send the appropriate dimming or other signals to those light sources. In certain fixtures or retrofit kits, the controller may be factory-installed and pre-wired to the driver or ballast. In other situations, the controller may be remotely mounted in the plenum. Some lighting control systems have centrally located controllers. These systems typically send signals along loops of low-voltage wiring run through the plenum to fixtures (and/or peripheral devices such as sensors and switches). Depending on the system, the signal may use 0-10V, DALI or other protocols. Not all electricians are familiar with these protocols or wiring methods for the low-voltage runs.

If the fixtures are totally self-contained (with all required control components factory-installed and pre-wired), it may not be necessary to provide additional training on how to install and wire them. However, in other situations, it is highly desirable to provide some minimum training in advance of installation to the electricians to familiarize them with new wiring methods and topologies.

Installation procedures

Depending on which electricians are present on a given day, the team of installers may physically install and power new fixtures separately from the task of connecting any other required wiring or equipment (such as low-voltage network wiring, sensors, switches, etc.). In a retrofit project, it is desirable to minimize the disruption to the existing space, as well as to minimize the number of times that the plenum must be accessed by opening ceiling tiles. Therefore it is preferable for electricians to install all required equipment in a given location and to pull all required wiring through the plenum at one time.

This may be more complex than separating those tasks. However, it may have a substantial effect on the reduction of disruption or even installation time. As long as all required documentation is on-site during installation, appropriate wire types and colors are used, all equipment is ready for installation, and personnel are available to provide adequate supervision, there’s no reason why all of these tasks cannot be completed simultaneously.

Wiring for peripherals (sensors and switches)

Some lighting control systems use one method of transmission and one protocol for control signals to light fixtures, and a different method or transmission and/or protocol for communicating with peripheral devices such as sensors and switches. It is not uncommon for both to run on a low-voltage network. However, except in certain situations (for example when using DALI-compliant sensors and switches), these networks must be separated. It is important to clarify this and provide clear documentation showing what goes on each network.

Control system panels

Some lighting control systems use centralized panels to contain equipment such as fixture controllers, power supplies for low-voltage networks, hubs for peripheral networks, phase-loss sensors for EM lighting, etc. Typically, the configuration of equipment in these panels is customized based on the project-specific conditions. Therefore, it is essential that the control system vendor provide drawings showing all wiring connections that must be made in the field, by the installing contractor.

Post-installation tasks – the following are tasks that are completed once all of the equipment has been installed. It is not uncommon for a project team to work on the system design and configuration before addressing these tasks. However, decisions about these issues will impact the system design and configuration. Therefore, they should be considered at the outset of a project, during the design phase.

Commissioning

The commissioning process often takes up a small percentage of the overall installation time on a project. However, the successful operation of the system (and subsequent energy savings) depends on commissioning to achieve the goals of the owner and designer. A lighting control system cannot be effectively commissioned unless the project team has determined appropriate zoning for fixtures and devices, as well as written clear and concise control profiles. Simply accepting a vendor's proposed default control profiles may not achieve the project goals.

IT/security/connectivity issues

Most lighting control systems are designed to work with a "standalone" topology, or to allow for the components to be connected via an owner's existing building network. Determining what topology will be used will have an enormous impact on the required control system components, installation cost and complexity, potential risks to security, and other factors. Therefore, it is essential to address these issues during the design phase.

Training/control system access/on-going system operation

It is important to discuss these issues during the design phase. Determining who (and how) the lighting control system will operate on a normal on-going basis may affect the choice of a system or the software to operate it. There may also be other requirements such as remote "dashboard" displays, regular reporting, etc. These may all have an effect on the selection of an appropriate type of lighting control system.

Process and communications

Surveys of the market for advanced daylighting and shading controls have found that many of the barriers to adoption lay outside concerns about the technical performance of the systems or their ability to meet energy savings expectations. We tracked the process of technology selection, permitting, installation, commissioning and occupancy and developed a set of key strategies in response to friction observed in the process. These strategies included recommendations with regard to team selection, internal and external project communication, timing of decision making, how the complexity of certain system types influences which contexts they are best suited to, and relevance of certain technologies to different types of commercial tenants and building owners.

RFI and specifications

The RFI and specifications were further refined based on lessons learned in both the procurement and installation phases of this project. This document was released publicly and can be downloaded at the following website:
https://facades.lbl.gov/nyclivinglab

5.3. Applicability to the commercial buildings sector

Throughout the design, installation and monitoring phases of the Living Lab project, the Building Energy Exchange (BEEx) was intimately involved with day-to-day interactions with the building owner and the technology vendors. As a result, BEEx was in the unique position to observe the work in progress and derive lessons from the project based on their knowledge of the New York City market. Recall that BEEx was advocating daylighting in their "Let There Be Daylight" campaign and were vested in promoting such an approach should findings indicate that the technologies could be cost effective and therefore scalable to the majority of commercial real estate in the New York City regions as well as central business districts across the U.S.

BEEx's key role at the conclusion of the monitoring phase was to translate the lessons learned from this project (and other projects they were developing) into educational and training resources for the local New York City lighting and daylighting community. These include virtual resources like case studies as well as live instruction modules. The following summarizes their findings from the different stages of the project for both the LL and BA buildings. Note that the BA building was similar to the LL building in that it was a high-rise LEED Platinum commercial office building with a gross square footage of approximately 2,100,000 ft^2 and occupied in 2008. Unlike the LL building, however, private offices were located at the window wall (with glass rear walls) and open plan workstations were located in the core zone.

5.3.1. Lessons learned

Energy use – existing conditions

Actual energy usage: The host sites were surprised by the energy usage of certain elements of their existing lighting systems. The monitoring period revealed areas in which switching or control systems have not been working properly (leading to far greater usage than assumed). This speaks to the need for routine metering of basic systems at a much more granular level than the panel, as well as a system of periodic commissioning that enables users to correct inefficiencies or functional problems.

Relative usage: Both sites include full floor metering of electrical usage, but more granular information was not available through the legacy lighting control systems. As a result, the host sites were aware of their total electricity bill for each floor and each had made assumptions about how much of that total was attributed to lighting, appliances and plugs. But these assumptions were not always correct. One site, for instance, had assumed that lighting was 50% of their bill and appliances and plugs the other 50%, when in fact lighting was only 20% of their total electricity usage. Plug loads on the monitored reference and test floors were within norms, leaving open the question of how much of the whole building energy use was due to other unknown sources (e.g., data centers, etc.). The detailed metering helped inform the owners' approach to the lighting retrofit options and indicated that a program similar to the Living Lab focused on whole building analysis would be beneficial.

Indoor environment findings – existing conditions

Shading/ BA building: The lack of automated shading in perimeter offices, and the limited functionality of the automated system within perimeter conference rooms, severely reduced adjustment of the shading system, with the majority of the blinds deployed either partially or fully, and rarely adjusted. This was equally problematic at perimeter offices and open plan areas.

Controls/ BA building: Lack of occupancy controls in some spaces, limited daylight sensors at the perimeter, and the clumsy motorized shade user interface in the conference rooms all contributed to a lighting system that was far from optimized.

Dimming/ BA building: The lack of dimming in the interior and open plan areas meant that the system could not be tuned for different uses or the desires of the occupants. For instance, occupants conducting tasks primarily on the computer (e.g., coding, web management, etc.) desired far less general illumination than others. As these divisions grew, the system could not be tuned and the owner could not realize the potential energy savings.

Shading/ LL building: Operations of the existing automated shading system were effective but the existing shading material failed to meet the needs of all facades. The west facing façade required nearly opaque shade material to adequately control the glare from low angle sunlight, which created a dark feeling when fully lowered.

Finance

Pricing: Pricing of lighting system components is extraordinarily complex, with manufacturers, their regional distributors, and the installation contractors each playing a part in the determination of the costs. Retrofits can be in an especially awkward position because lighting for new construction and major renovation projects are often purchased as a complete package, with the profit distributed unequally across the various stakeholders. Because retrofit projects often pick and choose among available components to limit complexity and disruption, pricing of individual components is important but not something the stakeholders are accustomed to providing. Clear specifications and clearly identified project management are critical to addressing this challenge.

Unfamiliarity: In a full scope renovation project, a lack of familiarity about one system on the part of one subcontractor might not significantly impact the overall project. In the case of a lighting retrofit, where you are often dealing with only one or two systems (lighting controls and light fixtures, for instance) the opposite can be the case, with a lack of experience on the part of the installer impacting both the costs and schedule significantly. Careful vetting of contractors that have extensive experience with the systems under consideration is critical to successful retrofits.

Bidding: Many building owners (as well as major tenants) have existing master service agreements with a single electrical and/or data wiring contractor. As a result, it is tempting to rely on pricing for lighting retrofit packages from this single source. Because familiarity, or lack thereof, with a specific luminaire or control system can play such a large role in installation pricing, utilizing a single bidder may not produce the most cost effective solution. In our experience, projects that bid to multiple installers have seen post-leveling pricing that varies by up to 50%, a remarkable margin. If a single bidder is at the expensive end of this range it could easily derail the feasibility of a lighting retrofit. As a result, we highly recommend multiple bidders for a project of almost any scale.

Off Hours Work: Retrofits, by definition, occur in occupied spaces. Unlike gut renovation or full scope tenant improvement work, retrofit work must be organized around the existing building occupants, which often means limiting all work to overnight hours and weekends. Night and weekend work requires protection of desks and other work surfaces, staging over furniture systems, and extensive clean up at the end of each shift. These, obviously, increase both the total labor hours, the labor rates and the overall construction schedule. The necessity to work in short shifts can also make mid-course corrections more time consuming. On a typical project, a site supervisor might phone a lighting designer for quick clarification and make any necessary adjustments right away, while issues encountered at 2:00 AM will have to wait for the next business day for resolution. Two recommendations stem from these issues. First, project stakeholders should carefully study swing space options that might open areas of office space for retrofits during normal business hours. Second, the project manager should make every reasonable effort to limit work on site, for example, by ensuring that all drivers, control modules and sensors are installed in the bodies of luminaires prior to shipping to site.

Selection and procurement process

Organizational process: Though both host sites are global institutions, their processes for consideration, selection and procurement of technology were significantly different from one another. As a result designers, energy managers or vendors hoping to raise interest in retrofit projects are faced with a situation in which there is no standardized process to interface with. In addition, when dealing with retrofits of existing offices each organization will have different processes in place for the selection and purchasing of equipment, and there may be situations or processes they have not yet considered. Each of these can become a barrier that should be understood as early in the process as feasible. They include:

- Technology vetting requirements (including testing requirements whether internal or code mandated);
- Procurement requirements (some organizations require vendors to be vetted and registered within a closed procurement system, vendors outside this system typically cannot even receive rudimentary project information);
- Non-disclosure agreements (often required simply to view the parameters of the project);
- Existing distribution/service agreements (many organizations have existing agreements in place which dictate where and from whom technology or equipment can be purchased and/or installed); and
- Equipment/Technology ownership (it is often unclear in existing offices which pieces of equipment are owned and/or serviced by the building owner vs. the tenant).

Goals & Thresholds: It is important to note that different owners/tenants will have both differing goals and differing thresholds at each stage for moving forward with any given project.

These should be determined as early as possible and reconfirmed regularly, particularly when new team members are brought on board by any party.

Technology Options: There are currently so many technology options available for lighting systems that it is difficult for owners/tenants to discern the real differences between them, let alone which is most suitable to their specific situation. Educational resources are needed that specifically outline these system typologies to help decision makers understand their options in the simplest terms possible.

Mid Lease Issues: The appetite for lighting retrofits will be significantly influenced by the time remaining on the relevant lease. Educational resources should identify the strategies available to short-, medium- and long-term lease holders.

Fixed Asset Depreciation: If a retrofit proposal includes the removal and replacement of technology, it may trigger payments related to fixed asset depreciation schedules. This should be noted as an early determinant of the feasibility of a lighting retrofit for a given location.

Monetizing Soft Benefits: Although many owners/tenants are very interested in the "soft", or non-energy, benefits of lighting retrofits, feasibility discussions are typically driven by stark monetary metrics like simple payback, making it difficult, despite a high level of interest, to account for these soft benefits in deliberations.

Unfamiliarity and Risk: Because retrofits happen in individual spaces infrequently (with a decade or more often between each renovation of an office) it is likely that many stakeholders for a given location have not been involved in such a project. Coupled with the rapid changes in technology the sector has seen and will continue to experience, there is a deep unfamiliarity with the lighting retrofit process that translates directly into a sense of risk. Even if projects move forward, this sense of risk can create friction and overly conservative decision making at each stage. Teams should simplify the process as much as possible.

Warranties: Many owners/tenants, especially large corporations, have guidelines that recommend (or strictly require) purchasing equipment or technology from legacy companies with a long track record that they can be assured will meet any warranty requirements or future project needs. There is an inherent tension between these internal requirements and desires to explore the latest technology, which is often offered by recently created clean-tech companies.

