September 3, 2020

REPORT #E20-315

# Luminaire Level Lighting Controls Replacement vs Redesign Comparison Study

Prepared For NEEA:
Chris Wolgamott, Sr. Product Manager,

Prepared by:
Alan Mahić
Jeff Kline
Dale Northcutt
Kevin Van Den Wymelenberg

University of Oregon Energy Studies in Buildings Laboratory
105A White Stag Building
70 Northwest Couch Street
University of Oregon
Portland, OR 97209

Northwest Energy Efficiency Alliance PHONE
503-688-5400
EMAIL
info@neea.org

# TABLE OF CONTENTS

# EXECUTIVE SUMMARY

### *Introduction*

Luminaire Level Lighting Controls (LLLC) systems have made significant advancements in recent years as indoor electric lighting solutions that integrate daylight harvesting and occupancy sensing controls into individual LED luminaires. Having a sensor in each luminaire simplifies installation and programming while they can operate independently, and multiple units are able to connect into larger networks via wireless gateways. As such, this technology provides versatility and expands potential design solutions for new construction, existing building renewal, and lighting retrofits. This study was conducted to determine if LLLC systems, applied as one-for-one (1:1) replacement retrofit solutions, can provide lighting energy savings and lighting quality comparable to more comprehensive networked lighting control (NLC) redesign solutions, which tend to also require significant cost investment in design, specification, and install. The key differences of the redesign NLC system include individual ceiling-mounted daylight harvesting and occupancy switching sensors, and luminaire grouping of daylight harvesting and occupancy zones via the control software. However, sensor capabilities remain the same between the LLLC 1:1 integrated sensors and the external sensors of the redesign solution. The findings summarized here show that LLLC systems are a cost-competitive 1:1 retrofit alternatives that provide comparable performance to more comprehensive NLC redesign solutions.

### *Methodology*

The study design included a 981ft2 space, 33' wide in the east-west direction and 27' deep in the north-south direction, with perimeter glazing along the north facade. There were nine 4' pendent lighting fixtures arranged in an evenly spaced 3 by 3 grid. In the center of the space, four workstations were positioned to represent a typical open office space.

Four LLLC systems were chosen from the DesignLights Consortium (DLC) Networked Lighting Control Qualified Products list to represent the 1:1 replacement retrofit solutions, and a fifth NLC system was chosen as part of a full redesign solution, also from the DLC list. All five were compared to a fluorescent baseline, which included two 32W T8 lamps controlled by a single wall switch, and to each other. The redesign solution employed a zoning approach that grouped luminaires into perimeter, middle, and core zones with the core zone falling outside the determined “daylit zone”. As such, the core zone incorporated occupancy switching but not daylight harvesting. Each system was installed and tested sequentially in three-week periods. Luminaire outputs were tuned to satisfy Illuminating Engineering Society of North America (IESNA) Lighting Handbook standard of 300 Lux as recommended for open-office horizontal work plane illuminance.

Lighting power consumption was monitored by current transformers. A human factors analysis was conducted to evaluate lighting quality. Participants were recruited to perform computer- and paper-based tasks and provide subjective responses to validated qualitative questionnaires. This included evaluations of light quality, brightness, distribution, comfort, and general, self-assessed well-being. Indoor and outdoor environmental metrics were also recorded. Other monitored factors included duration of install, equipment and labor costs, and other open-ended feedback from the installer.

Analysis methods included converting power consumption comparisons among the systems and the baseline to total and per-fixture energy savings for each retrofit solution. Additionally, measured energy consumption was correlated to exterior sky conditions and extrapolated to TMY3 weather data to estimate annual lighting energy savings for each system. The subjective questionnaire responses were evaluated using statistical analyses that focused on differences of mean values between systems per questionnaire item. Statistical correlations were used to examine significant relationships between questionnaire item responses and all other recorded indoor and outdoor environmental metrics. Linear regressions were then used to show the strength and direction of these relationships.

### *Results*

While the install of each system was completed without delays, logistical issues were encountered during equipment acquisition that required significant time to resolve. This involved specification accuracy, equipment compatibility, and miscommunications along the supply chain. Building closure due to severe weather and a public health emergency also required additional testing time for select systems. Programming and commissioning time and complexity varied across systems, with the main issues involving insufficient documentation of hardware and software.

The total costs are in favor of LLLC 1:1 solutions, which ranged from $6.04/ft2 to $7.44/ft2, compared to $17.57/ft2 for the redesign solution. Feedback from the electrician that installed each LLLC and NLC system suggests that hardware install was relatively smooth, while difficulties were encountered with some software functionality and insufficient documentation during programming of specific systems.

| *System* | *Fixture Zone ** | *Annual estimated lighting energy savings based on pre-tuning maximum energy consumption* | | | | | |
|---|---|---|---|---|---|---|---|
| | | *Savings due to all controls measures* | | *Savings due to daylight and occupancy* | | *Savings due to high-end trim* | |
| *LLLC System #1* | Perimeter | **74%** | **51%** | **74%** | **45%** | **0%** | **6%** |
| | Middle | **49%** | | **37%** | | **12%** | |
| | Core | **32%** | | **25%** | | **7%** | |
| *LLLC System #2* | Perimeter | **85%** | **74%** | **75%** | **40%** | **10%** | **34%** |
| | Middle | **74%** | | **23%** | | **51%** | |
| | Core | **71%** | | **31%** | | **40%** | |
| *LLLC System #3* | Perimeter | **80%** | **50%** | **80%** | **42%** | **0%** | **8%** |
| | Middle | **45%** | | **31%** | | **13%** | |
| | Core | **25%** | | **15%** | | **10%** | |
| *LLLC System #4* | Perimeter | **86%** | **63%** | **71%** | **43%** | **15%** | **20%** |
| | Middle | **58%** | | **35%** | | **23%** | |
| | Core | **47%** | | **26%** | | **21%** | |
| *Redesign System #5* | Perimeter | **86%** | **67%** | **71%** | **32%** | **15%** | **35%** |
| | Middle | **73%** | | **23%** | | **50%** | |
| | Core | **47%** | | **7%** | | **40%** | |

*Notes: Annual estimated lighting energy savings attributed to controls relative to pre-tuning maximum energy consumption of each fixture and system.*

The annual estimated lighting energy savings showed substantial savings for all systems compared to the fluorescent baseline. The 1:1 retrofit solutions ranged from 50% to 74% savings, and the redesign solution showed 67% savings. These savings numbers do not include savings from the LED upgrade. The table below shows energy savings in three different bins: due to all controls measures, including daylight harvesting, occupancy switching, and high-end trim; due to daylight harvesting and occupancy switching only; and due to high-end trim only.

The human factors analysis was based on 183 total 2-hour samples collected from 76 participants. Significant differences in lighting quality rating were found between the baseline and each of the 1:1 retrofit and redesign systems. These factors included overall brightness of the space, likely due to luminaire tuning to IES standards for open offices. LLLC 1:1 and redesign solutions were also rated as more calming and subdued than the baseline. Additionally, participants rated higher sense of alertness for LLLC 1:1 solutions, higher satisfaction with the amount of light at the workstation for paper- and computer-based tasks, and higher rating of lighting distribution at the workstation.

Significant differences were not found between the group of four LLLC 1:1 solutions and the redesign solution. However, there were specific cases where the redesign showed higher ratings of alertness, one LLLC 1:1 solution showed higher satisfaction with the amount of lighting available for paper-based tasks, another 1:1 solution that showed lower ratings of luminaires as a source of discomfort, and finally two more 1:1 solutions showed higher ratings of satisfactory lighting distribution at the workstation.

A statistical analysis including all measured data and questionnaire responses revealed some luminance-based metrics had strong correlations with questionnaire responses, suggesting the windows on the north facade may have influenced participants' ratings of discomfort during testing. However, other similar metrics that exclude the direct influence of the windows also maintain a strong correlation between the measured light intensity and the participants' rating of brightness in the space. As such, luminaires could not be ruled out or suggested as a source of discomfort glare by these data.

### ***Conclusions***

The measured energy comparison and annual estimated savings compared to the fluorescent baseline show a higher trend for the LLLC 1:1 solutions, ranging from 7% to 14% more savings than the redesign solution. However, it is important to note the different zoning approach of the redesign solution, which effectively illustrates the potential of daylight harvesting beyond the traditional daylit zone. This is also reflected by the annual estimated savings due to daylight harvesting and occupancy switching seen in the results table above. The annual estimated savings due to all controls measures (daylight harvesting, occupancy switching, and high-end trim) show more comparable savings with LLLC 1:1 solutions ranging from 50% to 74% and the redesign solution showing 67%. It is worth noting that the wattage rating and lumen output of each set of luminaires was kept as close as possible but did vary some by system. As such, the high-end trim savings data also reflect this variance.

The human factors data and statistical analysis showed a clear difference in performance between each LLLC 1:1 system, as well as the redesign system, as compared to the baseline, but they did not show significant differences among any of the five replacement systems. As such, the similarity in performance between 1:1 and redesign compared against the baseline provides reasonable confidence in equity of overall light and controls quality.

The cost data showed that LLLC 1:1 systems range between one-third to one-half the cost of more comprehensive NLC solutions, thus illustrating the value potential of LLLC 1:1 systems in lighting design. However, there is certainly room for improvement when it comes to equipment acquisition, install, and programming logistics and documentation.

These findings support LLLC systems as cost-competitive 1:1 retrofit alternatives that provide comparable performance to more comprehensive NLC redesign solutions. However, further research is recommended to validate these findings for larger scale installations and sample size.

# 1. INTRODUCTION

Luminaire Level Lighting Controls (LLLC) systems have been gaining ground as an effective way to integrate daylight harvesting and occupancy switching controls with LED fixtures, while also streamlining installation and programming. This technology is applicable to new construction, existing building renewal, and lighting retrofit. This study compares a baseline lighting installation, with a redesign solution, and several one-for-one (1:1) replacement solutions of existing lighting fixtures in a laboratory test space using LLLC direct-indirect pendant LED fixtures. These fixtures provide a mixture of direct lighting and indirect reflection off the ceiling. Comparing these strategies provides knowledge to guide best practices related to workplace lighting that includes considerations of electric lighting quality, lighting controls, human factors feedback, energy consumption, equipment costs, installation cost, and operating cost. Furthermore, it provides useful findings from the design, specification, procurement, installation, commissioning, and operations process.

The goal of this comparison study is to determine if LLLC 1:1 retrofit solutions offer a comparable alternative to full lighting redesigns from the perspective of energy savings, comfort, and cost. Many studies have examined the energy, comfort and satisfaction of lighting control systems including those where sensors and control logic are integrated into the fixtures [1,2,3,4,5]. These technologies are available from various manufacturers, however there is a lack of literature exploring performance, energy, and cost savings associated with LLLC 1:1 replacement in comparison to typical full lighting redesign strategies. This study means to fill this knowledge gap.

# 2. METHODOLOGY

## 2.1 Study test space

The human factors laboratory test space is located on the University of Oregon (UO) campus in Eugene, OR as part of the Energy Studies in Buildings Laboratory (ESBL). The space is 33 feet wide in the east-west direction and 27 feet deep in the north-south direction with a floor area of 981ft$^2$. The interior layout was adjusted to accommodate an approximate mock-up of a typical open office and is shown in Figure 1. Four workstations were set up in the center of the space, within the daylit zone but not adjacent to windows, oriented perpendicular to the north windows with two facing east and two facing west. The workstations did not include cubicle partitions, which would affect the commissioning process and luminaire tuning levels. Daylight harvesting performance would more than likely decrease based on partition height, positioning, and surface color; while occupancy sensing line-of-sight issues would also be likely depending on partition height and positioning. The center of the test space offered the most area and least obstructions, which provided the most consistent conditions possible for daylight harvesting and overall lighting distribution. This also helped to curb the effects of seasonal shift as system testing varied across the year. The workstations, seen in Figure 2, were the focus of the human factors data collection. The perimeter zone, adjacent to the north windows and underneath fixtures #3, #6, and #9, are occupied by lab staff.

**Figure 1. Study space diagram**

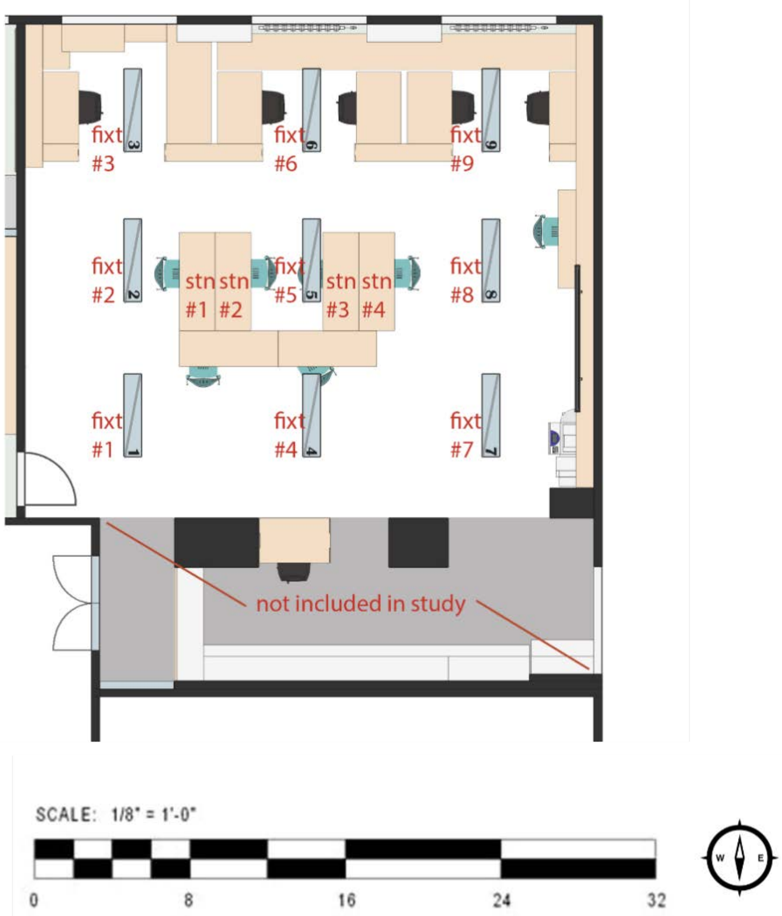


**Figure 2. The four workstations as seen from the north-east corner of the test space**

## 2.2 Retrofit lighting solution development and install

The retrofit lighting solutions included:

- A 32W fluorescent baseline.
- Four LLLC 1:1 retrofit solutions with fixture-integrated occupancy sensors, photosensors, and wireless distributed control systems.
- One full lighting redesign solution including a comprehensive NLC system with independent sensors, each capable of occupancy and photosensing.

The four 1:1 retrofit solutions and the full lighting redesign solution were selected from the DesignLights Consortium (DLC) Networked Lighting Control Qualified Products v.3.001 list. The selection criteria included:

- System complexity (install and programming)
- Intentional variety of system features (per the DLC criteria and ESBL discretion)
- Cost of hardware and install
- Market presence and impact
- Industry feedback (lighting design and architecture)
- A combination of “*smart*” and “*clever*” LLLC systems. For purposes of this report:
  - A "*smart*" system is considered anything that includes two-way communication that allows changes to be made based on feedback provided by the system. For example, sensing quantity of people in a space, or ability to connect to other systems and drive logic.
  - A "*clever*" system is considered anything that includes one-way communication though a simple driver, such as dimming, sensing, daylight harvesting, and changes to basic inputs from a Domain Name System (DNS).

Our team developed a third-party industry group to provide guidance in selecting luminaire and control solutions. Recommended solutions included systems from Cree, Eaton, Acuity Brands, Lutron, and Siemens Enlighted. Discussions with the industry group convened included:

- Industry opinion and experience with the market, manufacturers, and products. Additionally, there was some preference toward manufacturers that were proactive about integrating new technologies into their products.
- Choice of driver where 0-10V, an analog signal that uses voltage to represent a variable signal, is most ubiquitous in the industry.
- Demand response and color tuning are in the discussion as requirements for the next cycle of the Oregon code, which was slated for July of 2019. However, the color tuning argument is based primarily on the emerging field of circadian health and associated technologies.
- Third-party opinion and experience with the market, manufacturers, and products.
- The distinction between distributor-level systems and those more commonly used in the architectural lighting market.

All retrofit solutions make use of separate sets of nine indirect-direct 4' linear pendant luminaire (fixtures). The fixture styles and specifications were kept as consistent as possible across different manufacturers, as shown in Table 1 although some options were limited depending on manufacturer and compatibility between fixtures and control systems. Installation and initial commissioning were performed by a UO licensed electrician.

**Table 1. Fixture Specifications**

| ***System*** | ***Input power*** | ***Lumens*** | ***Color temperature*** | ***Indirect/direct ratio*** | ***CRI*** | ***Dimming*** |
|---|---|---|---|---|---|---|
| *LLLC System #1* | 32.0W | 3,700 | 3500K | 60/40 | 90 | 0-10V to 5% |
| *LLLC System #2* | 35.5W | 3,697 | 3500K | 50/50 | 85 | 0-10V to 1% |
| *LLLC System #3* | 32.0W | 4,373 | 3500K | 60/40 | 80 | 0-10V to 1% |
| *LLLC System #4* | 35.0W | 4,000 | 4000K | 60/40 | 85 | 0-10V to 1% |
| *Redesign System #5* | 35.5W | 4,592 | 3500K | 60/40 | 85 | 0-10V to 1% |

*Notes: Fixture specifications pertinent to energy consumption and light quality were matched as closely as possible.*

### 2.2.1 Baseline

The baseline lighting solution included nine indirect/direct linear pendant fixtures with two 32W T8 fluorescent lamps controlled by a single on/off wall switch.

### 2.2.2 LLLC System #1

As a distributor-level lighting control solution, LLLC System #1 served as a direct comparison to System #2 and System #3. However, while these systems share the basic core features, System #1 is the only one to account for color tuning controls. System #1 was proposed as one of the "*clever*" solutions, as per industry feedback. Intentional variety is a key factor in making these selections. As such, this system provides both variety of brand and features.

### 2.2.3 LLLC System #2

As a distributor-level wireless lighting control solution, LLLC System #2 falls into the "*clever*" category, which constitutes a low cost and low impact install and commissioning solution. This product is similar to System #1 from a market penetration standpoint, but includes system features such as scheduling, personal control, demand response, plug load control, and energy monitoring.

### 2.2.4 LLLC System #3

LLLC System #3 benefit from various acquisitions of technology that this company has been able to implement into a system that falls into both the "*smart*" and "*clever*" categories. System #3 has been chosen as a potentially high-performing 1:1 replacement solution based on their track record of technology integration and support.

### 2.2.5 LLLC System #4

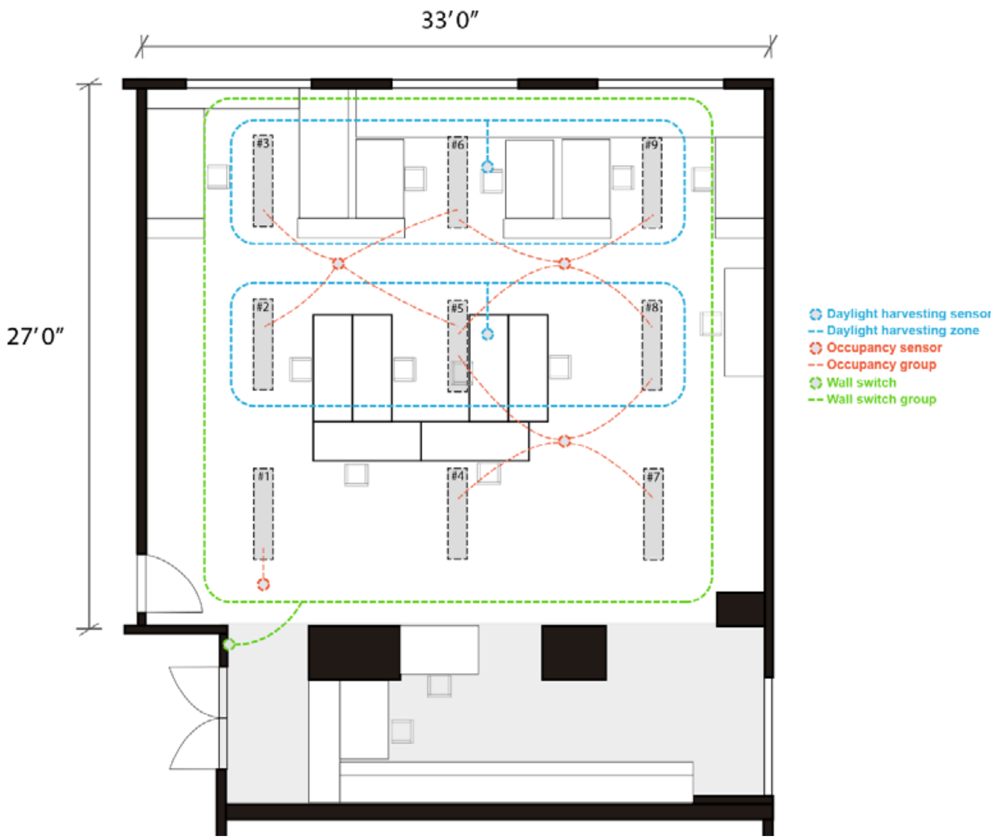
LLLC System #4 has established itself in the market as a premiere architectural option for a comprehensive lighting control system. This system fills the "*smart*" system category and can be installed as both a 1:1 replacement design solution option and/or a full lighting redesign of the test space. However, we feel it is better applied as a 1:1 replacement option since it is able to serve as the market-standard comparison to the rest of the 1:1 replacement systems.