Wireless Protocols: Despite the prevalence of wireless systems, many organizations have yet to install wireless controls in their offices and there may be specific guidelines in place regarding communications protocols, due to security concerns. These issues should be resolved as early as feasible. This can impact vendors' ability to remotely access the server to make changes, requiring the vendors to come to the site if there are any issues. It also puts additional burden on building engineers to learn a new system.

Technology Compatibility: It is fairly common for control system components (luminaires, LED drivers, control modules, etc.) from different companies to experience compatibility issues. With the multiple variables involved, and the large number of manufacturers in this sector, establishing certainty of compatibility can be very difficult. It is recommended that project owners either 1) procure all system components from a single manufacturer (although only a few are capable of this), 2) identify a single manufacturer as the lead and include responsibility for compatibility in the relevant specifications, or 3) require the construction manager or general contractor to physically build and test a mock-up of the system, including all components, prior to procurement.

Selection and procurement recommendations

Based on the findings and analysis of the Living Lab project, teams considering lighting retrofit projects should:

- Clearly delineate, before any work proceeds, the project goals in terms of energy savings, financial return, aesthetic and functional needs.
- Consider establishing a mission statement describing the motivation for action, from corporate image to employee well-being, to energy cost reductions and simple code compliance.
- Identify a project manager with relevant experience in both the technology under consideration as well as the decision making structure of the organization. Task this manager with treating the lighting retrofit like a fully-fledged construction project, with all relevant steps and care in management of the process.
- Coordinate retrofit plans with leasing terms or schedules of other work to ensure measures are cost-effective.
- Develop clear specifications that include any issues that will directly impact technology selection, including warranty requirements, post-occupancy technical support, wireless protocol or system compatibility requirements, etc.
- Select the simplest, least disruptive solutions that meet the highest priority goals.

Installation Process

The installation process findings listed here reflect high-level issues of most critical concern to decision makers and influential stakeholders. In addition to the findings listed here there are extensive and very important detailed findings related to the specifics of installation listed in Section 5.2.

Project Management: As noted elsewhere, identifying a dedicated project manager that will provide continuous oversight of the project is critical to the success of retrofits. Because lighting system retrofits deal with what users perceive to be a single system (lighting) it is often assumed that the projects will be simple and rigorous management not a priority. In reality, a lighting retrofit often involves the technical coordination of multiple vendors, with manufacturers of luminaires, lamps, controls, and sensors in some cases being different companies, and each of them may have different local representatives or distributors. Advanced lighting systems may integrate with the existing building management system as well as the data systems in a building, requiring input and sign off from multiple parties that may not have been initially included in the planning. In addition, retrofits impact working stakeholders that must be educated about activities and operations. The project manager should be responsible for coordinating all parties to the retrofit project, developing workflows and schedules and organizing any training required for installers or commissioning agents.

Drawings & Specifications: Because a lighting retrofit can be perceived as "simple", it is common for standard steps and procedures of larger projects to be ignored. Given the technical complexity of the systems under discussion, and the stop and start nature of off-hours work, it is imperative that accurate drawings be kept on site for all subcontractors and other parties to reference. These should include clear, project-specific (not boiler plate) instructions and diagrams for assembly and installation wherever required. Especially with new technologies, the standard or usual wiring protocols may be different and there is a steep learning curve for installers who may be unfamiliar with the systems.

Vendor Technical Representatives: It is highly recommended that vendors be required to identify, at time of bidding, a technical representative that will act as the project manager for the vendors' products and systems during procurement, installation and commissioning. This representative should not be a salesperson, unless they have significant technical background with the construction and operation of the systems under consideration. Even small details that are overlooked on a lighting retrofit project can cause significant problems. Without a designated technical representative it is often difficult for contractors or other stakeholders to know who to communicate with to quickly resolve technical issues.

Education & Training: The project manager, or other primary stakeholder, should be tasked with ensuring that all installers and contractors are properly trained in the assembly and install of all the systems under consideration. For example, it is not unusual for installers trained to install a single type of luminaire to arrive on site with no knowledge of how to assemble or wire the specified control modules. Proper training prior to the installation phase can greatly reduce delays and mistakes that might otherwise derail a project.

Installation process recommendations

Teams embarking on lighting retrofit projects should:

- Identify a project manager with relevant experience in both the technology under consideration as well as the decision making structure of the organization. Task this manager with treating the lighting retrofit like a fully-fledged construction project, with all relevant steps and care in management of the process.
- Develop accurate drawings and specifications for the project, including clear, project-specific (not boilerplate) fabrication and installation instructions. Ensure these documents are available on site at all times.
- Designate technical representatives from each vendor, and enlist their attendance at relevant project meetings.
- Ensure all subcontractors are properly trained in the installation of the specific technologies and that all facility staff are trained in operation of these systems.

BEEx cost estimate summary

The installed costs of lighting retrofit systems is of course a primary factor in determining whether projects move forward. Lighting retrofit are vulnerable to a very high degree of variability in costs due to the extreme range of intervention available, from simple relamping of existing fixtures to full redesign and replacement of the ceiling plane. Neverthless, BEEx worked with vendors and other stakeholders to understand the typical costs to both furnish and install the major components of a lighting retrofit. As of September 2014 our research indicated the following rough estimates to furnish or install lighting retrofit components (Table 39).

The figures assume replacing fixtures in situ, with no additional modifications to the ceiling plane and it does not include any additional costs associated with modifications to emergency circuits or systems. Payback estimates include modest savings from maintenance, and limited incentives, but they do not include any potential savings from productivity associated with an improved office environment.

Table 39. Lighting retrofit cost estimates, New York City (September 2014)

		Costs ($/ft^2)		Typ. Payback
Component	Furnish	Install	Total	
Lighting controls only	2	2.1	4.1	<5 yrs
Lighting fixtures & controls (on-board)	8	2.1	10.1	<9 yrs

5.3.2. Outreach and education

As an energy efficiency resource center in Manhattan, the Building Energy Exchange (BEEx) works with the largest and most concentrated commercial area in the United States. BEEx advances energy and lighting efficiency through professional training, high profile panel discussions, exhibits, case studies and other resources, both physical and virtual.

Like most BEEx programs, educational materials derived from the Living Lab project are intended to be shared nationwide by creating virtual compliments of each deliverable, including video of live training sessions. BEEx works with multiple like-minded organizations in collaborative relationships to maximize the reach and impact of content.

BEEx developed the following educational materials as a result of this Living Lab project:

- Technical training modules: 4 modules, 90 minutes each, delivered at least 12 times over 18 months at the BEEx center; modules focused on codes and regulations, luminaire selection, control selection, and lighting retrofit strategies. As of September 2016 these modules will have been delivered on four separate occasions.
- Symposia: panel discussions at four different international conferences with audiences of 50-100 people per symposium (i.e., Light + Building in Frankfurt, Germany; LightFair International 2014 & 2015; GreenBuild 2014).
- Press/ Blog Posts for placement in industry press
- Lighting the Future – Advanced Lighting Controls Exhibit at the BEEx center, from December 2015 to December 2016.
- Further material will be developed beyond the conclusion of this project.

6. SUMMARY FINDINGS AND CONCLUSIONS

Summary findings and conclusions are given in the Executive Summary and are not repeated here. The following provides a perspective on the changes that have occurred in the lighting controls industry since the inception of the Living Lab project.

There have been significant changes in the lighting controls industry. These changes have been driven by internal as well as external forces on the market. One of the biggest external forces has been the significant expansion of controls requirements in energy codes. As an example, both ASHRAE 90.1-2013 as well as California Title 24-2013 now mandate the automatic control of fixtures in "primary" as well as "secondary" daylight zones in most interior spaces. Additionally, fixtures in each zone must be able to dim to different levels (based on their relative distance to the window wall). Previous code iterations allowed for manual control of fixtures in only the "primary" daylight zone. Needless to say, these new requirements necessitate the use of significantly more advanced control equipment (e.g., lighting control systems).

Another example of more complex controls requirements is demand response. California Title 24-2013 now requires that most spaces greater than 10,000 ft^2 be "demand response capable". At a minimum, this has forced vendors of lighting control systems to incorporate programming options that allow for the automatic reduction of lighting loads based on receiving some form of signal or other input telling the system to react to a load-shedding event. Even in states that do not require this functionality, some utilities are already offering incentives for voluntary participation in demand response programs, thereby necessitating the installation of controls with these advanced capabilities.

Internally within the market itself, vendors have been reacting to and taking advantage of rapid changes in technology. For example, LED fixtures are now viable for almost all applications and their performance and life often rivals or exceeds that of fluorescent or other types of light sources. At the outset of work on the Living Lab project, this was not yet the reality. Because it is significantly easier and less expensive to dim LED fixtures and lamps, this change in the market will have an enormous impact on the viability of installing controls and requiring control strategies that rely on dimming. Additionally, dimming of LED fixtures is now mandated by certain codes (e.g., California Title 24-2013).

As for the control equipment itself, there has been a paradigm shift in recent years to think about controls as "data points", and to incorporate digital protocols throughout as much of the system architecture as possible. Envisioning the equipment as a digital network has prompted vendors to incorporate many options and variables with regard to programming and operation. These new system types are flooding the market and owners as well as contractors are becoming increasingly more comfortable installing such systems.

As the paradigm continues to shift toward "digitization", entirely new control methods have emerged. For example, several Power-over-Ethernet (PoE) systems are now commercially available. PoE systems pose significant challenges. One such issue is that PoE control systems do not easily lend themselves to incorporating methods of code-compliant emergency lighting. (Remember that every commercial project must have some legal means of emergency egress lighting.) Another issue is that PoE systems for lighting control distribute power to fixtures over low-voltage wiring. Historically, light fixtures have been powered by line-voltage wiring, installed by electrical contractors who are experienced with appropriate wiring methods for line-voltage distribution. It is not yet clear who will typically install PoE wiring on a given project, and if that might cause any friction between types of installing contractors (especially if any are union employees).

Another major driver that has significantly changed in recent years is the increasing miniaturization of embedded controls components. The cost and size of effective occupancy sensors as well as photosensors is low enough at this time to make it viable to incorporate these on a per-fixture basis. Additionally, some vendors that did not previously offer embedded controllers now offer those. These changes are an indication that the market is moving in the direction of maximum granularity as far as equipment (as well as zoning).

None of these recent changes in market forces and direction obviate the benefit and applicability of advanced lighting control systems such as the systems used in the Living Lab project. Those systems will continue to be deployed throughout many large commercial and institutional projects. The evolution in the market, however, will allow vendors to expand their offerings to include other system types and methods that may be applicable for certain project types or sizes.

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APPENDICES

Appendix A: Fixture Cut Sheets for the LL test floor

TYPE FA
NEO-RAY™

DESCRIPTION

Driven by performance and a clean aesthetic, the Straight and Narrow Series in LED represents the ultimate in simplicity; a narrow, uniform line of light. Constructed with premium materials with industry leading technology, the Straight and Narrow family is availible in configurable runs and individual lengths of 2', 3', 4', 6' and 8'. Fully compatible with Cooper Controls FifthLight DALI and shipped standard with 0-10V dimming, the Straight and Narrow family integrates seamlessly with today's modern building management systems. With virtually unlimited applications, the Straight and Narrow family allows architects and designers the freedom to experiment with their designs without exceeding ever decreasing energy budgets.

Catalog #		Type
Project		
Comments		Date
Prepared by		

SPECIFICATION FEATURES

Construction
Housing extruded from premium 6063 aluminum. Nominal 2', 3', 4', 6' or 8' illuminated sections. Used in run configuration and/or individual fixtures. All components are RoHs compliant.

Lens
Available in snap-in or lay-in profiles, two diffusion options are available. Satin white provides the highest aesthetic uniformity while the high transmission lens provides the most superior efficacy.

Finish
Fixture housings are high reflectance white using electrostatically applied polyester powder coat paint.

Electrical
Long-life LED system coupled with electrical driver to deliver optimal performance. LED's are available in 3000K, 3500K or 4000K with a typical CRI ≤ 85. Projected life is 50,000 hours at 70% lumen output. Electronic drivers are available for 120-277V applications

Controls
Equipped standard with a 0-10V continuous dimming driver compatible with most standard dimmming devices (refer to website for specific compatibility reference). Combine with FifthLight DALI and other energy saving products like sensors, daylighting controls and building management systems to maximize energy savings.

Mounting
Suspended.
Pendant with adjustable single cable and circular canopy. Standard length of cable is 48".

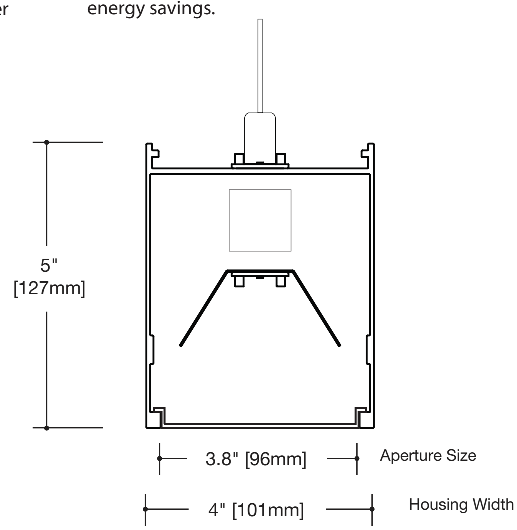
(SCST) = Single Cable - Structure
(SCETG) = Single Cable - 15/16" T-grid
(SCFTG) = Single Cable - 9/16" T-grid
(SCSTG) = Single Cable - 9/16" Slot Grid
(SCJB) = Single Cable - Junction Box (Sheet Rock)

Warranty
Five year warranty.