### 2.2.6 Redesign System #5

Redesign System #5 fills the "*smart*" system category as a comprehensive NLC solution for the test space. This system is DLC-approved and incorporates an additional feature of anonymous asset tracking, which provides spatial occupancy data. These data can be used to analyze occupant density and movement in a space. This feature can be used in several ways to analyze spatial and whole building energy use and controls trends more accurately.

A professional lighting designer was consulted during the development of the redesign retrofit solution. However, we found that the existing 3-by-3 luminaire layout was still optimal. This was also confirmed via lighting simulation of several fixture styles and layouts. In addition to budget constraints, we decided to maintain the 3-by-3 layout of the luminaires and optimize occupancy and photosensor placement. Figure 3 shows the luminaire and sensor layout of the installed luminaires and controls. The daylight harvesting zones were defined within a section depth relative to two times the head-height of the north windows. The daylight harvesting sensors were rod-mounted to the same height as the pendant luminaire frames to avoid line of sight issues. The occupancy sensors were mounted flush with the ceiling plane, while the occupancy grouping was set to maximize total coverage area and ensure enough sensor overlap to avoid occupancy blind spots.

**Figure 3. Redesign Solution Fixture Zoning and Control Sensor Placement**




### 2.2.7 Bench-testing, install, programming, and commissioning

We performed bench-testing to evaluate fixture and controls hardware, programming, and technical documentation prior to install. This information was made available to the UO electrician on the day of installation for each retrofit solution. The lighting fixtures were installed in the order of #1 through #9 as numbered in Figure 1.

The hardware install involved wiring and suspension of LED pendant light fixtures along with controls peripherals such as communication hubs and data processors, if available, followed by programming of controls software. The mounting of each set of fixtures was relatively easy since the baseline and each retrofit solution were all cable-hung pendants. The fixtures were pig-tailed and connected to existing power outlets available above the dropped ceiling. The ease of mounting and wiring was confirmed during bench testing and the estimated time required is included as part of the labor cost and install time totals shown in Table 3 and Table 12, respectively. The commissioning process involved tuning specific controls variables, such as high-end trim to maintain 300 Lux of horizontal illuminance at the work plane of each office workstation mock-up, as per the Illuminating Engineering Society of North America (IESNA) Lighting Handbook standards for recommended open-office horizontal illuminance on the work plane (300 Lux) [6]. Table 2 shows a summary of primary variables that were considered during programming and commissioning, and Table 3 shows the time required to install each retrofit solution.

**Table 2. Primary Variables Considered During Programming and Commissioning**

| **Controller/Fixture** | | ***LLLC System #1*** | ***LLLC System #2*** | ***LLLC System #3*** | ***LLLC System #4*** | ***Redesign System #5*** |
|---|---|---|---|---|---|---|
| *Occupancy* | *Mode* | Auto on/Auto off | | | | |
| | *Occ. Level* | 100% | | | | |
| | *Unocc. level* | 0% | | | | |
| | *Sensitivity* | Medium | High | Normal | High | 1 for motion, 10 for daylight |
| | *Zone* | Each luminaire | 1 or 2 luminaires per group (limited to 6) | Each luminaire | Each luminaire | 4 groups, 3 overlapping |
| | *Timeout* | 15 min | | | | |
| *Daylight* | *Zone* | Each luminaire | Each luminaire | Each luminaire | Each luminaire | 3 groups parallel to window wall |
| | *ON* | Enable | closed loop | Enable | Enable | Enable |
| | *Minimum* | 5% | 0% | 1% | 0% | 0% |
| *Trim* | *High-end* | 75-100% depending on fixture | 40-100% depending on fixture | 75-100% depending on fixture | 70-89% depending on fixture | 50-85% depending on fixture |

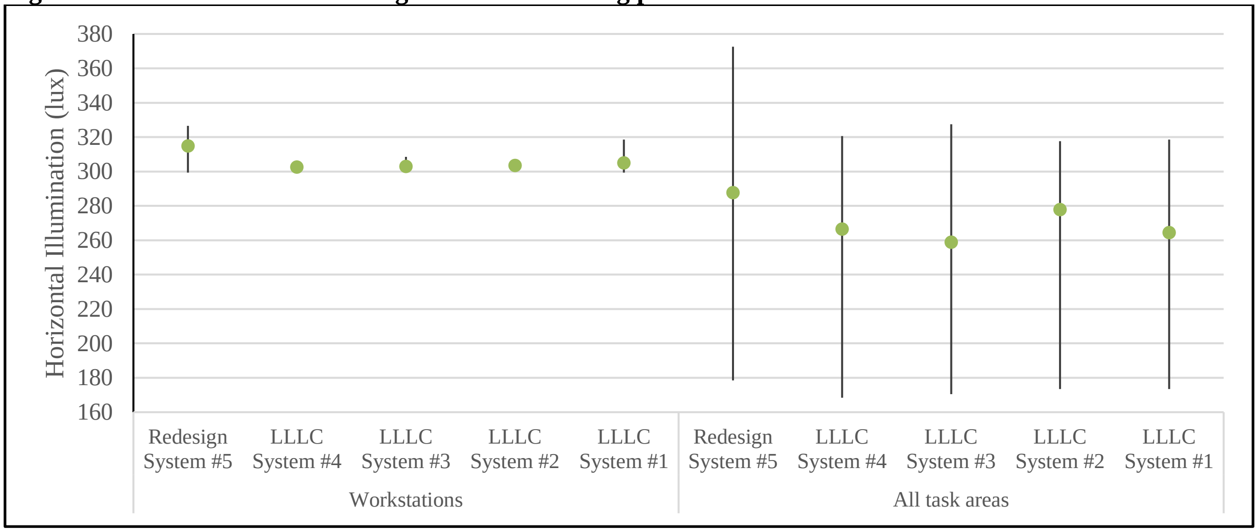
**Table 3. Time Required for Install, Programming, and Commissioning**

| ***System*** | ***Hardware install (HH:MM)*** | ***Programming (HH:MM)*** | ***Commissioning (HH:MM)*** | ***Total (HH:MM)*** |
|---|---:|---:|---:|---:|
| *LLLC System #1* | 05:15 | 00:45 | 03:00 | **09:00** |
| *LLLC System #2* | 05:50 | 02:45 | 04:30 | **13:05** |
| *LLLC System #3* | 05:40 | 00:35 | 04:30 | **10:45** |
| *LLLC System #4* | 03:30 | 00:30 | 02:30 | **06:30** |
| *Redesign System #5* | 07:05 | 02:35 | 06:00 | **15:40** |

Figure 4 shows the measured horizontal illuminances at the work plane of the workstations. The left portion of this chart accounts for only the workstations while the right portion includes workstations near the north-facing windows and the desks adjacent to the four main workstations. Table 4 includes the minimum, average, and maximum values of these measurements, taken post-commissioning and calibration during evening hours and confirm that the maximum output of luminaires maintains 300 Lux, following IESNA standards.

The programming was performed by the UO electrician as part of the install process. Additional commissioning was performed by project staff to fine-tune the fixture outputs and conform to both the IESNA standards and the specifications summarized in Table 2.

**Figure 4. Results of Commissioning and Fixture tuning process**




*Notes:* The green markers show the average horizontal illuminance (Lux) at the work plane of the four workstations used for research participants and the gray lines indicate the minimum and maximum spread.

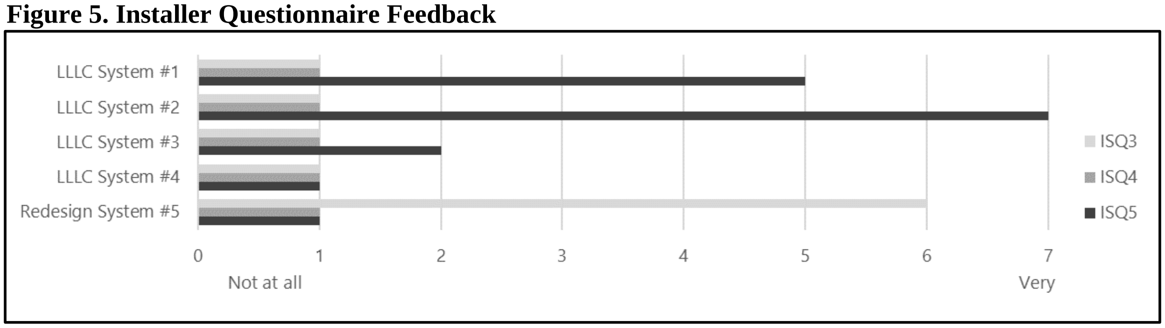
**Table 4. Horizontal Illuminance (Lux) on Four Workstations**

| *System* | *Min (Lux)* | *Average (Lux)* | *Max (Lux)* |
|---|---|---|---|
| *Baseline* | 349 | 381 | 412 |
| *LLLC System #1* | 300 | 305 | 318 |
| *LLLC System #2* | 301 | 304 | 306 |
| *LLLC System #3* | 300 | 303 | 308 |
| *LLLC System #4* | 301 | 315 | 304 |
| *Redesign System #5* | 300 | 315 | 326 |

The UO electrician completed a survey at the end of the installation process. Figure 5 shows responses to three questions, which are based on a 7-point Likert type scale with 1 representing "*Not at all*" and 7 representing "*Very*". The questions are as follows:

- ISQ3: *How difficult was the wiring required to install the current fixtures and system?*
- ISQ4: *How difficult was the mounting of the current fixtures and system?*
- ISQ5: *How difficult was the programming of the current fixtures and system?*

**Figure 5. Installer Questionnaire Feedback**




*Notes:* Feedback received from the UO electrician following install and programming of each retrofit solution.

An open-ended question was included to capture more nuanced feedback about encountered difficulties, which yielded some additional insights into each system from the electrician's perspective:

- For LLLC System #1 mounting of the indirect/direct 4' linear pendent fixtures was not difficult. The one-button set-up feature using the wireless remote was straight forward for the initial programming. Although additional tuning required that each fixture be adjusted individually. This process was slightly cumbersome and time-consuming, but relatively easy after 10-15 minutes of getting acquainted with the tool. The documentation was helpful, but not as thorough as expected.
- For LLLC System #2, mounting of the indirect-direct 4' linear pendent fixtures was not difficult, but the fixtures themselves needed additional attention before install. Some were missing screws, and some had gaps between frame plates that needed to be tightened. The interface of the iPhone version of the programming mobile app proved very difficult to work with. There was also a lack of technical documentation and programming instructions.
- For LLLC System #3, mounting of the indirect/direct 4' linear pendent fixtures was not difficult, but the form factor was relatively thick, requiring some adjustment to match the suspension height of the other fixture models. The lenses of the integrated sensors were dented during shipping on 7 of the 9 fixtures, but the repairs were simple as the lenses are plastic and malleable.
- For LLLC System #4, mounting of the indirect/direct 4' linear pendent fixtures was not difficult. The mobile app was easy to navigate, and the programming was straightforward and smooth compared to the rest of the field.
- For Redesign System #5, mounting of the indirect/direct 4' linear pendent fixtures was not difficult. However, the controller needed to be wired into each fixture, increasing install time. An electrical box was also installed to house the energy manager and 4G modem. The software came pre-programmed by the manufacturer, making initial programming much easier than expected. The programming/management software is quite thorough and allows for detailed control of daylight and occupancy zoning.

Overall, the process was relatively smooth with a few time-consuming challenges primarily involving programming and commissioning of controls, lacking technical documentation for software and mobile app operability, and minor physical defects that needed to be addressed before fixtures could be installed.

It is worth noting that there were significant difficulties and delays during acquisition of control systems and luminaire hardware, which significantly disrupted the project and testing timeline. We believe this was a result of a combination of factors:

- Specification accuracy and product/hardware availability.
- Supply chain disruptions because of macro-economic forces, particularly during Q3 and Q4 of 2019.
- Interorganizational miscommunication along the supply chain (researchers, suppliers, representatives, and manufacturers).

- Hardware incompatibilities that required multiple iterations of testing and troubleshooting with manufacturers.

Human factors testing periods were affected by inclement weather events and enactments of COVID-19 stay-at-home policies. Testing schedules were adjusted to accommodate as best as possible and without risk to human factors testing participants. It is also worth noting that a portion of the luminaires and controls components were generously donated for this study. It is likely this played a role as well by deviating from the standard supply chain of the retail market.

### 2.2 Empirical data collection

This study is reporting on data collected with current transformers attached to each of the nine fixture circuits and logged on a one-minute interval. The equipment was manufactured by Onset Computing and consists of an EG4115 15-channel data logger and nine T-ACT-0750-020 20 Amp Accu-CT Split-Core Current Transformers.

The study was submitted to the UO Research Compliances Services for Institutional Review Board review and approved with exempt status. The available participant populations consist primarily of UO students, aged between 18 and 30, and a limited sample of lab personnel not involved with the project that included a mix of students and staff aged between 18 and 45. Participants committed to 2-hour testing periods, which included self-directed paper and computer tasks. Each participant was allowed up to four 2-hour sessions per retrofit solution but were not required to do so or to partake in testing of every retrofit solution. The comfort comparison is based on responses to subjective questionnaire items. A summary of questionnaire items is available in Table 8. The questionnaire items use 7-point Likert, semantic differential responses, or continuous graphic scales (coded with a 0-100-point range). The questionnaires were administered on paper and consist of four parts:

(1) Participant information questionnaire contains age, gender, and whether participants wear corrective lenses. Administered once per participant.

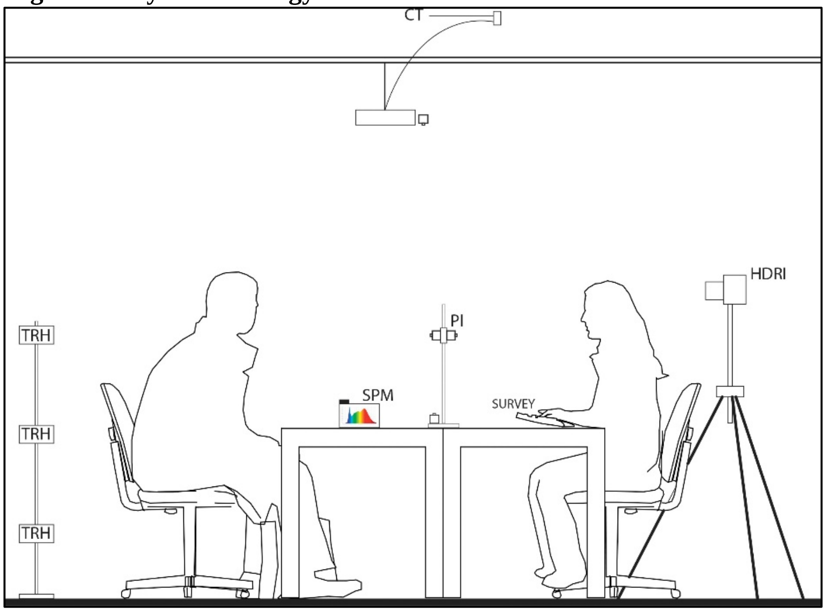
(2) Introductory questionnaire contains questions on health, sensitivity to light, whether primarily paper- or computer-based tasks will be performed during the session, level of stress, level of fatigue, rating brightness of the visual environment, rating uniformity of ceiling, and rating brightness of ceiling. Administered once at a participant's first 2-hour session of the day.

(3) Visual comfort assessment contains questions on caffeine intake, rating lighting quality between keywords, rating sense of alertness, rating satisfaction with amount of light for computer work, rating satisfaction with amount of light for paper-based work, rating light distribution, and rating satisfaction with the amount of light available at the work station for the intended work.

(4) Exit questionnaire contains questions rating perception of changes in lighting levels, rating distraction of any variation in lighting, rating level of stress, rating level of fatigue, and rating the lighting fixtures as a source of discomfort.

Study participants did not have access to the lighting controls so as not to interfere with the automated control systems of each retrofit solution.

**Figure 6. Layout of Energy and Human Factors Data Collected**




*Notes:* SURVEY: The human factors questionnaire; HDRI: High Dynamic Range Imaging, 30-min. interval; PI: Photopic illumination, 1 min. interval; SPM: Spectrophotometer, 30 min. interval; TRH: Temperature and relative humidity, 1 min. interval; CT: Current transducer, 1 min. interval.

Figure 6 shows the layout of data collection points within the context of the seated participant at one of the four workstations. The monitoring of each scenario includes the following indoor metrics:

- Lighting energy consumption
- Lighting run-time *(Monday-Friday, 8:00am-5:00pm workday)*
- Illuminance levels *(Horizontal and vertical)*
- Color temperature
- Spectral power distribution
- Color Rendering Index
- Fidelity Index *(TM-30; The accurate rendition of color so that they appear as they would under familiar (reference) illuminants; similar to CRI)*
- Gamut Index *(TM-30; The average level of saturation relative to familiar reference illuminants)*
- Luminance spatial intensity and distribution with High Dynamic Range Imaging (HDRI) captures of scenes for glare analysis. *(30-minute interval)*
- Ambient air temperature
- Relative humidity
- Human subjective responses to validated qualitative questionnaire encompassing lighting quality, visual comfort, discomfort glare, overall satisfaction, self-assessed productivity.

The monitoring of each scenario includes the following outdoor metrics:

- Direct Solar Irradiance
- Diffuse Solar Irradiance
- Global Horizontal Irradiance

### 2.4 Analysis methods

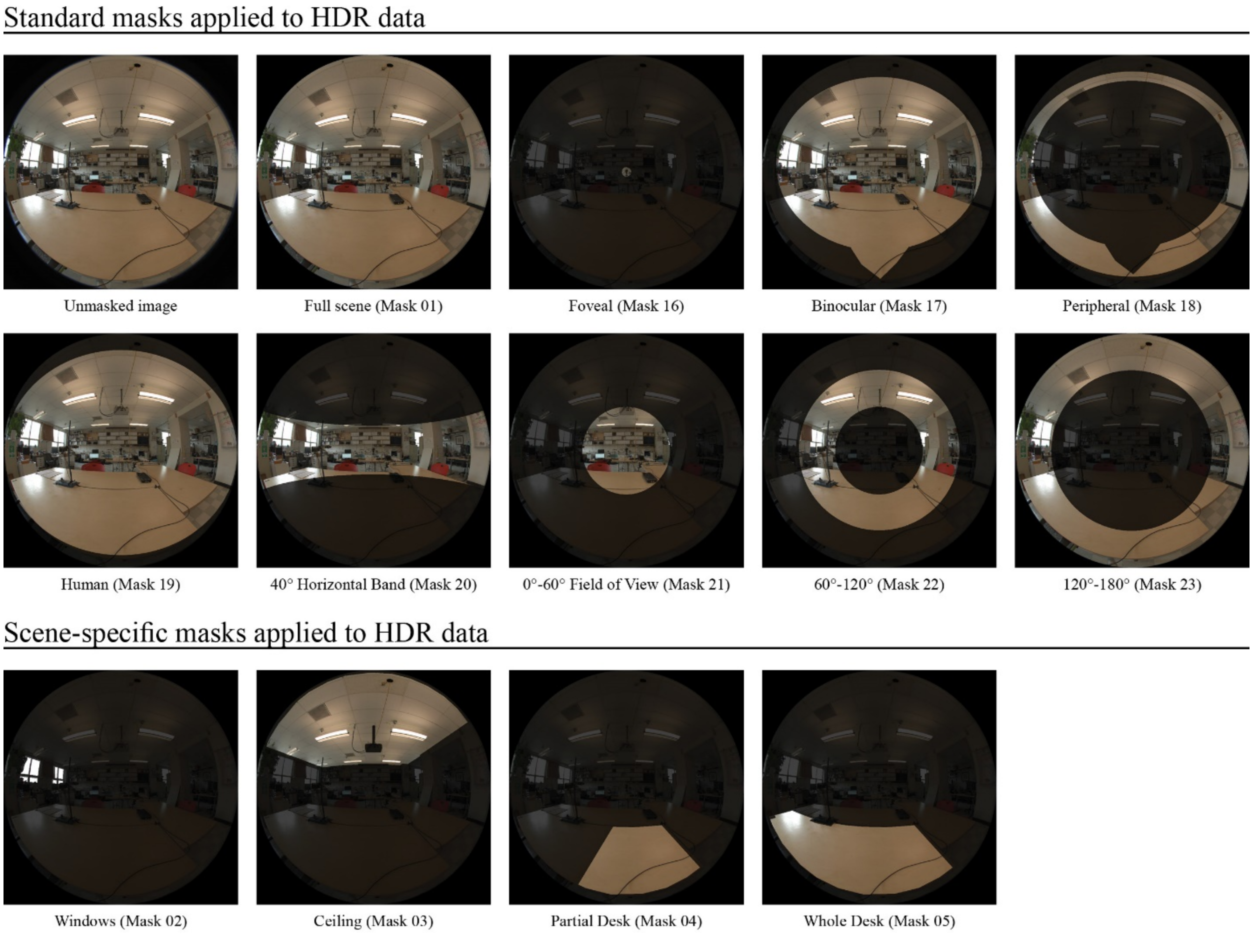
Energy monitoring data was processed with Microsoft Excel and included in the R-based statistical analysis. Total and per-fixture power values of 1-minute intervals were converted into an area-based intensity metric, Watt-hours per square foot (Wh-$ft^2$), for the baseline and each lighting retrofit solution.