23-DIP
Straight & Narrow
LED

Suspended
Direct / InDirect

powered by fifthlight technology



ORDERING INFORMATION

Sample Number: S23-DIP-2L35-ETG-4-U-DD-SI-S92-W

S23 | DI | P – [ ] [ ] – [ ] – [ ] – [ ] [ ] – [ ] [ ] – [ ] [ ]

Series
- S23 = Series 23

Mounting
- P = Pendant

Light Output
- DI = Direct / InDirect

LED Color Temp
- L30 = LED, 3000K
- L35 = LED, 3500K
- L40 = LED, 4000K

Light Level
LED (3500K) per foot
- 1 = Light Level 1[1]
  UP: 515 Lumens, 7 Watts, 73 LPW
  DOWN: 515 Lumens, 7 Watts, 73 LPW
- 2 = Light Level 2[1]
  UP: 650 Lumens, 9.25 Watts, 70 LPW
  DOWN: 650 Lumens, 9.25 Watts, 70 LPW

Mounting Type
- SCST = Structure
- SCETG = 15/16" T-grid
- SCFTG = 9/16" T-grid
- SCSTG = 9/16" Slot Grid
- SCJB = Junction Box (Sheet Rock)

Length
- 2 = 2 foot Individual
- 3 = 3 foot Individual
- 4 = 4 foot Individual
- 6 = 6 foot Individual
- 8 = 8 foot Individual
- xx = Configurable Run (Specify length in 1ft increments)

5' LENGTH

Driver Options
- DD = 0-10V Dimming
- 5LT = FifthLight DALI
- LUT = Lutron DALI

Voltage
- 1 = 120V
- 2 = 277V
- 3 = 347V(remote transformer)
- U = Universal Voltage

Emergency Options
- EM = Battery Pack[2]
- EC = Emergency Circuit

Circuiting Options
- SI = Single Circuit
- DU = Dual Circuit

Lens Options
- S93 = Satin Lay-in Lens
- S93S = Satin Snap-in Lens[3]
- S93HT = High Transmission Lay-in Lens
- S93HTS = High Transmission Snap-in Lens[3]

Color Options
- W = Matte White
- S = Silver
- XX = Custom Color

NOTES:
Not all options available. Please consult your local Cooper Lighting Representative for availability.
Specifications and dimensions subject to change without notice.
1. Light Level measured at 3500K; add 10% lumen output for 4000K or subtract 10% lumen output for 3000K.
2. Battery packs must be remote mounted
3. For vertical and horizontal in-wall mounting use snap-in lens

T 604.549.9379
F 604.549.9555
W fluxwerx.com

FLUXWERX

Specification Data

Luminaire	PROFILE 40 UP I 60 DN LED (PR1)	Type
Project		
Product		
Notes		

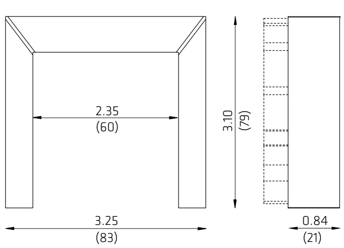
Performance Summary	40 Up I 60 Down			
	A	B	C	D
Light (lm)	2150	2700	3400	4100
Energy (W)	24	29	39	49
Efficacy (lm/W)	92.5	92.0	87.6	83.5
Color Rendering (CRI)	85	85	85	85
Color Accuracy (SDCM)	< 2	< 2	< 2	< 2
L70 Estimate (h)	200,000	200,000	200,000	200,000
Lumen Maintenance per TM21 (@ 60,000 h)	L90	L90	L90	L90

Performance summary values are nominal and based on 4000K CCT
DLC qualified for 29W and 39W in 4000K/3500K and 49W in 4000K

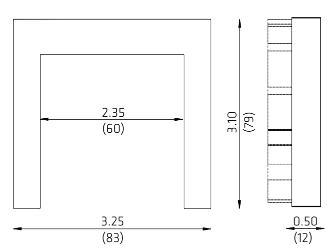
ENDCAPS + DIMENSIONS

inches (mm)

BEVEL



FLAT



SPECIFICATION

1	2	3	4	5	6	7	8	9	10	11	OPTIONS

1. FAMILY
- **PR1** Profile

2. ENDCAP
- **B** Bevel
- **F** Flat

3. OPTICAL DISTRIBUTION
General Area Lighting
- **A** 40 Up I 60 Dn
- **B** 100 Dn

4. ENERGY
- **A** 24 W
- **B** 29 W
- **C** 39 W
- **D** 49 W

Nominal values / 4 ft module at 120 - 277 V AC ; 50 - 60 Hz
For 347 V draw add 4 W to above

5. CCT
- **35** 3500 K
- **40** 4000 K

6. FINISH
- **A** Clear Anodized
- **B** Black Powdercoat
- **W** White Powdercoat

7. LENGTH
- **04** 4 ft
- **08** 8 ft
- **xx** x ft*

PER PLAN LENGTH

* Specify run length in 4' nominal increments

8. CEILING + MOUNTING INTEGRATION
Integrated driver with mounting, power feed, suspension + canopy
- **D** Drywall
- **G** Grid
- **S** Surface
- **R** Remote

9. DRIVER
- **B** 50% Bi Level [3]
- **D** 0 - 10 V Dim
- **L** Lutron [1]
- **S** Standard

DALI

10. VOLTAGE
- **M** 120 - 277 V
- **3** 347 V [2, 4]

11. SUSPENSION
- **03** ≤ 3 ft
- **06** ≤ 6 ft
- **12** ≤ 12 ft

18"

OPTIONS
- **A** Alternate Wiring
  - AV Presentation Switching
  - EM/NL or 2 circuit modules
- **B** Battery Pack [2, 3]
- **C** Chicago Plenum

[1] Maximum suspension is ≤ 3' for Lutron drivers. [2] Available [illegible] and (R) Remote. [3] Available for 120 - 277V. [4] Lutron + 347 V requires Ecobus controls

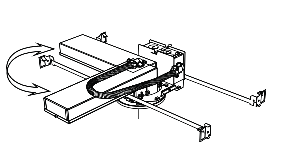
Due to continuous product improvements, specifications and dimensions are subject to change without notice. Certain options have limited compatibility with some other product selections. Consult www.fluxwerx.com for most current technical information.

Integrated Driver, Mounting, Power Feeds + Suspension

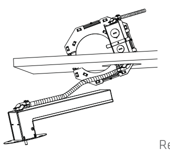
Refer to separate product specification datasheets for detailed dimensions of mounting hardware components, driver enclosures, canopies and wiring

(D) DRYWALL — New or Retrofit

Integrated driver, power feed and mounting suspension points suitable for GWB or plaster thicknesses of < 0.875" (22 mm)



Perpendicular or Parallel



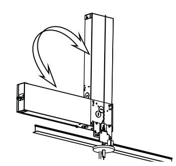
Retrofit Method

■ 120-277V □ 347V □ Battery Pack

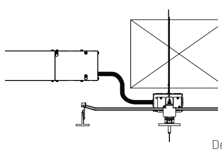
■ 0-10V Dim ■ Lutron ■ 50% BiLevel

(G) GRID — ON or OFF Grid

Integrated clip, driver, power feed and mounting suspension points suitable for accessible ceiling grid heights of < 1.75" (44mm)



Horizontal or Vertical



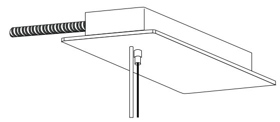
Detached Method

■ 120-277V ■ 347V ■ Battery Pack

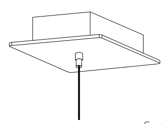
■ 0-10V Dim ■ Lutron ■ 50% BiLevel

(S) SURFACE — Hard Lid Ceilings

Integrated driver with mounting, power feed, suspension + canopy suitable for exposed surface conduit or recessed junction boxes



Power Feed Canopy



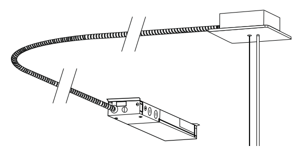
Suspension Canopy

■ 120-277V □ 347V □ Battery Pack

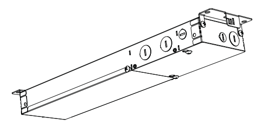
■ 0-10V Dim ■ Lutron ■ 50% BiLevel

(R) REMOTE — Hard Lid Ceilings

External remote mounted driver. Power feed and suspension points suitable for exposed conduit or recessed junction boxes



Power Feed



Multivolt 120 - 277 V driver

■ 120-277V ■ 347V ■ Battery Pack

■ 0-10V Dim ■ Lutron ■ 50% BiLevel

Construction

- Anodized, extruded + machined architectural grade aluminum
- Precision machined aluminum joints and endcaps are factory preinstalled for seamless fit
- Stainless steel fasteners
- 1/32" (0.8 mm) stainless steel aircraft cable suspensions
- Clear anodized surface finish or powdercoated in white or black

Optical

- Anidolic optical structures with linear light extraction elements
- Precision injection molded high transmittance clear acrylic lenses
- Long life mid-flux LED system designed for typical TM21 lumen maintenance ≥ L90 @ 60,000 h
- Available in CCTs 3500 K or 4000 K with CRI ≥ 80 and R9 ≥ 0, all with color accurate binning ≤ 2 SDCM (see photometric data for details)

Electrical

- No electrical connections are required at fixture level for installation; shipped with LV power cords factory preinstalled
- Agnostic driver design for simple integration with any sensor, lighting control or building energy management system
- High efficiency multivolt drivers for 120–277V or 347V; 50 - 60 Hz integrated with suspension and mounting canopy components
- Power Factor > 0.90
- Total Harmonic Distortion < 20%
- BiLevel Switching: 50 / 100%
- 0 – 10 V Dim Range: 5 - 100% (CCR)
- Optional Battery: Bodine BSL722 rated for ~ 2000 lm @ 90 minutes
- Optional Lutron: Hi-lume A-Series L3D LED drivers for 100 - 1% (PWM) dim range; factory prewired for EcoSystem or 3-wire controls
- DALI : Consult factory for details

Weight

- Fixture Only: ~ 2.0 lb./ft. (3 kg/m)

Warranty

- 5 year limited warranty on all components and workmanship

Environmental

- Designed for use in damp or dry indoor environments with room side operating temperatures of 0 - 30° C (32 - 95° F)

Independent Testing

- IESNA LM79
- IESNA LM80 (LED@ 10,000 h)

Approvals

- UL Listed (USA + Canada)
- CCEA Chicago Plenum
- LED Lighting Facts®
- DesignLights Consortium®

Due to continuous product improvements, specifications and dimensions are subject to change without notice. Certain options have limited compatibility with some other product selections. Consult www.fluxwerx.com for most current technical information.

OPEN AREA
ZONE G3 / CRESTRON CONTROL

TYPE FC

selux

Date: ____________ Customer: ____

Project: ____

Type: ____ Qty: ____________

M36
LED Direct/Indirect

FIXTURE TO BE EQUIPPED AND WIRED TO HAVE SEPARATE UP AND SEPARATE DOWN CONTROLLABILITY

Order Code: L36DI - ___ - ___ - ___ - ___ - ___ - ___ - ___ - ___ - ___ - ___ - ___ - ___ - ___

L36DI	Series	L36DI M36 LED Direct/Indirect					
	Direct Light Engine	1A35[1,2] 704lm/8.8W per foot	1A30[1,2] 620lm/7.6W per foot	1A25[1,2] 521lm/6.3W per foot	1A20[1,2] 422lm/5.1W per foot		
	Indirect Light Engine	1A35[1,2] 670lm/8.8W per foot	1A30[1,2] 590lm/7.6W per foot	1A25[1,2] 496lm/6.3W per foot	1A20[1,2] 402lm/5.1W per foot		
	CCT	27 2700K	30 3000K	35 3500K	40 4000K		
	Direct Shielding	LW LED Optimized white lens	MI Clear Lens w/microprism	NB LMO Symmetric	A2 LMO Asymmetric 20° Wall Washer	A5 LMO Asymmetric 5° Wall Grazer	BW LMO Batwing
	Indirect Shielding	LW LED Optimized white lens	MI Clear Lens w/microprism	NB LMO Symmetric	A2 LMO Asymmetric 20° Wall Washer	A5 LMO Asymmetric 5° Wall Grazer	BW LMO Batwing
	Mounting	C Cable	S Swivel Stem	RS Rigid Stem	W Wall Mount		
	Finish	WH White	BK Black	SV Silver	SP Specify Premium Color		
	Voltage	120 120 Volt	277 277 Volt	UNV 120 thru 277 50/60hz capable			
	Fixture Options	DL[3] Damp Location Rated	FS[3] In-Line Fuse	SS[3] Separate Switching			
	Dimming Options	DML[4] eldoLED 0-10V (Logarithmic)	DMD[4] eldoLED DALI (Logarithmic)	DC2[4,5] Lutron 2-Wire	DC3[4] Lutron 3-Wire	DCE[4] Lutron Eco-System	
	Emergency Options	EC[6] Emergency Circuit Wiring					
	Configuration Options	IL90[7] Lit Horizontal 90° Corner	IT90[7] Lit "T" section	IX90[7] Lit "X" section			

Nominal Fixture Length: 02 2 ft. · 03 3 ft. · 04 4 ft. · 05 5 ft. · 06 6 ft. · 07 7 ft. · 08 8 ft. · 09 9 ft. · 10 10 ft. · 11 11 ft. · 12 12 ft. · XX Runs (over 12') are available in 1' nominal increments, round up to the nearest foot and replace the "xx" with the # (i.e. 13=13' nominal)

Individual fixtures, Runs and Configurations are supplied in nominal lengths to ensure full, even, illumination. See pages 2 thru 5 for additional details.