Since long-term (year-long) energy use data could not be attained for each lighting system tested, a detailed relationship was established between the monitored lighting energy data, exterior illumination, and cloud cover. Exterior illumination was acquired from the University of Oregon Solar Radiation Monitoring Laboratory (UO-SRML), which maintains a weather station on the roof of the Pacific Hall building where the test space is located. Cloud cover data was acquired from the National Oceanic and Atmospheric Administration (NOAA). The observed relationships were applied to TMY3 global illuminance and cloud cover data from the Mahlon Sweet Airport in Eugene, OR to extrapolate annual estimated lighting energy consumption and savings for each system tested.

The questionnaire responses were entered into digital Qualtrics forms and curated with Filemaker Pro, Microsoft Excel, and R [7]. Curation involved spot-checking data entries, formatting consistency, and consolidation of the four questionnaire parts. Statistical analysis was then performed using R.

High Dynamic Range Imaging (HDRI) data was collected in 30-minute intervals and coincided with the human factors testing in the test space. Two Canon EOS 5D cameras with SIGMA 8mm F3.5 EX DG fisheye lenses were positioned to represent the participant's point of view from workstations #1 (east-facing) and #4 (west-facing). These cameras captured 180-degree fields of view in opposite directions of each other, effectively capturing the lighting throughout the entire test space. The HDR data was processed using a combination of scripts written in the BASH shell language, which involved automated glare analyses using the *evalglare* software [8] for equation-based metrics like Daylight Glare Probability (DGP). Custom calculations were also performed for standard brightness metrics like means, averages, minimums, maximums, etc. A masking technique was used to isolate specific regions of each HDR image, and the metrics were calculated for each mask region individually. This was done to achieve a more detailed analysis of surface luminance and angular distribution of luminance in a scene. A total of thirteen masks are applied to each HDR image during this process, as shown in Figure 7.

**Figure 7. HDR Masking for Luminance-based Metrics Calculations**




Luminance-based metrics were curated and combined with human factors data and measured empirical data before statistical analyses were performed using R. Given the inherent differences among the three data sets, significant curation was necessary to synchronize data intervals and fit them together into a uniform format. Group means and variance of the questionnaire item responses are compared between the baseline, LLLC 1:1 retrofit solutions, and the redesign retrofit solution. This was done using a few different analysis methods: Welch two-sample t-test, Pearson correlation, linear regression, and analysis of variance.

The Welch two-sample t-test compares the difference of means between two pairs of sample data. In this case the questionnaire items of each retrofit solution are paired with those of the other systems. A significant difference exists between each pair if $p \leq .05$ is satisfied by the calculated p-value. The Pearson correlation takes a matrix of all data available as input and compares every metric available to all others to determine if there are significant relationships between the lighting metrics calculated. The squared correlation coefficient, *r*, is calculated to express the strength of correlation between each pair of sample data. This includes human factors data, measured empirical data, and luminance-based HDR data. Linear regression is then used to express the strength and direction of the linear relationships between metrics and how they change in relation to one another. Analysis of variance (ANOVA) is used to determine if individual variables are statistically significant in improving multiple regression models.

# 3. RESULTS

## 3.1 Fixture energy consumption

The total and per-fixture energy consumption for the baseline, LLLC 1:1, and redesign solutions are shown in Table 5. The baseline showed a total daily average consumption of 5.11 Wh/ft$^2$ for all nine fixtures, with a per-fixture minimum and maximum of 0.45 Wh/ft$^2$ and 0.59 Wh/ft$^2$ respectively. Measurements and calculations are based on the standard workday period of 8:00am to 5:00pm, Monday-Friday. System #1 showed a total daily average consumption of 1.54 Wh/ft$^2$, with a per-fixture minimum and maximum of 0.08 Wh/ft$^2$ and 0.25 Wh/ft$^2$ respectively. System #2 showed a total daily average consumption of 1.18 Wh/ft$^2$, with a per-fixture minimum and maximum of 0.04 Wh/ft$^2$ and 0.26 Wh/ft$^2$ respectively. System #3 showed a total daily average consumption of 1.25 Wh/ft$^2$, with a per-fixture minimum and maximum of 0.05 Wh/ft$^2$ and 0.24 Wh/ft$^2$, respectively. System #4 showed a total daily average consumption of 1.55 Wh/ft$^2$, with a per-fixture minimum and maximum of 0.03 Wh/ft$^2$ and 0.43 Wh/ft$^2$ respectively. And the redesign solution with System #5 showed a total daily average consumption of 1.90 Wh/ft$^2$, with a per-fixture minimum and maximum of 0.02 Wh/ft$^2$ and 0.41 Wh/ft$^2$ respectively.

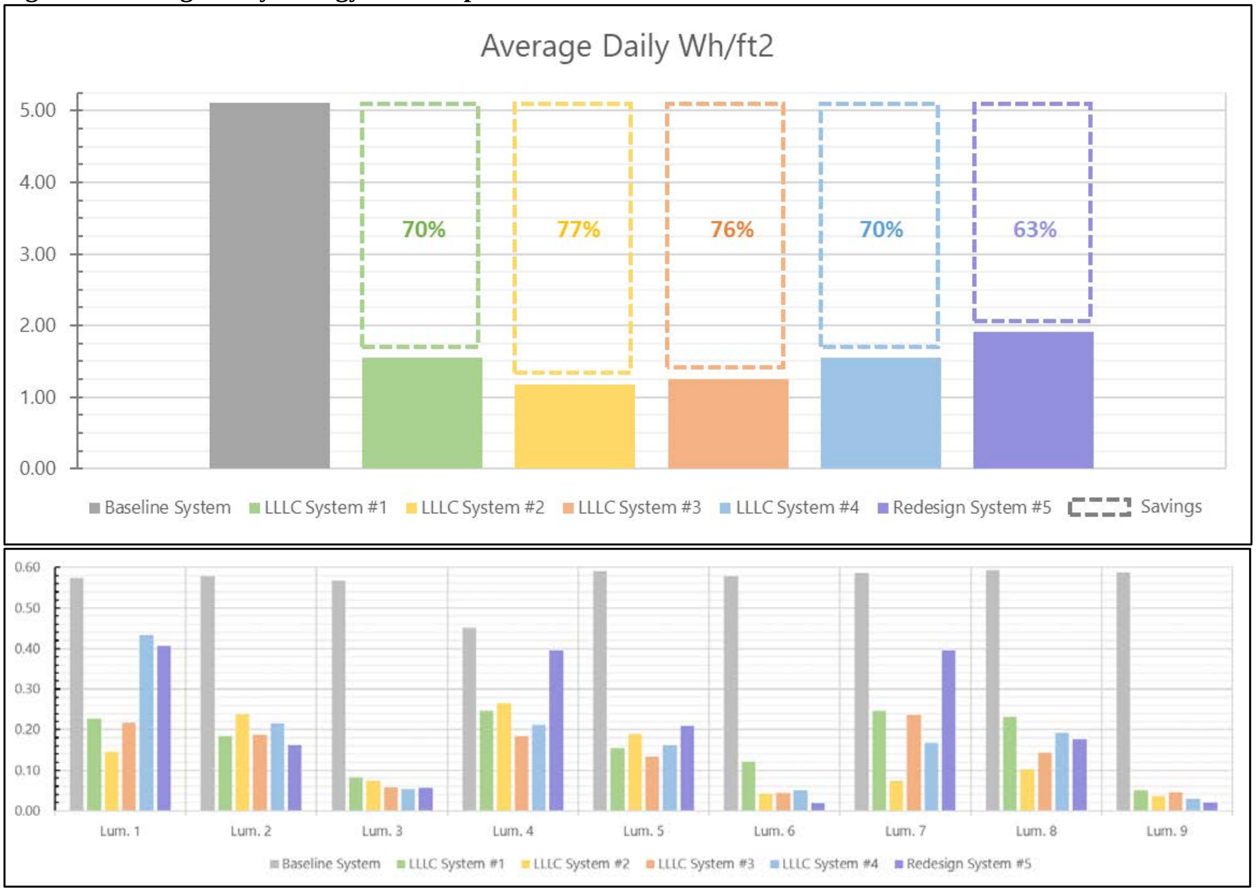
**Table 5. Average Energy Consumption**

| | ***Wh/ft$^2$*** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ***Total*** | ***Lum. 1*** | ***Lum. 2*** | ***Lum. 3*** | ***Lum. 4*** | ***Lum. 5*** | ***Lum. 6*** | ***Lum. 7*** | ***Lum. 8*** | ***Lum. 9*** |
| *Baseline* | **5.11** | 0.57 | 0.58 | 0.57 | 0.45(1) | 0.59 | 0.58 | 0.59 | 0.59 | 0.59 |
| *LLLC System #1* | **1.54** | 0.23 | 0.18 | 0.08 | 0.25 | 0.15 | 0.12 | 0.25 | 0.23 | 0.05 |
| *LLLC System #2* | **1.18** | 0.15 | 0.24 | 0.07 | 0.26 | 0.19 | 0.04 | 0.07 | 0.10 | 0.04 |
| *LLLC System #3* | **1.25** | 0.22 | 0.19 | 0.06 | 0.18 | 0.13 | 0.04 | 0.24 | 0.14 | 0.05 |
| *LLLC System #4* | **1.55** | 0.43(2) | 0.22 | 0.05 | 0.21 | 0.16 | 0.05 | 0.17 | 0.19 | 0.03 |
| *Redesign System #5* | **1.90** | 0.41 | 0.16 | 0.06 | 0.40 | 0.21 | 0.02 | 0.40 | 0.18 | 0.02 |

*Notes:* Average energy consumption (Wh/ft$^2$) totals and by individual luminaire.
[1] Baseline luminaire #4 showed a consistently lower power draw than the other fixtures.
[2] System #4 luminaire #1 needed to be tuned higher than expected (based on rated LED wattage) in order maintain the IESNA open office lighting standard.

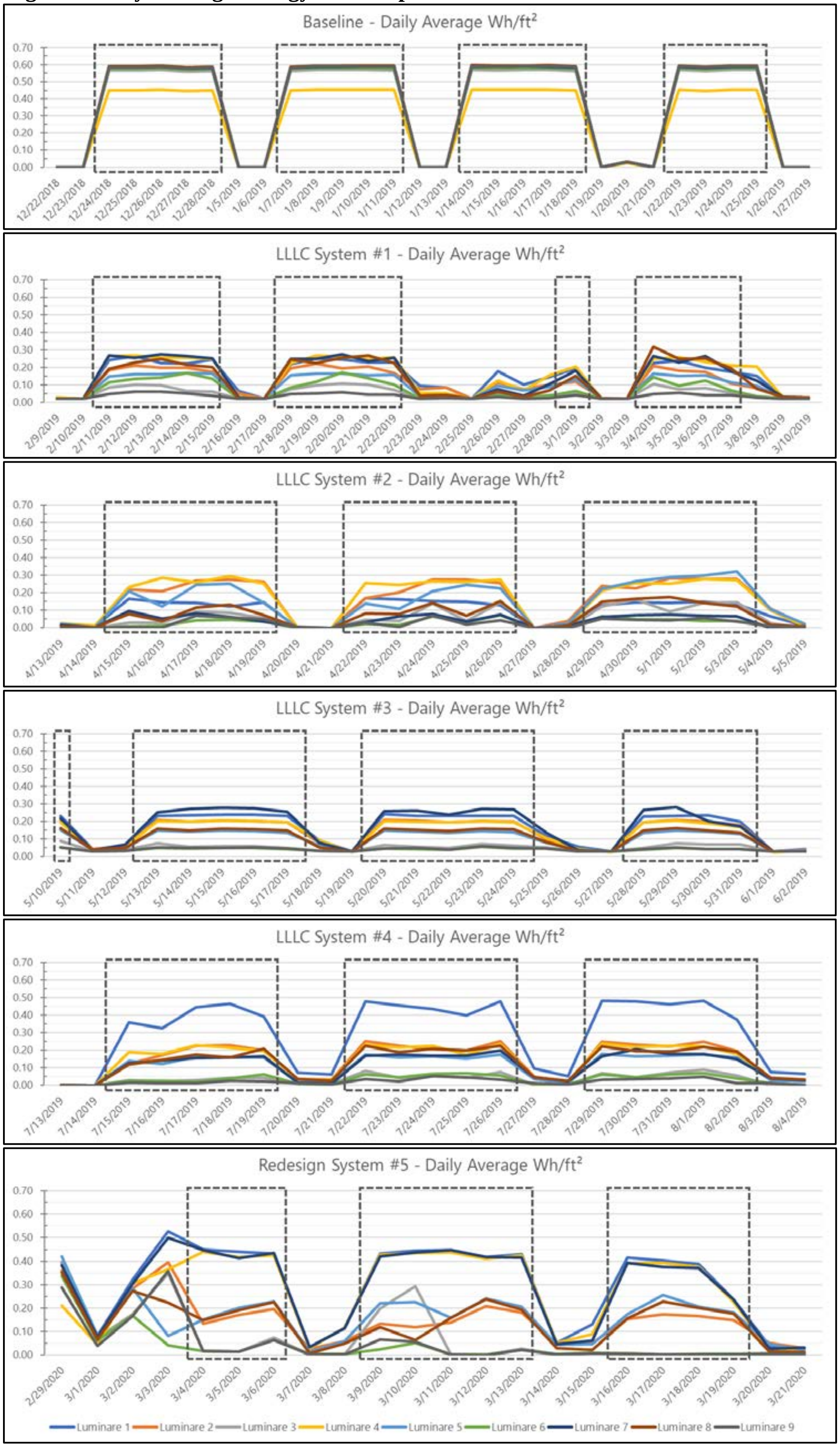
Figure 8 shows the total calculated energy saving between the baseline and each LLLC 1:1 and redesign solution, including lamp and controls upgrades. This was 70% for LLLC system #1, 77% for LLLC system #2, 76% for the LLLC system #3, 70% for LLLC system #4, and 63% for the Redesign system #5. These figures are based on the measured daily average Wh/ft$^2$ values shown in Table 5.

**Figure 8. Average Daily Energy Consumption**




The series of charts in Figure 9 show daily average energy profiles for the baseline, LLLC 1:1 retrofit solutions, and the redesign retrofit solution. Days are grouped by week and labeled on the x-axis of each chart. The baseline fixtures show consistent energy use apart from Luminaire #4 which was using approximately 80% of the energy that the other eight fixtures used, likely due to a ballast that was either different from the others or showing wear over time. The baseline fixtures had been installed in this space for some time and could be viewed as representative of real-world circumstances. The LLLC and redesign systems, by contrast, show more variability across the day and individual fixtures. This is attributed to tuning, occupancy switching, and daylight harvesting. Note that in the third week of testing System #1 1:1 LLLC system, an extreme weather event forced the closure of the University for several days resulting in a significantly different occupancy pattern. These days have been excluded from the energy calculations. Likewise, the time span of energy data collection for the System #5 was shortened by the COVID-19 coronavirus pandemic and the data affected by this event is excluded from the energy savings calculations.

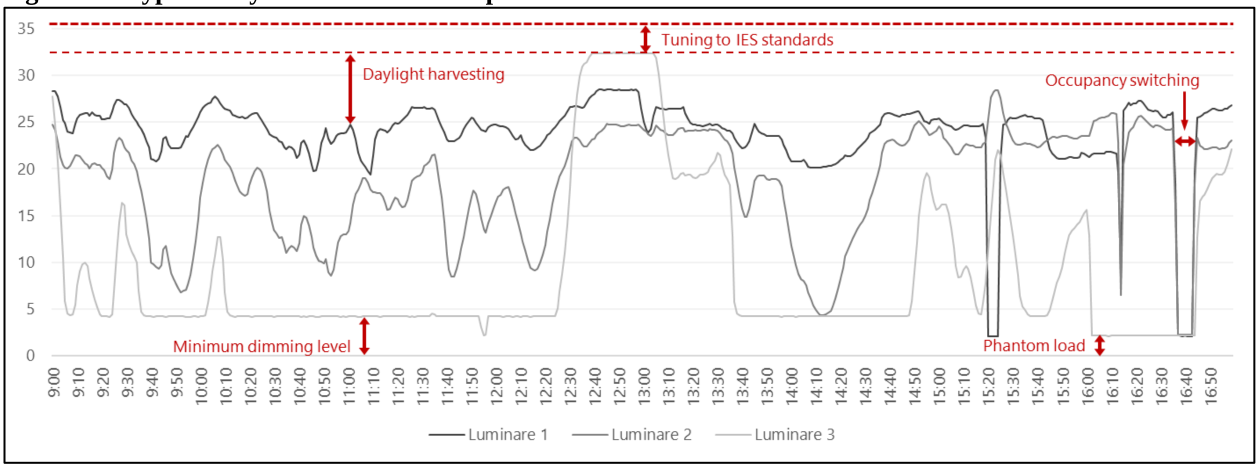
**Figure 9 Daily Average Energy Profiles per Retrofit Solution**




*Notes:* Usable data periods highlighted by dashed lines.

There are three factors responsible for the savings: occupancy switching, daylight harvesting, and tuning of high-end trim for the fixtures to meet the previously mentioned IESNA standard of adequate open-office horizontal illuminance (300 Lux). Figure 10 shows an example of these effects for fixtures #1, #2, and #3 in a north-to-south row with fixture #1 next to the window, fixture #2 in the center, and fixture #3 in the back of the space. This figure also shows that the LLLC 1:1 and redesign systems incur phantom loads while the fixtures are powered off. This includes occupancy sensing and system processing power.

**Figure 10. Typical Day Load Profile Example**




*Notes:* The graph indicates: the difference between the fixtures at full power before and after trimming; occupancy switching; daylight harvesting; the phantom load; and the minimum dimming level.

### 3.2 Annual estimated lighting energy savings

Since each system were only be observed in 3-week periods, annual measurements were not possible. The measured performance of each system was correlated with the measured outdoor conditions (sky cover and solar intensity) and applied to Typical Meteorological Year (TMY3) solar intensity data to estimate comparable annual performances of each system.

Table 6 shows the annual estimated energy savings based on the difference between the annualized performance of the baseline and each respective LLLC 1:1 and redesign retrofit solution. This calculation includes the savings contribution of the LED lamp upgrades from the fluorescent baseline. The savings of each tested system compared to the baseline are as follows: System #1 showed 70% savings, System #2 showed 75% savings, System #3 showed 73% savings, System #4 showed 72% savings, and the System #5 redesign solution showed 59%.

Calculations were performed per luminaire zone where the "*perimeter*" zone is based on fixture #3, #6, and #9; the "*middle*" zone is based on fixture #2, #5, and #8; and the "*core*" zone is based on fixture #1, #4, and #7. For the perimeter zone, System #1 showed 85% savings, System #2 showed 90%, System #3 showed 89%, System #4 showed 90%, and the System #5 redesign solution showed 84% savings. For the middle zone, System #1 showed 66% savings, System #2 showed 66%, System #3 showed 70%, System #4 showed 70%, and the System #5 redesign solution showed 65% savings. And for the core zone, System #1 showed 58% savings, System #2 showed 70%, System #3 showed 60%, System #4 showed 56%, and the System #5 redesign solution showed 28% savings.

**Table 6. Annual Estimated Lighting Energy Savings Compared to the Baseline**

| ***System*** | ***Fixture Zone**** | ***Annual Estimated Lighting Energy Savings*** | |
|---|---|---|---|
| *LLLC System #1* | Perimeter | **85%** | **70%** |
| | Middle | **66%** | |
| | Core | **58%** | |
| *LLLC System #2* | Perimeter | **90%** | **75%** |
| | Middle | **66%** | |
| | Core | **70%** | |
| *LLLC System #3* | Perimeter | **89%** | **73%** |
| | Middle | **70%** | |
| | Core | **60%** | |
| *LLLC System #4* | Perimeter | **90%** | **72%** |
| | Middle | **70%** | |
| | Core | **56%** | |
| *Redesign System #5* | Perimeter | **84%** | **59%** |
| | Middle | **65%** | |
| | Core | **28%** | |

*Notes:* Annual estimated lighting energy savings compared to the baseline including savings attributed to daylight harvesting, occupancy switching, high-end trim, and LED upgrade.
*** The fixtures were zoned as follows:** "*Perimeter*" zone is based on fixture #3, #6, and #9; "*Middle*" zone is based on fixture #2, #5, and #8; "*Core*" zone is based on fixture #1, #4, and #7.