Custom colors are available, Please consult factory

50% DIRECT/50% INDIRECT DISTRIBUTION

DIRECT SHIELDING TO BE MICROPRISM

MOUNTING REQUIREMENTS TO BE COORDINATED WITH APPROVED CEILING SPECIFICATION; TOP OF FIXTURE TO BOTTOM OF SCHEDULED CEILING TO MEASURE 1'-8"

VOLTAGE AS REQUIRED PER E.E.

[1] Values calculated from a 4' fixture @4000°K using LW Shielding and standard driver. For additional information please see page 2.

[2] Mixed output available 4' and up, see page 7 for details.

[3] See page 7 for full details and restrictions

[4] See page 6 for full details

[5] 120V only

[6] See page 7 for full details and restrictions

[7] See page 8 for full details and restrictions

NRTL DAMP · 5 YEAR LED WARRANTY · ARRA Compliant · ADA Compliant · RoHS

OPEN AREA
ZONE G3 / CRESTRON CONTROL

TYPE FC-1

SPECIFICATIONS

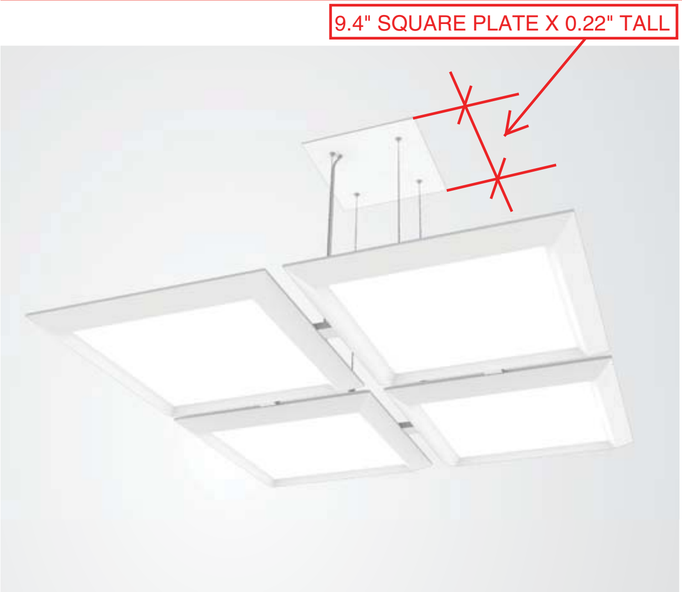
Peerless® Lighting for People®

Vellum LED

VMMQP | LED | Quad Pendant — I/D or Direct | Suspended

Type:

Project:

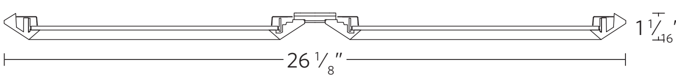


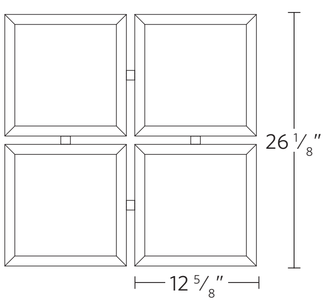
HIGHLIGHTS

- Peerless 360˚ Total System Integration features 5-year limited warranty by Acuity Brands covering all components and construction
- Up to 112 lm/W
- Three distributions available: (see page 2)
- Softshine®-engineered comfort optics
- High performance batwing distribution using light technology guide
- Flicker-free dimming to dark (0.1%) powered by eldoLED® driver
- Integrated nLight® control module for system networking (optional)
- Integrated sensor for daylight dimming and/or occupancy detection (optional)
- White, black, painted aluminum or custom color
- LED Lighting Facts® partner

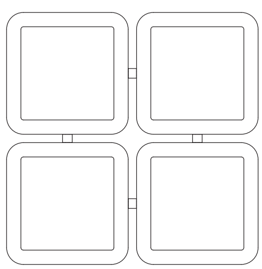
DIMENSIONS

☐ **VMMQP**





Bottom View Squared



Bottom View Rounded; Option RDEP

LUMEN PACKAGES

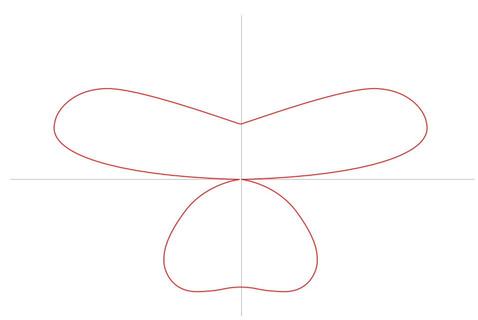
Based on 3500K. Additional color temperatures available.

Lumen Packages:	High (HI)
Delivered Lumens*	6903
Input Watts*	63
Lumens Per Watt*	109

COMPANION LUMINAIRE(S)

STANDARD DISTRIBUTION

60% Up | 40% Down



CUSTOMIZATION

Ask us about the following possibilities: Higher lumen outputs, alternate voltages, custom colors.

Type:

Project:

Peerless® Lighting for People®

Vellum LED

VMMQP | LED | Quad Pendant — I/D or Direct | Suspended

SPECIFICATIONS

Housing
Four (4) one-piece, die-cast aluminum housings mechanically attached together with no exposed fasteners form a single luminaire. Squared corners standard. For rounded corners choose option RDEP.

Color
Color for housing is white, black or painted aluminum. Consult factory for custom colors.

Source
Edge-lit LEDs using light guide technology deliver up to 6900 nominal lumens. Three available color temperature options (3000K, 3500K and 4000K) — all within 2.5 MacAdam ellipses.

Optics
Softshine® optical system consists of high performance acrylic lens and film.

Embedded Sensor
Optional sensor is embedded directly into the lens surface following Peerless' proprietary SubtleView Integration™ process.

Remote Dimming Driver
Remote eldoLED® driver (see page 3) provides "natural dimming" with smooth, continuous and flicker-free dimming to dark (0.1%). Syncing for controls: 2mA max. THD: < 20%. Insignificant inrush current at 120 and 277VAC. FCC Class A and B tested for EMI and RFI.

For 0-10V driver details go to: PeerlessLighting.com/561S
For DALI driver details go to: PeerlessLighting.com/560S

Controls and System Networking Options
For wired networking via Cat-5e, choose an integrated nLight® module (driver: ENNB). For daylight dimming and/or dual technology occupancy detection, see Page 5 for integrated sensor options.
One control module per luminaire.

Lumen Management
For constant lumen output at 80% of initial light output, choose lumen management (LMES20).

Electrical
LED light engine — consisting of modular LED boards and eldoLED® dimming driver — is rated for 50,000 hours (L_{80}) at 25° C ambient temperature. Specify 120V, 277V or 347V. Pre-wired with 18AWG fixture wire. For special circuiting or wire gauge, consult factory. Plug-in electrical connectors included.

Environment
Ambient operating temperature between 0° C and 25° C. For damp location label, choose option DL.

Validation
CSA/CUS listed. LM-79 tested. Individual luminaire meets FCC Part 15 requirements. Lighting Facts partner.

Packaging
Recycled cardboard box and inserts. Biodegradable, protective luminaire bag. Recycled kraft paper tape.

Warranty
5-year limited warranty. Complete warranty terms located at www.acuitybrands.com/CustomerResources/Terms_and_conditions.aspx

Actual performance may differ as a result of end-user environment and application.

Actual wattage may differ by +/- x% when operating between y-zV +/- 10%.

NOTE: FIXTURE IS NOT EQUIPPED FOR SEPARATE UP AND SEPARATE DOWN CONTROLLABILITY

MODEL NUMBER

Example: VMMQP HI 120 SCT EZB LP835 F1C/18 C041

Luminaire	Light Output	Distribution	Voltage	Switching
VMMQP	**HI** 6900 nominal delivered lumens* *For higher lumen packages, consult factory.*	~~**(Blank)** Std. 60% up; 40% down~~ **20/80** 20% up; 80% down ~~**0/100** 0% up; 100% down~~ *Nominal distribution. Refer to photometric tests for exact distribution.*	**120** **277** **347** *Not available with LMES20 and sensor.*	**SCT** Single circuit

20% DIRECT/80% INDIRECT DISTRIBUTION

VOLTAGE AS REQUIRED PER E.E.

Remote Dimming Driver with Integrated System Networking	Integrated Sensor	Integrated Lumen Management	LED Color Temperature
ENNB eldoLED with integrated nLight controller **ENNBN** Linear dimming curve	**(Blank)** No sensor **__DSCNL** Daylight only **__MSD7NL DSCNL** Daylight/occupancy	**(Blank)** None **LMES20*** 80% lumen management *Available with EZBN and ENNBN only.*	**LP830** 3000K 80+ CRI 17-20+ R9 **LP835** 3500K 80+ CRI 17-20+ R9 **LP840** 4000K 90+ CRI 17-20+ R9 **LP930*** 3000K 90+ CRI 50 R9 **LP935*** 3500K 90+ CRI 50 R9 **LP940*** 4000K 90+ CRI 50 R9 * *Longer lead times - consult factory.*
Remote Dimming Driver **EZB** eldoLED 0-10V **EZBN** Linear dimming curve	**(Blank)** No sensor **__DSCNL** Daylight only **__MSD7N DSCN** Daylight/occupancy	**Non-Integrated Lumen Management** **(Blank)** None **XLMES20*** 80% lumen management **EZBN must be selected if planning to install a separate, non-integrated nLight networking system with lumen management.*	
EDAB eldoLED DALI *Driver must be paired with sensor option from the same row. Ex: ENNB 2DSCNL*	**(Blank)** No sensor *Indicate number of zones per row. Ex: 3DSCN*		

CRESTRON DIGITALLY ADDRESSABLE DIMMING DRIVER (DALI)

Mounting Type /	Overall Suspension	Color	Options
F1C/ T-bar ceiling /hard ceiling	**12** 12" **18** 18" **24** 24" **36** 36" **48** 48" **XX** XX" *Measured from ceiling to bottom of luminaire.*	**C041** White white (low gloss) **C110** Painted aluminum (fine textured) **C201** Black (low gloss) **C099** Custom color	**CSA** Meets Canadian standards. (Must select with Canadian orders) **DL** Damp location label **DU** Dust cover **GLR** Fusing (fast blow) **GMF** Fusing (slow blow) **RDEP** Rounded corners

MOUNTING REQUIREMENTS TO BE COORDINATED WITH APPROVED CEILING SPECIFICATION

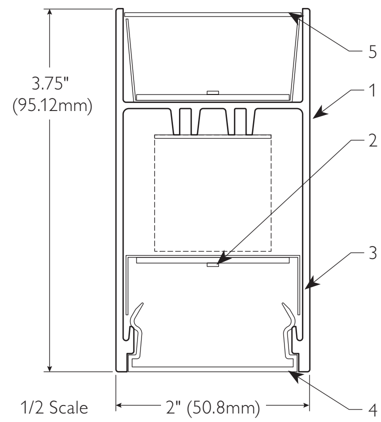
TOP OF FIXTURE TO BOTTOM OF SCHEDULED CEILING TO MEASURE 1'-8"

MicroSquare LED

Lighting Systems, Pendant bidirectional, LED

Catalog number:

Notes: Type:



Ordering Information

Family	Mounting	Distribution	Lamp Type	LED Color	Lumen Category	Lower Optics	Upper Optics	Row Length	Wiring	Voltage	Ballast	Finish
MQ	0	6	L			F	F	5'			E	
MicroSquare	0 = Pendant	6 = Bidirectional	L = LED	A = 4000k B = 3500k C = 3000K	G = Hi Lumen, 5400 lumens (Combined Up and Down per 4 ft. nominal) K = Standard Lumen, 3000 lumens (Combined Up and Down per 4 ft. nominal)	F = Frost lens	F = Dust cover	Enter the total run length in feet (4 ft. increments)	1 = 1 circuit 2 = 2 circuit (Up/Down Switch) B = 2 circuit (Tandem Switch) 7 = 1 circuit Dimming (0-10v) X = Custom wiring (Consult factory)	1 = 120v 2 = 277v	E = Electronic	W = White A = Aluminum C = Custom color (Consult factory)

Features

1. **Housing:** Single piece of high purity extruded aluminum, a portion from recycled material.
2. **Light source:** Philips FortimoLED line system standard.
3. **Reflector:** Die-formed MIRO-SILVER® aluminum.
4. **Lower optics:** Extruded snap in matte frost acrylic lens.
5. **Upper optics:** Acrylic lay in dust cover standard.
6. **Alignment mechanism:** Draw tight mechanism ensures a hairline joints.
7. **Finish:** Standard powder coat finish is textured matte White or Aluminum. Custom colors available, consult factory.

Electrical

Driver: 0-10v electronic driver standard. Unless ordered as dimming, fixture will be wired for non-dim operation (purple and gray wires will not be connected). Dimmed output range for optional dimming configuration is 10%-100%.

Lumen maintenance: At an ambient operating temperature of 25°C, the LED lifetime expectation is L_{80} > 60,000 hours. Reported L_{85}(6k) > 36,000 hours per IES TM-21-11, which is limited to six times the 6,000 hours of LED LM-80-08 testing time.

Connections: Pre-wired with 18 gauge wires and polarized cannon plug connectors for simultaneous mechanical/electrical connection. No mid-row feeds offered.

Mounting

See mounting option specification sheet, Suspension Mounting.

Labels

Complies to US and Canadian Safety Standards.

UL or ETL listed and suitable for damp locations.

PHILIPS
LIGHTOLIER

Appendix B: Sequence of Operations for Automated Lighting Controls on the LL test floor

A standard sequence of operations (SQO) was spelled out and was to be applied to all test floor lighting control systems in the four quadrants:

During the work day in the open plan areas (Monday through Friday, 7 AM to 7 PM):

- Target task illuminance was set to 30 fc.
- Uplights
  - All uplights were to remain on irrespective of occupancy status, manual switch, and daylighting. The intent was to ensure a near-uniform ceiling brightness across the entire area irrespective of occupancy.
  - In the daylit zone 1 (row of lights parallel and closest to the window), uplights were to provide 5 fc of task illuminance.
  - In the daylit zone 2 (row of lights parallel and 2^{nd} closest to the window), uplights were to provide 7.5 fc of task illuminance.
  - In the daylit zone 3 (row of lights parallel and 3^{rd} closest to the window), uplights were to provide 10 fc of task illuminance.
- Downlights
  - When occupied, lights were to be switched on to the defined task illuminance level.
  - When occupied, the downlights were to be dimmed in response to daylight to meet the target task illuminance level.
  - When unoccupied, lights were to be switched off after a 15 min delay.
  - Downlights could be switched on or off with the manual switch. The system was to revert back to normal operations after a 2 h delay.

During after hours (weekday nights, weekends, and holidays):

- Target task illuminance was set to 30 fc.
- Uplights
  - When occupied or when manually switched, lights were to be switched on to the defined task illuminance level.
  - In the daylit zones 1-3, lights were to be dimmed with the same operational mode as workdays 7 AM to 7 PM (see above).
  - When unoccupied or manually switched, lights were to be turned off after a 15 min delay.
- Downlights
  - Same operational mode as workdays.

Delays and fade rates were specified:

- Uplights and downlights were to be faded up or down over 15 seconds from previous state.
- Uplights and downlights were to fade up or down over 5 seconds from previous state after change in photosensor readings.
- Uplight or downlight output was not to be changed until 15 seconds after a change in photosensor readings.

Appendix C: Comparability of Lighting Energy Use Between Floors

Prior to the installation of the new lighting technologies, lighting energy consumption measurements were performed on the test and reference floors in order to establish an energy use baseline and assess comparability between the two floors. If each of the test areas on the two floors had comparable lighting energy use, then differences in lighting energy use measured after the new technologies were installed could be attributed to the technologies rather than other confounding factors.

This task was actually more difficult to achieve in practice than in theory, primarily because the layout of the electrical circuits did not match between the two floors and because the space use and layout did not entirely match. In order to obtain data for the same area between floors, submetering needed to be installed on the power feeds within the ceiling plenum. Identifying the correct location to meter power in the ceiling was complicated by the high associated cost for the labor needed to trace the power feeds in the ceiling plenum associated with a particular circuit. Therefore, in the pre-retrofit phase, lighting energy use data was limited to the circuit breaker level.

Table C1 lists the periods that were used for this pre-retrofit comparison. Circuit panel A covered the west half of the floor (Areas G1-G2) and circuit panel B covered east half (Areas G3-G4) area of the floor. Note that there were gaps in the data of about 3-4 months for the reference floor caused by lapses in connectivity between the cellular network and the data loggers. These were addressed by installing additional antenna repeaters in the parts of the building affected. To the extent possible for each area, data spanning a 12-month period were selected to evaluate comparability between floors.

Table C2 summarizes the annualized energy use intensities (EUI) at the individual circuit level and whole floor level. At the whole floor level, the reference floor lighting annual EUI was 13% greater than the test floor (24 hour, 7 days per week, 1 year period). When analyzing each circuit individually, the likely cause of the discrepancies was identified and was listed in the table.

Table C1. Period of analysis for pre-retrofit metering of reference and test floors.

Floor	Circuit panel	Start date	End date	No. of days included	Major gaps
Reference Floor	A	Mar 12 2014	Mar 11 2015	311	May 23 - Jul 15, 2014
	B	Jun 04 2014	Jun 03 2015	273	Jun 4 - Sep 9, 2014
Test Floor	A	Mar 12 2014	Mar 11 2015	365	No gaps
	B	Mar 12 2014	Mar 11 2015	365	No gaps

Table C2. Circuit level annual lighting energy use intensity (kWh/ft^2-yr) for the one-year period prior to the lighting retrofit.

		Ref		Test		Diff (%)		Factors contributing to differences
		All hrs	9-17 h	All hrs	9-17 h	All hrs	9-17 h	
G1	Interior	4.04	2.02	3.05	1.45	25%	28%	Higher operating LPD on ref. floor; slightly higher test floor occupancy
G2	Interior	3.87	1.96	4.05	1.91	-5%	2%	Slightly higher operating LPD on ref. floor; somewhat higher test floor occupancy
G3	Interior	3.46	1.68	4.02	1.88	-16%	-12%	Higher operating LPD on test floor; somewhat higher evening occupancy on test floor
	Perimeter	3.16	1.21	2.39	1.12	24%	7%	Higher evening occupancy on ref floor; slightly higher operating LPD on ref floor, similar daylight harvesting sensitivity
G4	Interior	3.84	2.20	3.59	1.69	6%	23%	Higher operating LPD on ref. floor; higher evening occupancy on test floor
	Perimeter	2.49	1.23	2.14	1.04	14%	15%	Differences in daylight harvesting operation (ref. floor slightly less sensitive)

Note: For periods when there was missing data, comparison was omitted from the calculation and the annual lighting energy use was projected from a less comprehensive dataset.

For circuits that matched well between the two floors in terms of floor area covered and space type, several factors became apparent. For lighting circuits that covered the interior open plan office areas, there were significant differences in 1) operating lighting power density (LPD) (i.e., differences in tuned “full power” levels), and 2) evening occupancy patterns. Daytime occupancy patterns, however, appeared well matched between floors. This is illustrated in a comparison of daily EUI data for a two-month period in Figure C1. Lighting energy use on the reference floor was consistently greater than the test floor for this example period. Examination of typical lighting load profiles between the two floors revealed that while the patterns of occupancy appeared to be similar, the total connected load was greater on the reference floor, which explains much of the discrepancies between floors (Figure C2). To determine to what degree differences in evening occupancy affected comparability between floors, annual EUI was calculated for daytime high-occupancy hours (9 AM to 5 PM). Any remaining differences would be due to differences in LPD and/or daylighting.

In perimeter zones, the operation of the daylight harvesting systems differed between floors. Some of these differences could be attributed to differences in daylight availability between floors; the circuit level data did not allow disaggregation of the two effects. However, given that pre-retrofit shading operation was the same between the two floors, and the absence of nearby obstructions, it is likely that the main factor was the difference in calibration or sensitivity of the two different daylight harvesting systems, either due to differences in photosensor placement or sensitivity/ calibration settings of the photosensor. Comparison of daylight dimming profiles in the perimeter zones (0-15 ft from the window) in Figure C3 showed close agreement during the morning period but significant differences in the evening period due to occupancy.

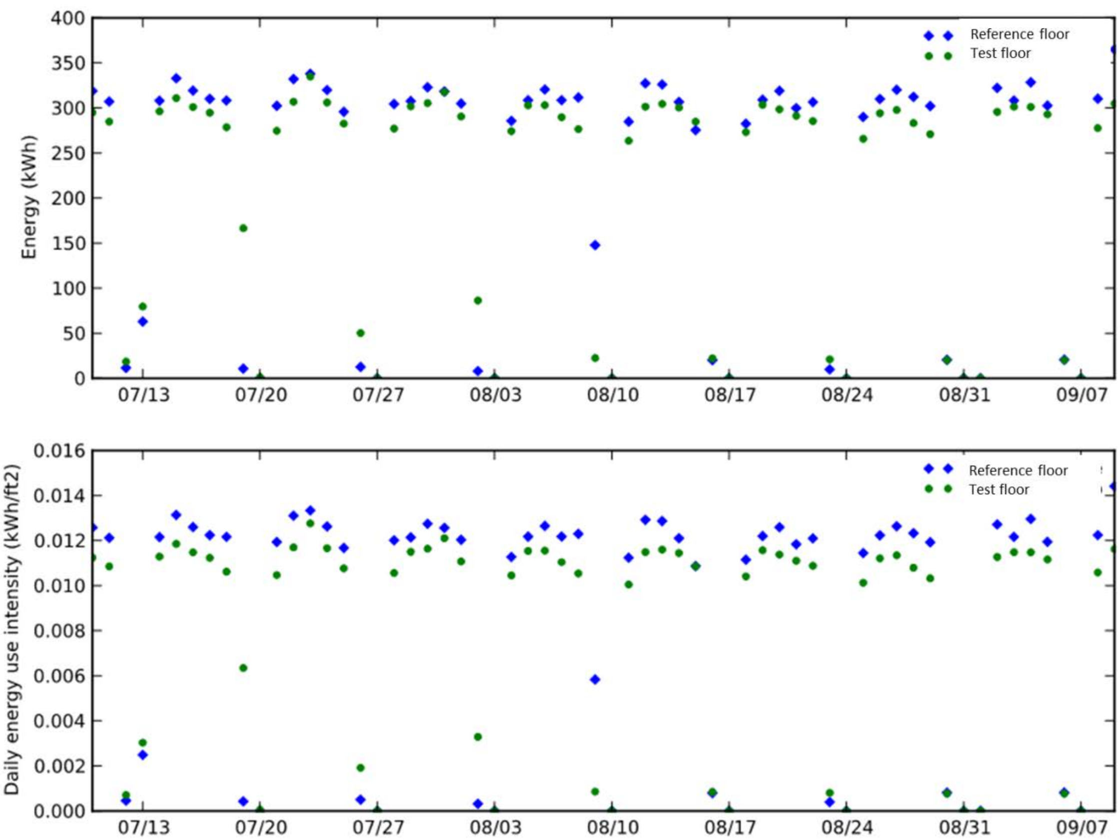


Figure C1. Whole-floor daily lighting energy use (kWh upper graph, kWh/ft^2 lower graph) for a typical 2-month period.

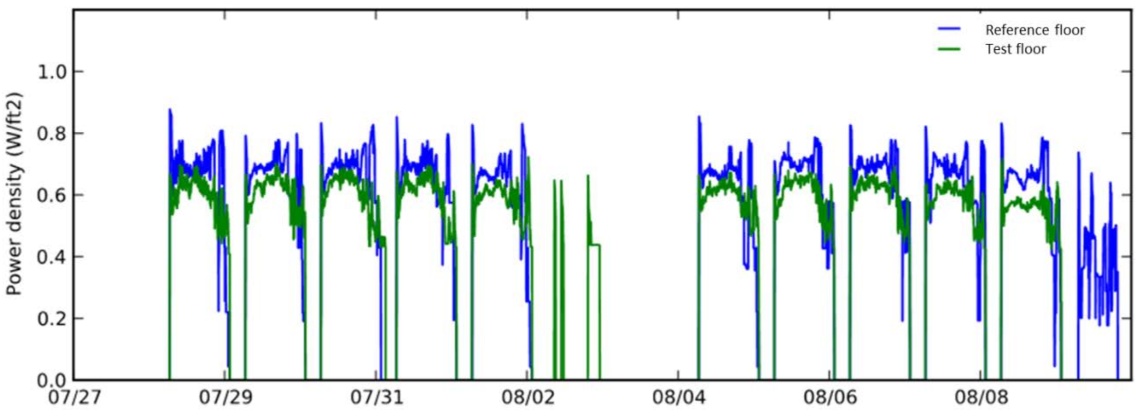


Figure C2. Example comparison of whole floor lighting energy use between the reference and test floors.