**Table 7. Annual Estimated Lighting Energy Savings Attributed to Controls**

| ***System*** | ***Fixture Zone **** | ***Annual estimated lighting energy savings based on pre-tuning maximum energy consumption*** | | | | | |
|---|---|---|---|---|---|---|---|
| | | ***Savings due to all controls measures: daylight harvesting, occupancy switching, and high-end trim*** | | ***Savings due to daylight harvesting and occupancy switching*** | | ***Savings due to high-end trim*** | |
| *LLLC System #1* | Perimeter | **74%** | **51%** | **74%** | **45%** | **0%** | **6%** |
| | Middle | **49%** | | **37%** | | **12%** | |
| | Core | **32%** | | **25%** | | **7%** | |
| *LLLC System #2* | Perimeter | **85%** | **74%** | **75%** | **40%** | **10%** | **34%** |
| | Middle | **74%** | | **23%** | | **51%** | |
| | Core | **71%** | | **31%** | | **40%** | |
| *LLLC System #3* | Perimeter | **80%** | **50%** | **80%** | **42%** | **0%** | **8%** |
| | Middle | **45%** | | **31%** | | **13%** | |
| | Core | **25%** | | **15%** | | **10%** | |
| *LLLC System #4* | Perimeter | **86%** | **63%** | **71%** | **43%** | **15%** | **20%** |
| | Middle | **58%** | | **35%** | | **23%** | |
| | Core | **47%** | | **26%** | | **21%** | |
| *Redesign System #5* | Perimeter | **86%** | **67%** | **71%** | **32%** | **15%** | **35%** |
| | Middle | **73%** | | **23%** | | **50%** | |
| | Core | **47%** | | **7%** | | **40%** | |

*Notes:* Annual estimated lighting energy savings attributed to controls relative to the pre-tuning maximum energy consumption of each fixture and system. (Left) Savings due to all controls measures including daylight harvesting, occupancy switching, and high-end trim. (Center) Savings due to daylight harvesting and occupancy switching. (Right) Savings due to high-end trim.
*** The fixtures are zoned as follows:** "*Perimeter*" zone is based on fixtures 3, 6, and 9; "*Middle*" zone is based on fixtures 2, 5, and 8; "*Core*" zone is based on fixtures 1, 4, and 7.

Table 7 shows annual estimated lighting energy savings attributed to controls relative to the maximum energy consumption of each fixture and system before tuning. These calculations were included to quantifying the savings of each system's controls, and the savings are split into three bins, from left to right:

- Annual estimated savings including *all controls measures* (daylight harvesting, occupancy switching, and high-end trim) for System #1 showed 51% savings, System #2 showed 74% savings, System #3 showed 50% savings, System #4 showed 63% savings, and the System #5 redesign solution showed 67%.
- Annual estimated savings including *only daylight harvesting and occupancy switching* for System #1 showed 45% savings, System #2 showed 40% savings, System #3 showed 42%, System #4 showed 43%, and the System #5 redesign solution showed 32%.
- Annual estimated savings including *only high-end trim* for System #1 was 6%, System #2 was 34%, System #3 was 8%, System #4 was 20%, and System #5 was 35%.

The savings values for each zone, each system, and each savings bin are included in Table 7. The high-end trim savings values vary because the wattage rating and lumen output of each set of luminaires was different and tuning was required to meet IES standards for open-office horizontal work plane illuminance at each of the four workstations where human factors data was collected.

### 3.3 Human factors responses

The subject demographics and statistics relative to the number of participants and 2-hour samples collected during testing of each system are shown in Table 8. The number of 2-hour sessions collected for each system ranged from 22 to 36 with a total of 183 sessions. The participants pool was comprised primarily of college students between the ages of 18 and 30, with 76 total participants, 57% of which were female. Additionally, just over one-third of participants reported using vision correction.

**Table 8. Study Participant Demographics and Sample Statistics**

| | *Total # subjects* | *Female/ male* | *Age* | | | *Vision correction* | *Total # 2-hr session* |
|---|---|---|---|---|---|---|---|
| | | | *18-30* | *31-45* | *46-55* | *Y/N* | |
| *Baseline* | 8 | 4/4 | 7 | 0 | 1 | 5/3 | 22 |
| *LLLC System #1* | 16 | 8/8 | 13 | 3 | 0 | 6/10 | 34 |
| *LLLC System #2* | 12 | 7/5 | 8 | 4 | 0 | 5/7 | 28 |
| *LLLC System #3* | 10 | 7/3 | 7 | 3 | 0 | 4/6 | 34 |
| *LLLC System #4* | 15 | 8/7 | 11 | 3 | 1 | 6/9 | 36 |
| *Redesign System #5* | 15 | 9/6 | 14 | 0 | 1 | 4/11 | 29 |
| *Total* | **76** | **43/33** | **60** | **13** | **3** | **30/46** | **183** |

#### 3.3.1 Difference of means testing

Eighteen questionnaire items, a mixture of 7-point Likert scales and semantic differential scales, have been tested for difference of means: (1) between the baseline and each of the five LLLC 1:1

and redesign retrofit solutions, and (2) between the redesign retrofit solution and the four LLLC 1:1 retrofit solutions. A summary of the relevant questionnaire response items and their referenced short-form designations are shown in Table 9. The resulting differences in mean values are shown in Table 10 for each questionnaire item and each system pairing, with significant differences as determined by p-values of $p \leq .05$ highlighted.

**Table 9 Summary of Questionnaire Items Tested**

| ***Label*** | ***Questionnaire item*** | ***Scale*** | ***Options** (Low – High)* |
|---|---|---|---|
| ***P2Q7*** | Rate your current level of stress | 7-point Likert | Low stress – High stress |
| ***P2Q8*** | Rate your current level of fatigue | 7-point Likert | Low fatigue – High fatigue |
| ***P2Q9*** | I find the visual environment in this space to be… | Semantic Differential | Too Dim– Too Bright |
| ***P2Q10*** | I find the ceiling to be... | Semantic Differential | Uniform – Non-Uniform |
| ***P2Q11*** | I find the ceiling to be... | Semantic Differential | Too Dim – Too Bright |
| ***P3Q3*** | How do you perceive the lighting quality in this space, choosing between the pairs of words? | 7-point Likert | Calming – Exciting |
| ***P3Q4*** | How do you perceive the lighting quality in this space, choosing between the pairs of words? | 7-point Likert | Subdued – Stimulating |
| ***P3Q5*** | How do you perceive the lighting quality in this space, choosing between the pairs of words? | 7-point Likert | Dim – Bright |
| ***P3Q6*** | Rate your current sense of alertness using the scale provided? | 7-point Likert | Drowsy – Alert |
| ***P3Q7*** | I am satisfied with the amount of light for computer work... | 7-point Likert | Very Strongly Disagree – Very Strongly Agree |
| ***P3Q8*** | I am satisfied with the amount of light for paper-based work... | 7-point Likert | Very Strongly Disagree – Very Strongly Agree |
| ***P3Q9*** | The lighting at the workstation is distributed well... | 7-point Likert | Very Strongly Disagree – Very Strongly Agree |
| ***P3Q10*** | I am satisfied with the amount of light at the workstation for the intended work... | 7-point Likert | Very Strongly Disagree – Very Strongly Agree |
| ***P4Q2*** | How perceptible were changes in the lighting levels? | 7-point Likert | Not at all – Very |
| ***P4Q3*** | How distracting was the variation in lighting during the time you spent here? | 7-point Likert | Not at all – Very |
| ***P4Q4*** | Rate your current level of stress using the scale provided | 7-point Likert | Low stress – High stress |
| ***P4Q5*** | Rate your current level of fatigue using the scale provided | 7-point Likert | Low fatigue – High fatigue |
| ***P4Q6*** | While you were working here, were the lighting fixtures a source of discomfort? | 7-point Likert | Not at all – Very |