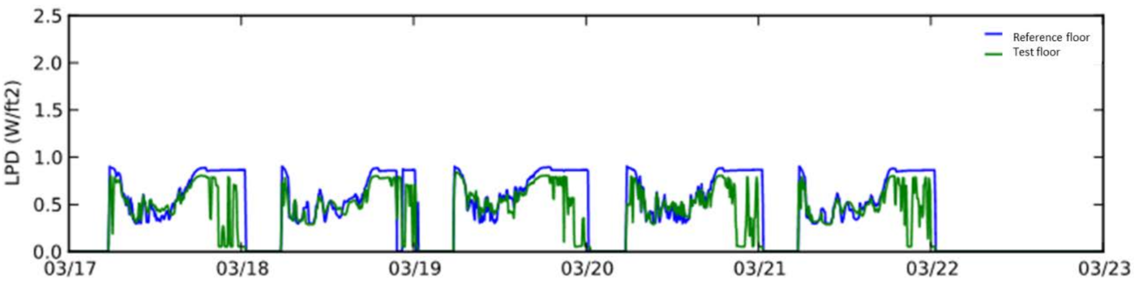


Figure C3. Example comparison of reference and test floor perimeter zone lighting energy use with daylighting controls. The areas on the two floors were the same both in location and space use.

In summary, annual lighting energy use for existing conditions was between 2.98 to 3.43 kWh/ft^2-yr for two typical floors, where floor-to-floor differences can be attributed primarily to operating LPD and, to a lesser extent, differences in patterns of evening occupancy.

For the post-retrofit period, data were collected simultaneously on the two floors for a six-month solstice-to-solstice period. The monitored areas between the reference and test floors were also made identical with the installation of submetering on circuits within the ceiling. Only the post-retrofit data were used to determine savings, not data monitored before and after the retrofit. Therefore, in the comparison of energy performance between floors in the post-retrofit condition, data were not normalized between the reference and test floors due to differences in operating LPD, which was viewed as an inherent property of the existing lighting solution, nor occupancy patterns, which in any event could not be disaggregated given the available data.

Appendix D: Occupant Survey and Protocol

LIVING LAB OCCUPANT SURVEY

Welcome!
Thank you for participating in the evaluation of the advanced lighting and shading systems at 200 West Street. This study, sponsored by the US Department of Energy and the New York State Energy Research and Development Authority, is being conducted by the Lawrence Berkeley National Laboratory (LBNL).

Your feedback will help the researchers understand how well these lighting and shading systems meet the needs of office occupants, such as yourself.

Survey Details

- **Time:** The survey takes approximately 5 minutes to complete.
- **Confidentiality:** Your answers are confidential. Survey responses will not be linked to an individual's identity. To avoid bias, please do not discuss your impressions with anyone else.
- **Voluntary Participation:** Your participation in this study is voluntary. You are free to skip any questions you don't want to answer and to end your participation at any time by exiting your web browser at any point during the survey.
- **Questions:** If you have any other questions about the study, please contact LBNL or GS.

Instructions
Please fill out this questionnaire as completely as possible; you may skip any question you are unable to answer or do not want to answer. Please respond to all of the items as openly and honestly as possible. There are no right or wrong answers.

[*NOTE: survey should be set up so that a "No" answer to the question below results in exiting the survey*]

I have read the information above and I'd like to take the survey:

a) Yes
b) No

Part A: Background Information

1) Please assign a rating from 1 (unimportant) to 5 (very important) to the following items indicating what makes a pleasant and productive office environment.

Item — Rating

Unimportant … Very Important

1 2 3 4 5

a) Comfortable ambient temperature |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

b) Ability to control temperature |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

c) Good lighting |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

d) Windows |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

e) A view outside |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

f) Privacy |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

g) A quiet workplace |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

h) Controllable lights or windows |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

i) An aesthetically appealing environment |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

j) Other (specify) ___________________ |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

2) Please assign a rating from 1 (least sensitve) to 5 (very sensitive) indicating your sensitivity to the following items.

Item — Rating

Least Sensitive 1 — 2 — Moderately Sensitive 3 — 4 — Very Sensitive 5

a) Glare |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

b) Cold |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

c) Heat |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

d) Darkness |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

e) Noise |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

f) Visual distractions |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

3) When you perform your work tasks, what is your preferred light level in your workspace**?**

Very Low 1 — Low 2 — Moderate 3 — Bright 4 — Very Bright 5

Light level |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

Part B: Subjective Evaluation

1) During the period **from February 1st, 2016 to present**, what was the location of your usual workstation?

   a) 17th floor
   b) 23rd floor

2) During the period **from February 1st, 2016 to present,** in which area of the floorplan shown below was your usual workstation located?
   [If answer to question 1 is floor 17, show the diagram below]

   [If answer to question 1 is floor 23, show the diagram below]

   a) SW
   b) NW
   c) NE
   d) SE

3) During the period **from February 1st, 2016 to present**, when you were at your usual workstation, what percentage of your time was spent on each of the following tasks?

Task	**Percent**
Computer-based tasks	____%
Paper-based tasks	____%
Telephone-based tasks	____%
Other (please specify)_________________________	____%

4) During the period **from February 1st, 2016 to present,** when you were at your usual workstation, what percentage of the time did you face the following directions:

Task	**Percent**
Facing the window	____%
With the window to the side	____%
Away from Window	____%
Other (please specify)_________________________	____%

5) During the period **from February 1st, 2016 to present**, was your usual workstation:

   a) A private office?
   b) An open-plan workstation?

5a) [This question only to come up when the answer to question 5 is a)] Does your private office have a window to the exterior?

   a) Yes?
   b) No?

5b) [This question only to come up when the answer to the question 5 is b) and reported location is not SW quadrant of the 23th floor] Is your open-plan workstation:

a) Right next to a window?
b) The second workstation away from the window?
c) The third or higher workstation away from the window?

5b2) [This question only to come up when the answer to the question 5 is b) and reported location is SW quadrant of the 23th floor] Where is your workstation located relative to the windows?

a) Right next to a window.
b) The second open-plan workstation away from the window.
c) The third or higher open-plan workstation away from the window.
d) There is a private office between my workstation and the windows.

6) Please assign a rating from 1 to 5 to the following conditions of your usual workstastion **since February 1st, 2016**.

Item	Rating
	Too Cold — Just Right — Too Hot
	1 2 3 4 5
a) Temperature during warm/hot weather	|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----| N/A
	Too Cold — Just Right — Too Hot
	1 2 3 4 5
b) Temperature during cool/cold weather	|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----| N/A
	Too Dark — Just Right — Too Bright
	1 2 3 4 5
c) Light level	|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
	Poorly Distributed — Well Distributed
	1 2 3 4 5
c) Lighting distribution in general	|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
	Poorly Distributed — Well Distributed
	1 2 3 4 5
d) Lighting distribution on the ceiling	|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

7) Please rate the level of glare in your usual workstastion **since February 1st, 2016**.

	Not Perceptible	Perceptible	Acceptable	Uncomfortable	Intolerable
	1	2	3	4	5

From the windows |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

	Not Perceptible	Perceptible	Acceptable	Uncomfortable	Intolerable
	1	2	3	4	5

From the lights |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

	Not Perceptible	Perceptible	Acceptable	Uncomfortable	Intolerable
	1	2	3	4	5

Other bright surfaces |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

8) **Since February 1st, 2016**, at my usual workstastion, bright light on my task made it difficult to read or see:

	Disagree		Neutral		Agree
	1	2	3	4	5

a) My computer monitors |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

b) Other tasks (e.g., paper-based) |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

9) Indicate your level of agreement/disagreement (disagree = 1, agree = 5) with the following statements regarding your usual workstation **since February 1st, 2016**:

Disagree 1 — 2 — Neutral 3 — 4 — Agree 5

a) The electric lighting is comfortable |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

b) The electric lighting is too dark |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

c) The shades are too noisy |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

d) The dimming of the lights is pleasant |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

e) The operation of the shades is distracting |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

f) The automated shades allow me to better focus on my work |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

g) The dimming of the lights is distracting |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

h) I find it odd when lights are not all dimmed to the same level |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

i) The ceiling is pleasantly lit |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

j) The shades block the view too much |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

k) I am satisfied with the operation of the shades |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

l) I am satisfied with the operation of the lights |----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

10) Please enter any comments about the operation of the automated lighting and shading in the area surrounding your workspace **since February 1st, 2016**.

11) Please enter any comments that you feel would be helpful in making your usual workstation a better space.

Appendix E: Occupant Survey Responses

N = number of responses
Avg. and Std. Dev. = Average and standard deviation of responses
p-value < 0.05 is considered to be statistically significant (shown in **boldface**)
Scale: 1-5

Area G1

Question	Reference Floor N	Avg.	Std. dev.	Test Floor N	Avg.	Std. dev.	p-value
When the external temperature is warm/hot, the internal temperature is...	3	3.00	1.73	4	3.50	1.00	0.65
When the external temperature is cool/cold, the internal temperature is...	3	2.67	1.53	4	3.00	0.00	0.67
Light level	3	3.33	0.58	3	1.67	0.58	**0.02**
Lighting distribution in general	3	4.00	0.00	4	3.25	0.96	0.24
Lighting distribution on the ceiling	3	4.00	0.00	4	3.00	1.15	0.20
Level of glare from the windows	3	3.00	1.00	4	3.00	0.82	1.00
Level of glare from the lights	3	4.00	1.00	4	4.25	0.96	0.75
Level of glare from other bright surfaces	3	4.67	0.58	4	4.50	1.00	0.81
Bright light made it difficult to read or see my computer monitors	3	2.33	1.53	4	3.50	1.00	0.27
Bright light made it difficult to read or see other tasks (e.g., paper-based)	3	2.00	1.00	3	2.67	1.15	0.49
The automated shades are too noisy	3	1.33	0.58	4	2.25	0.50	0.07
The automated shades allow me to better focus on my work	3	4.00	1.00	4	3.25	0.50	0.24
The operation of the shades is distracting	3	1.67	0.58	4	2.25	0.50	0.21
The transparency of the shades allows me to see outside	3	2.67	0.58	4	3.25	0.96	0.40
The dimming of the lights is pleasant	3	3.33	0.58	4	3.25	0.96	0.90
The electric lighting is comfortable	3	3.67	0.58	4	3.00	1.15	0.41
The electric lighting is too dark	3	2.00	0.00	4	3.25	1.50	0.22
Lights not all dimmed to the same level is distracting	3	2.33	0.58	4	2.25	0.50	0.85
The ceiling is pleasantly lit	3	3.67	0.58	4	3.25	0.50	0.35
I am satisfied with the overall operation of the shades	3	3.33	1.15	4	3.25	0.96	0.92
I am satisfied with the overall operation of the electric lights	3	3.33	1.15	4	2.75	0.96	0.50

Area G2

Question	Reference Floor			Test Floor			p-value
	N	Avg.	Std. dev.	N	Avg.	Std. dev.	
When the external temperature is warm/hot, the internal temperature is...	8	2.63	0.92	12	2.92	1.16	0.56
When the external temperature is cool/cold, the internal temperature is...	8	2.50	0.93	12	2.92	0.29	0.16
Light level	8	3.13	0.64	12	3.25	0.87	0.73
Lighting distribution in general	8	3.50	0.93	11	3.27	1.19	0.66
Lighting distribution on the ceiling	8	3.38	0.92	11	2.91	1.22	0.38
Level of glare from the windows	8	4.13	0.99	12	3.08	0.90	**0.03**
Level of glare from the lights	8	3.63	1.06	12	3.58	1.31	0.94
Level of glare from other bright surfaces	8	3.88	0.99	12	3.75	1.42	0.83
Bright light made it difficult to read or see my computer monitors	8	3.00	1.07	12	3.25	1.14	0.63
Bright light made it difficult to read or see other tasks (e.g., paper-based)	8	2.13	0.83	12	2.33	1.15	0.67
The automated shades are too noisy	8	2.13	1.13	12	2.83	0.94	0.14
The automated shades allow me to better focus on my work	8	2.88	0.64	12	3.08	1.00	0.61
The operation of the shades is distracting	8	2.25	1.16	12	3.08	0.90	0.09
The transparency of the shades allows me to see outside	8	3.25	1.39	12	2.00	0.85	**0.02**
The dimming of the lights is pleasant	8	3.38	0.52	12	3.00	1.13	0.39
The electric lighting is comfortable	8	3.63	0.52	12	3.33	1.07	0.49
The electric lighting is too dark	7	2.43	1.27	11	2.00	0.63	0.35
Lights not all dimmed to the same level is distracting	7	2.57	1.40	12	2.58	1.24	0.98
The ceiling is pleasantly lit	8	3.63	0.52	12	3.08	1.08	0.21
I am satisfied with the overall operation of the shades	8	3.25	0.89	12	2.83	0.94	0.33
I am satisfied with the overall operation of the electric lights	8	3.50	0.53	12	3.17	1.03	0.41

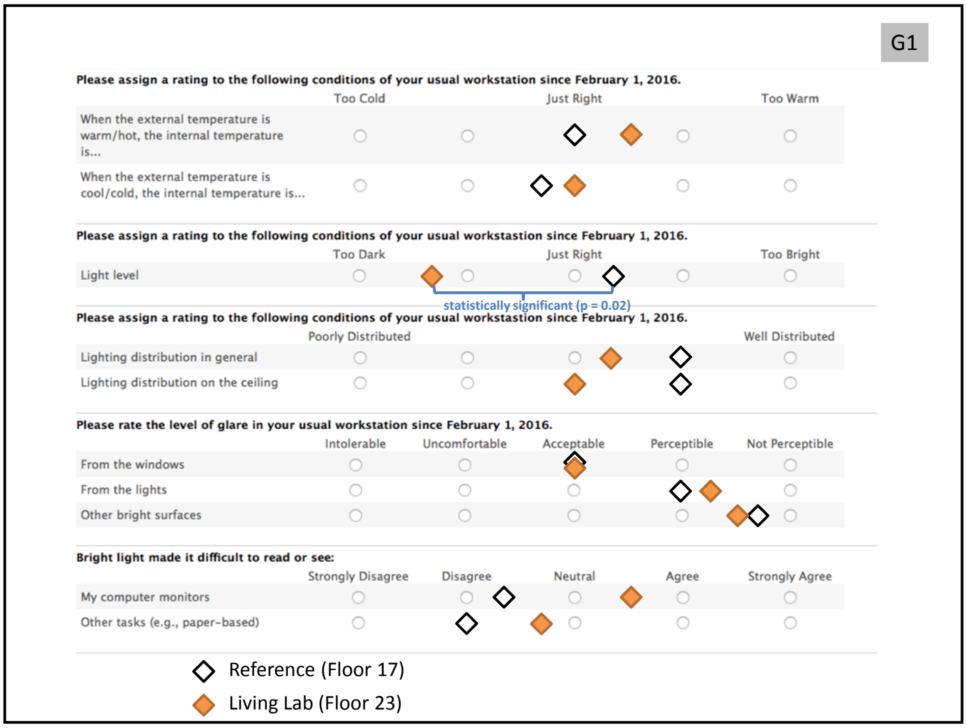
Area G3

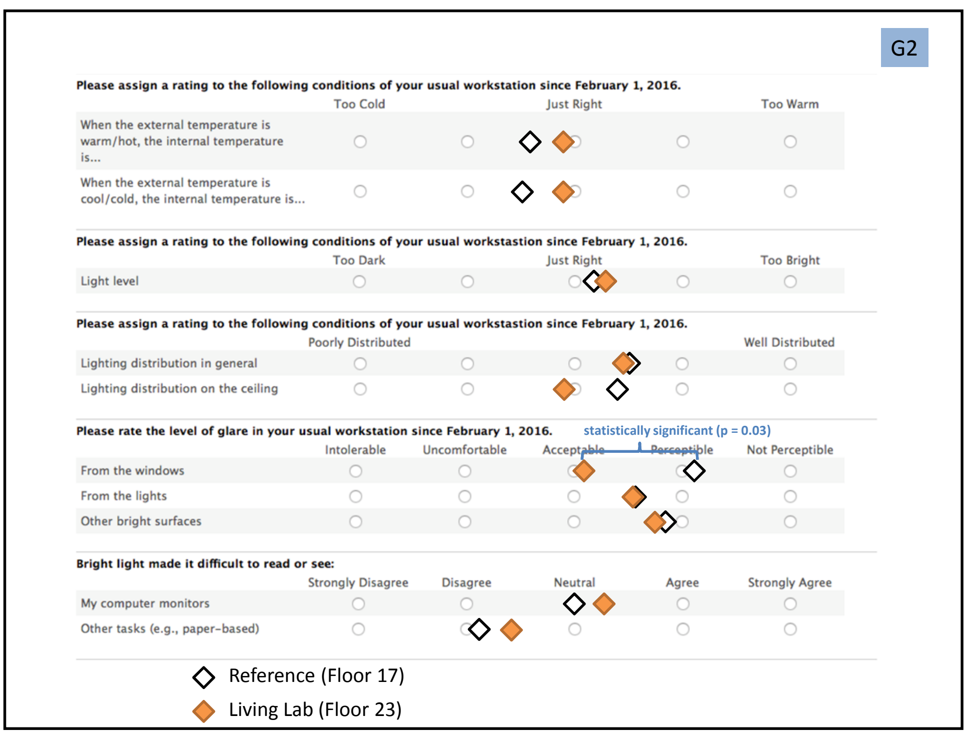
Question	Reference Floor			Test Floor			p-value
	N	Avg.	Std. dev.	N	Avg.	Std. dev.	
When the external temperature is warm/hot, the internal temperature is...	6	3.17	1.17	30	3.10	0.92	0.88
When the external temperature is cool/cold, the internal temperature is...	6	2.83	1.33	30	3.00	0.91	0.71
Light level	6	3.33	0.82	29	3.34	1.29	0.98
Lighting distribution in general	5	3.60	0.89	30	3.03	1.30	0.36
Lighting distribution on the ceiling	6	3.67	1.03	30	3.13	1.14	0.30
Level of glare from the windows	6	2.50	0.55	28	2.57	1.45	0.91
Level of glare from the lights	6	3.17	0.41	28	3.86	1.08	0.14
Level of glare from other bright surfaces	5	2.40	0.89	28	3.54	1.32	0.08
Bright light made it difficult to read or see my computer monitors	6	4.00	0.89	29	3.41	1.52	0.37
Bright light made it difficult to read or see other tasks (e.g., paper-based)	5	2.60	0.55	29	2.66	1.29	0.93
The automated shades are too noisy	6	2.67	1.03	30	2.33	1.12	0.51
The automated shades allow me to better focus on my work	6	3.33	0.52	30	2.63	1.10	0.14
The operation of the shades is distracting	6	2.33	0.52	30	2.57	1.14	0.63
The transparency of the shades allows me to see outside	6	2.17	0.75	30	2.57	1.14	0.42
The dimming of the lights is pleasant	6	3.17	0.41	30	3.00	0.91	0.67
The electric lighting is comfortable	6	3.33	0.82	30	3.23	0.94	0.81
The electric lighting is too dark	6	2.17	0.75	30	2.53	0.97	0.39
Lights not all dimmed to the same level is distracting	6	2.50	0.55	30	2.80	1.00	0.48
The ceiling is pleasantly lit	6	3.33	0.82	30	3.23	0.90	0.80
I am satisfied with the overall operation of the shades	6	3.50	0.55	30	2.63	1.38	0.14
I am satisfied with the overall operation of the electric lights	6	3.83	0.75	30	3.27	1.08	0.23

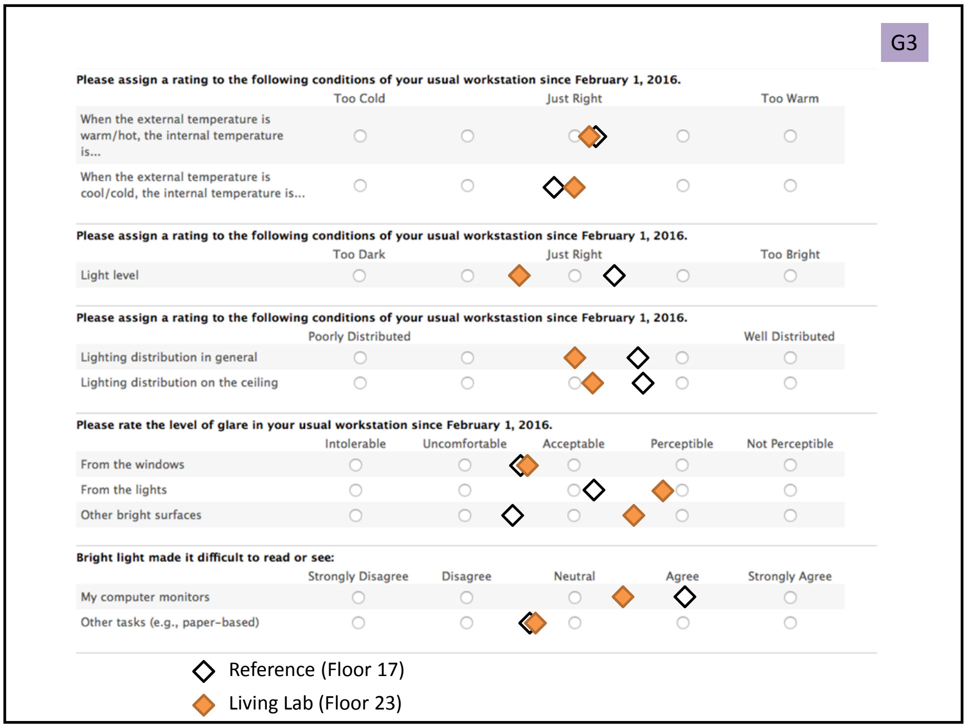
Area G4

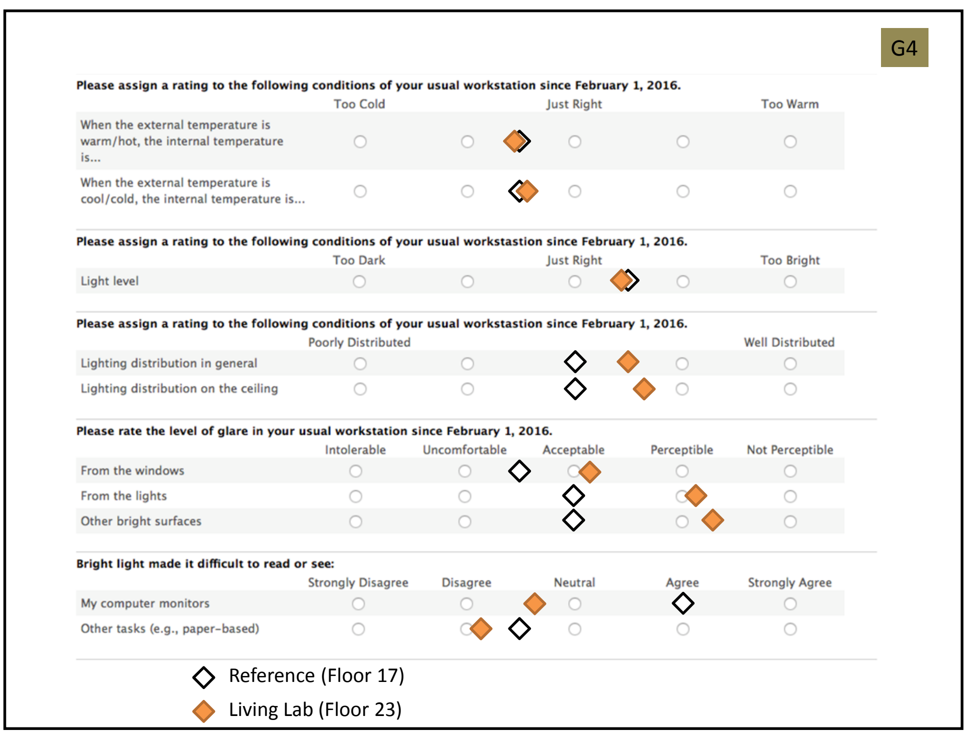
Question	Reference Floor			Test Floor			p-value
	N	Avg.	Std. dev.	N	Avg.	Std. dev.	
When the external temperature is warm/hot, the internal temperature is...	2	2.50	0.71	11	2.45	1.29	0.96
When the external temperature is cool/cold, the internal temperature is...	2	2.50	0.71	11	2.64	1.12	0.87
Light level	2	3.50	0.71	10	3.40	0.97	0.89
Lighting distribution in general	2	3.00	0.00	10	3.50	1.18	0.58
Lighting distribution on the ceiling	2	3.00	0.00	11	3.64	1.21	0.49
Level of glare from the windows	2	2.50	0.71	11	3.09	1.45	0.59
Level of glare from the lights	2	3.00	0.00	9	4.11	1.17	0.23
Level of glare from other bright surfaces	2	3.00	0.00	9	4.22	0.97	0.12
Bright light made it difficult to read or see my computer monitors	2	4.00	0.00	11	2.64	1.43	0.22
Bright light made it difficult to read or see other tasks (e.g., paper-based)	2	2.50	0.71	10	2.10	1.10	0.64
The automated shades are too noisy	2	2.00	0.00	11	2.82	1.33	0.42
The automated shades allow me to better focus on my work	2	3.00	0.00	10	2.70	1.06	0.71
The operation of the shades is distracting	2	2.00	0.00	11	3.27	1.19	0.17
The transparency of the shades allows me to see outside	2	4.00	0.00	10	2.70	1.25	0.19
The dimming of the lights is pleasant	2	3.50	0.71	10	3.00	0.82	0.44
The electric lighting is comfortable	2	4.00	0.00	11	3.91	0.54	0.82
The electric lighting is too dark	2	2.50	0.71	11	2.45	0.69	0.93
Lights not all dimmed to the same level is distracting	2	2.50	0.71	11	3.27	1.01	0.33
The ceiling is pleasantly lit	2	2.50	0.71	11	3.45	0.82	0.15
I am satisfied with the overall operation of the shades	2	3.00	1.41	11	2.64	1.12	0.69
I am satisfied with the overall operation of the electric lights	2	3.00	1.41	11	3.27	0.65	0.65

Average subjective response to select survey questions

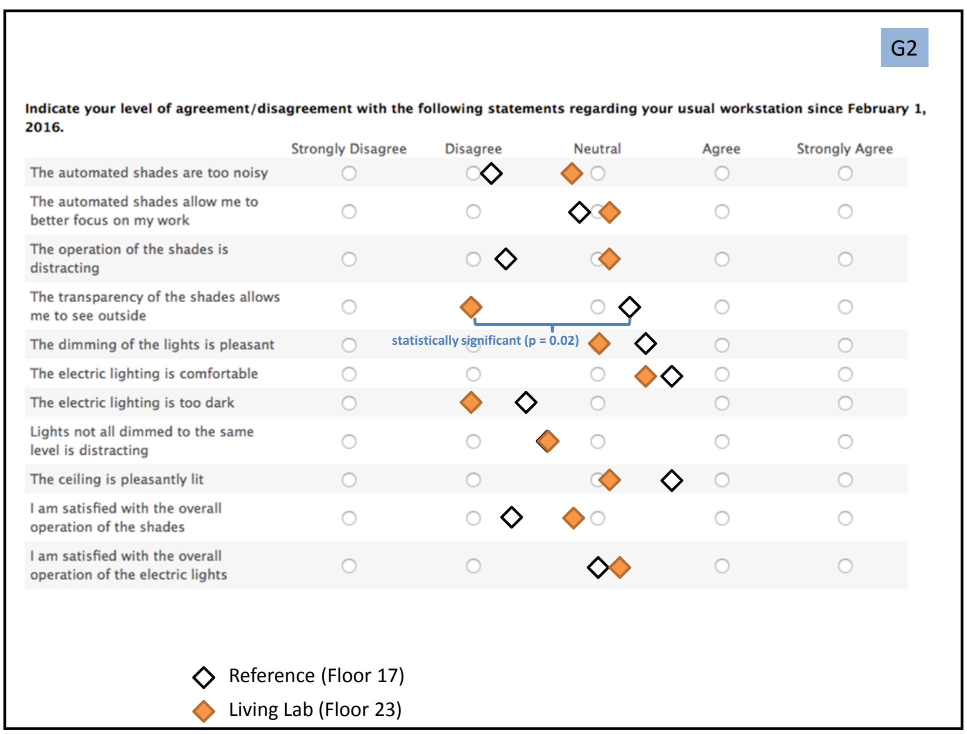

G1
Please assign a rating to the following conditions of your usual workstation since February 1, 2016.
Too Cold
Just Right
Too Warm
When the external temperature is warm/hot, the internal temperature is...
When the external temperature is cool/cold, the internal temperature is...
Please assign a rating to the following conditions of your usual workstastion since February 1, 2016.
Too Dark
Just Right
Too Bright
Light level
statistically significant (p = 0.02)
Please assign a rating to the following conditions of your usual workstastion since February 1, 2016.
Poorly Distributed
Well Distributed
Lighting distribution in general
Lighting distribution on the ceiling
Please rate the level of glare in your usual workstation since February 1, 2016.
Intolerable
Uncomfortable
Acceptable
Perceptible
Not Perceptible
From the windows
From the lights
Other bright surfaces
Bright light made it difficult to read or see:
Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree
My computer monitors
Other tasks (e.g., paper-based)
Reference (Floor 17)
Living Lab (Floor 23)

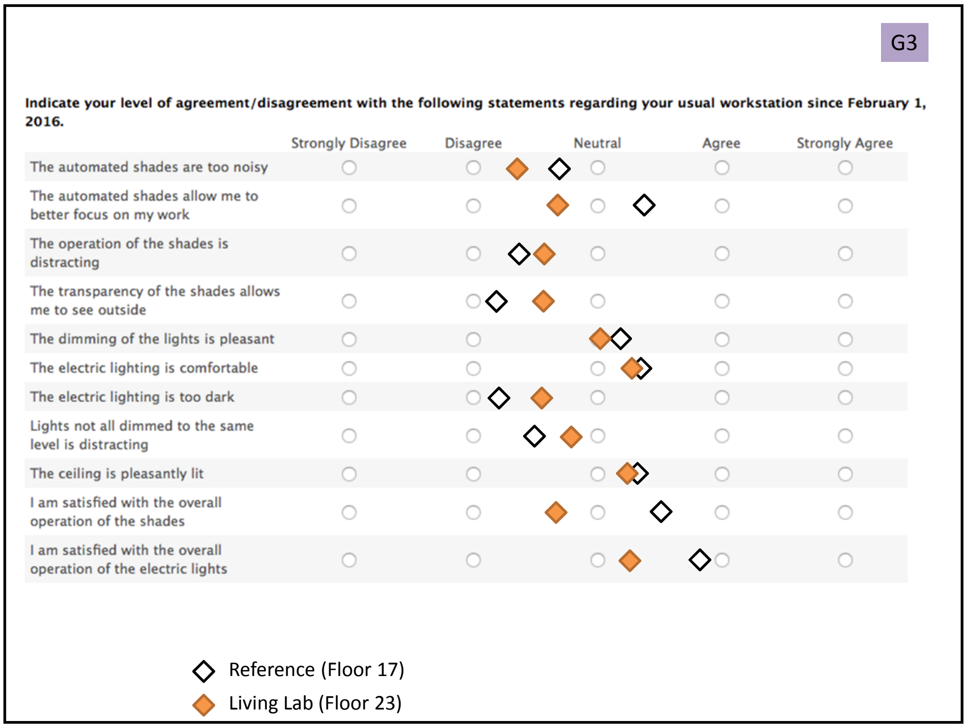

G2
Please assign a rating to the following conditions of your usual workstation since February 1, 2016.
Too Cold
Just Right
Too Warm
When the external temperature is warm/hot, the internal temperature is...
When the external temperature is cool/cold, the internal temperature is...
Please assign a rating to the following conditions of your usual workstastion since February 1, 2016.
Too Dark
Just Right
Too Bright
Light level
Please assign a rating to the following conditions of your usual workstastion since February 1, 2016.
Poorly Distributed
Well Distributed
Lighting distribution in general
Lighting distribution on the ceiling
Please rate the level of glare in your usual workstation since February 1, 2016.
statistically significant (p = 0.03)
Intolerable
Uncomfortable
Acceptable
Perceptible
Not Perceptible
From the windows
From the lights
Other bright surfaces
Bright light made it difficult to read or see:
Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree
My computer monitors
Other tasks (e.g., paper-based)
Reference (Floor 17)
Living Lab (Floor 23)

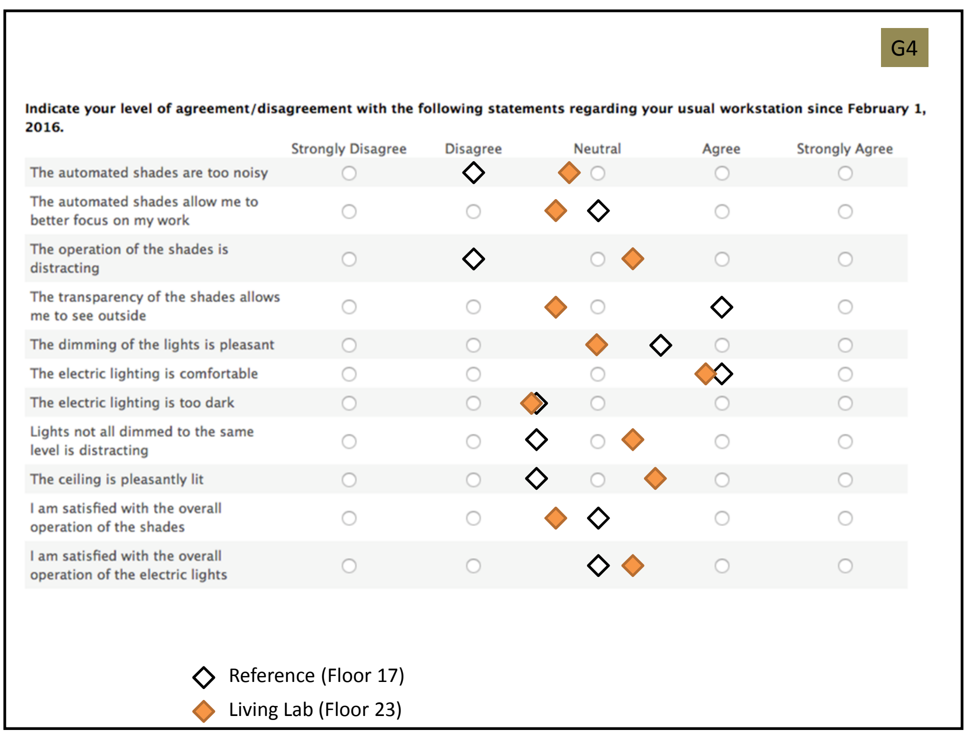

G3
Please assign a rating to the following conditions of your usual workstation since February 1, 2016.
Too Cold
Just Right
Too Warm
When the external temperature is warm/hot, the internal temperature is...
When the external temperature is cool/cold, the internal temperature is...
Please assign a rating to the following conditions of your usual workstastion since February 1, 2016.
Too Dark
Just Right
Too Bright
Light level
Please assign a rating to the following conditions of your usual workstastion since February 1, 2016.
Poorly Distributed
Well Distributed
Lighting distribution in general
Lighting distribution on the ceiling
Please rate the level of glare in your usual workstation since February 1, 2016.
Intolerable
Uncomfortable
Acceptable
Perceptible
Not Perceptible
From the windows
From the lights
Other bright surfaces
Bright light made it difficult to read or see:
Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree
My computer monitors
Other tasks (e.g., paper-based)
Reference (Floor 17)
Living Lab (Floor 23)


G4
Please assign a rating to the following conditions of your usual workstation since February 1, 2016.
Too Cold
Just Right
Too Warm
When the external temperature is warm/hot, the internal temperature is...
When the external temperature is cool/cold, the internal temperature is...
Please assign a rating to the following conditions of your usual workstastion since February 1, 2016.
Too Dark
Just Right
Too Bright
Light level
Please assign a rating to the following conditions of your usual workstastion since February 1, 2016.
Poorly Distributed
Well Distributed
Lighting distribution in general
Lighting distribution on the ceiling
Please rate the level of glare in your usual workstation since February 1, 2016.
Intolerable
Uncomfortable
Acceptable
Perceptible
Not Perceptible
From the windows
From the lights
Other bright surfaces
Bright light made it difficult to read or see:
Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree
My computer monitors
Other tasks (e.g., paper-based)
Reference (Floor 17)
Living Lab (Floor 23)


G1
Indicate your level of agreement/disagreement with the following statements regarding your usual workstation since February 1, 2016.
Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree
The automated shades are too noisy
The automated shades allow me to better focus on my work
The operation of the shades is distracting
The transparency of the shades allows me to see outside
The dimming of the lights is pleasant
The electric lighting is comfortable
The electric lighting is too dark
Lights not all dimmed to the same level is distracting
The ceiling is pleasantly lit
I am satisfied with the overall operation of the shades
I am satisfied with the overall operation of the electric lights
Reference (Floor 17)
Living Lab (Floor 23)


G2
Indicate your level of agreement/disagreement with the following statements regarding your usual workstation since February 1, 2016.
Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree
The automated shades are too noisy
The automated shades allow me to better focus on my work
The operation of the shades is distracting
The transparency of the shades allows me to see outside
statistically significant (p = 0.02)
The dimming of the lights is pleasant
The electric lighting is comfortable
The electric lighting is too dark
Lights not all dimmed to the same level is distracting
The ceiling is pleasantly lit
I am satisfied with the overall operation of the shades
I am satisfied with the overall operation of the electric lights
Reference (Floor 17)
Living Lab (Floor 23)


G3
Indicate your level of agreement/disagreement with the following statements regarding your usual workstation since February 1, 2016.
Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree
The automated shades are too noisy
The automated shades allow me to better focus on my work
The operation of the shades is distracting
The transparency of the shades allows me to see outside
The dimming of the lights is pleasant
The electric lighting is comfortable
The electric lighting is too dark
Lights not all dimmed to the same level is distracting
The ceiling is pleasantly lit
I am satisfied with the overall operation of the shades
I am satisfied with the overall operation of the electric lights
Reference (Floor 17)
Living Lab (Floor 23)


G4
Indicate your level of agreement/disagreement with the following statements regarding your usual workstation since February 1, 2016.
Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree
The automated shades are too noisy
The automated shades allow me to better focus on my work
The operation of the shades is distracting
The transparency of the shades allows me to see outside
The dimming of the lights is pleasant
The electric lighting is comfortable
The electric lighting is too dark
Lights not all dimmed to the same level is distracting
The ceiling is pleasantly lit
I am satisfied with the overall operation of the shades
I am satisfied with the overall operation of the electric lights
Reference (Floor 17)
Living Lab (Floor 23)