**Table 10. Difference of Means Values for All Questionnaire Items**

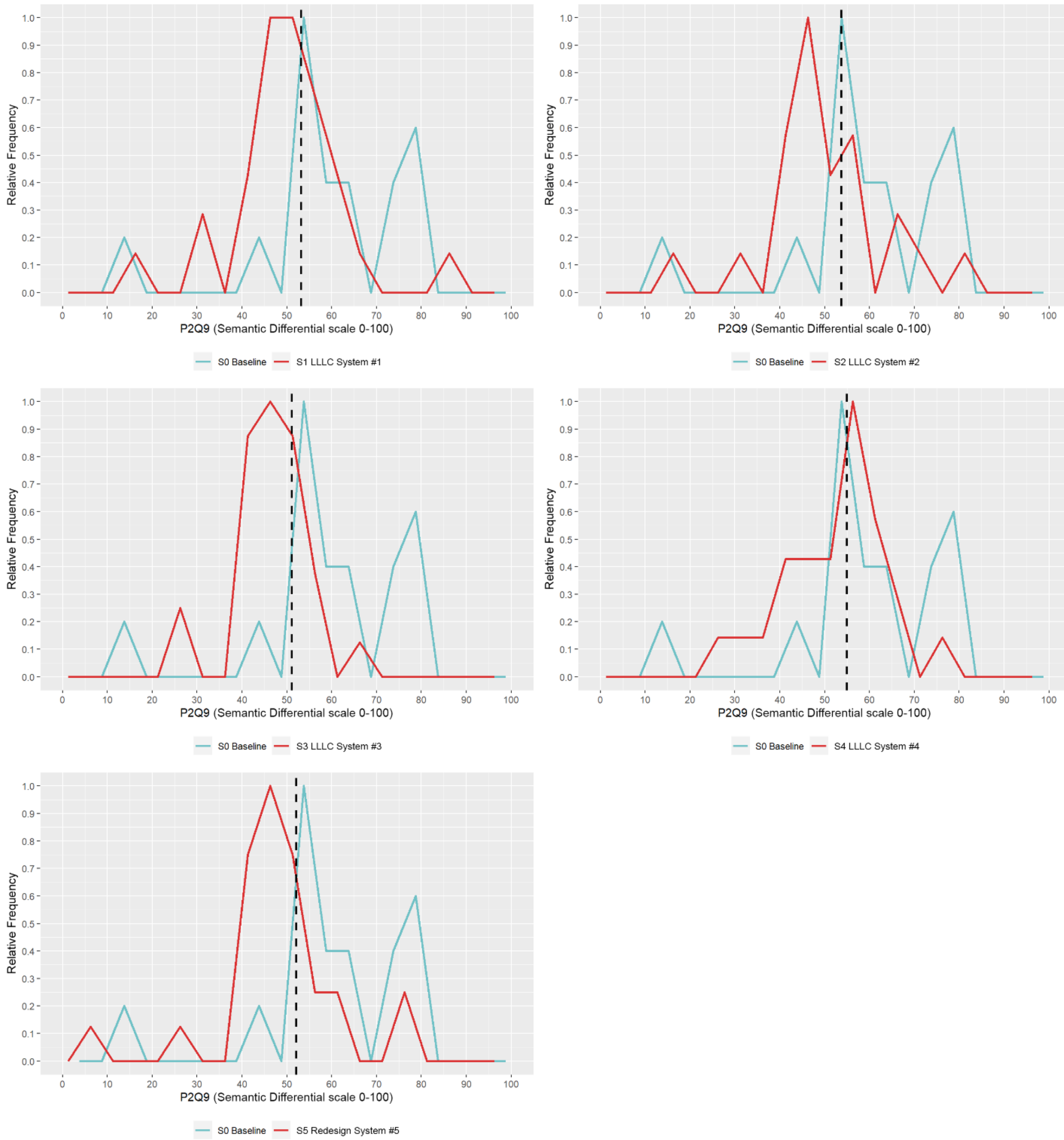
| *Data Samples* | *LLLC System #1* | *LLLC System #2* | *LLLC System #3* | *LLLC System #4* | ***Redesign System #5*** | *LLLC System #1* | *LLLC System #2* | *LLLC System #3* | *LLLC System #4* |
|---|---|---|---|---|---|---|---|---|---|
| | ***Baseline*** | ***Baseline*** | ***Baseline*** | ***Baseline*** | ***Baseline*** | ***Redesign System #5*** | ***Redesign System #5*** | ***Redesign System #5*** | ***Redesign System #5*** |
| *P2Q7* | 0.30 | -0.21 | 0.07 | -0.65 | -0.29 | -0.01 | 0.08 | 0.36 | -0.37 |
| *P2Q8* | 0.43 | 0.29 | 0.48 | 0.01 | 0.41 | 0.01 | -0.12 | 0.07 | -0.40 |
| *P2Q9* | **-12.08*** | **-12.17*** | **-15.55***** | **-9.83*** | **-14.04***** | 1.97 | 1.88 | -1.51 | 4.21 |
| *P2Q10* | 3.97 | 9.10 | **19.54*** | 14.67 | 15.50 | -11.53 | -6.40 | 4.04 | -0.83 |
| *P2Q11* | -7.16 | **-11.33*** | **-11.07*** | **-11.22*** | **-12.01*** | 4.85 | 0.68 | 0.94 | 0.79 |
| *P3Q3* | **-0.90***** | **-0.67*** | -0.35 | **-1.00***** | **-0.64*** | -0.26 | -0.04 | 0.28 | -0.36 |
| *P3Q4* | **-1.14***** | **-1.02***** | **-1.03***** | **-1.43***** | **-1.19***** | 0.04 | 0.17 | 0.16 | -0.25 |
| *P3Q5* | **-0.73***** | **-0.68***** | **-0.94***** | **-0.88***** | **-1.05***** | 0.32 | 0.37 | 0.11 | 0.17 |
| *P3Q6* | **-0.93***** | -0.47 | **-0.72***** | **-0.75***** | -0.39 | **-0.54*** | -0.08 | -0.33 | -0.37 |
| *P3Q7* | 0.32 | 0.57 | **0.66*** | 0.22 | 0.62 | -0.30 | -0.05 | 0.03 | -0.40 |
| *P3Q8* | 0.35 | 0.27 | 0.50 | 0.37 | -0.11 | 0.46 | 0.38 | **0.62*** | 0.49 |
| *P3Q9* | **0.84***** | **0.96***** | **1.04***** | 0.46 | 0.37 | 0.47 | **0.59*** | **0.67*** | 0.09 |
| *P3Q10* | **0.63*** | **0.67*** | **0.95***** | 0.41 | 0.61 | 0.02 | 0.06 | 0.34 | -0.20 |
| *P4Q2* | 0.61 | 0.21 | 0.00 | 0.35 | 0.14 | 0.48 | 0.08 | -0.13 | 0.21 |
| *P4Q3* | -0.11 | -0.40 | -0.43 | 0.05 | -0.26 | 0.15 | -0.13 | -0.17 | 0.32 |
| *P4Q4* | -0.18 | -0.19 | -0.24 | -0.46 | 0.24 | -0.42 | -0.43 | -0.48 | -0.69 |
| *P4Q5* | 0.81 | 0.08 | 0.41 | 0.16 | 0.39 | 0.42 | -0.32 | 0.02 | -0.23 |
| *P4Q6* | NA | NA | NA | NA | NA | -0.30 | **-0.55*** | -0.20 | -0.16 |

*Notes:* Comparing each LLLC 1:1 and redesign solution to the baseline (Left) and comparing each LLLC 1:1 solution to the redesign solution (Right). Significant differences of $p \leq .05$ resulting from Welch two-sample t-tests are bolded and highlighted with the level of significance noted as follows:
*** denotes a 5% level of significance (p ≤ .05);**
**** denotes a 1% level of significance (p ≤ .01);**
***** denotes a 0.1% level significance (p ≤ .001).**

One of three questionnaire items that include significant differences across all LLLC 1:1 and redesign retrofit solutions is item P2Q9, "*I find the visual environment in this space to be...*", with responses varying continuously between "*Too dim*" and "*Too bright*", and a midpoint marked in-between on a semantic differential scale (0-100). This question is asked at the start of a subject's session and as such represents an initial impression. The baseline system is rated somewhat higher than the LLLC and redesign systems as shown in Figure 11, where the dashed line marks the mean across all responses. This result may be driven by the fact that the LLLC systems were tuned to IES standards for open office horizontal illuminance (300 Lux) and were providing less light than the baseline system. It is likely that ballast dimming due to daylight harvesting played a role here as well.

This trend is extended to additional questionnaire items including P2Q11, "*I find the ceiling to be...*", with responses varying continuously between "*Too dim*" and "*Too bright*" along a semantic differential scale. This question is also asked at the start of a subject's session and all retrofit solutions except one show significant difference compared to the baseline. This question draws attention to the ceiling brightness and the quality of the indirect component of each system.

**Figure 11. Welch Two-sample T-test for Questionnaire Item P2Q9**




*Notes:* Welch two-sample t-test, p-values for questionnaire item P2Q9,
"I find the visual environment in this space to be [Too dim – Too bright]", semantic differential scale (0-100) with the dashed line marking the mean value of all responses. The baseline condition is compared to each retrofit solution.
Left-to-right, top-to-bottom:
LLLC System #1, p = 0.016; LLLC System #2, p = 0.018;
LLLC System #3, p = 0.002; LLLC System #4, p = 0.044;
Redesign System #5, p = 0.007

The relationships shown by P2Q9 and P2Q11 are also seen in questionnaire item P3Q5, which is another item that includes significant differences across all five retrofit solutions when compared to the baseline. This item asked, "*How do you perceive the lighting quality in this space, choosing between the pairs of words?*" and allowed responses on a 7-point Likert scale varying between (1) "*Dim*" and (7) "*Bright*". However, this question is part of the visual comfort assessment, as described in Section 2.2, and sampled more frequently than either P2Q9 or P2Q11. As such this questionnaire item provides a larger sample size, while corroborating the trends of items P2Q9 and P2Q11.

Questionnaire items P3Q3 and P3Q4 are related to P3Q5 and share the same question format with different allowed responses for the 7-point Likert scale. P3Q3 varies between (1) "*Calming*" and (7) "*Exciting*" and shows significant differences for all retrofit solutions except one, suggesting that LLLC 1:1 and redesign solutions are considered more calming than the baseline. Item P3Q4 is yet another item that includes significant differences across all five retrofit solutions and varies between (1) "*Subdued*" and (7) "*Stimulating*", which suggests that LLLC 1:1 and redesign solutions are consistently considered more subdued compared to the baseline.

Questionnaire items P3Q9 and P3Q10 show significant differences for three of the four LLLC 1:1 retrofit solutions only, with the redesign solution just on the edge of significance for P3Q10. Item P3Q9 "*The lighting at the workstation is distributed well...*" allowed responses on a 7-point Likert scale varying between (1) "*Very Strongly Disagree*" and (7) "*Very Strongly Agree*" and may suggest that LLLC 1:1 retrofit solutions provide a better sense of lighting distribution at the workstation compared to the baseline. Similarly, item P3Q10 "*I am satisfied with the amount of light at the work station for the intended work...*" allowed responses on a 7-point Likert scale varying between (1) "*Very Strongly Disagree*" and (7) "*Very Strongly Agree*" and may suggest that LLLC 1:1 retrofit solutions provide a better sense of satisfaction with the amount of light available at the workstation.

One of the LLLC 1:1 retrofit solutions also showed significant differences for questionnaire items P2Q10 and P3Q7, which focus on light uniformity on the ceiling and satisfaction with the amount of light available for computer work, respectively. This suggests that the retrofit solution in question had less uniformity at the ceiling, but higher satisfaction with the amount of light available for vertical tasks like computer monitor screens.

The comparison of the redesign retrofit solution with the LLLC 1:1 retrofit solutions yielded few questionnaire items with significant differences. Items P3Q6, P3Q8, and P4Q6 each show one LLLC 1:1 solution with significance, while P3Q9 shows two. Item P3Q9 stated, "*The lighting at the workstation is distributed well...*" and allowed responses on a 7-point Likert scale varying between (1) "*Very Strongly Disagree*" and (7) "*Very Strongly Agree*". This could suggest that select LLLC 1:1 retrofit solutions show stronger agreement in human subjects' rating of lighting distribution on the workstation compared to the redesign retrofit solution. Item P3Q8 stated, "*I am satisfied with the amount of light for paper-based work...*" and allowed responses on a 7-point Likert scale varying between (1) "*Very Strongly Disagree*" and (7) "*Very Strongly Agree*". This could suggest that a select LLLC 1:1 retrofit solution shows stronger agreement in human subjects' rating of adequate lighting for paper-based work. Item P3Q6 stated, "*Rate your current sense of alertness using the scale provided?*" and allowed responses on a 7-point Likert scale varying between (1) "*Very Strongly Disagree*" and (7) "*Very Strongly Agree*". While it did not show high significance for all but one retrofit solution, it may suggest that a select LLLC 1:1 retrofit solution shows stronger agreement in human subjects' increased alertness during testing. And lastly, item P4Q6 asked, "*While you were working here, were the lighting fixtures a source of discomfort?*" and allowed responses on a 7-point Likert scale varying between (1) "*Not at all*" and (7) "*Very* ". This item was added mid-testing to try and capture possible instances of glare induced by the LLLC 1:1 and redesign systems. As such, it is a missing data point for the baseline condition. However, a significant difference was found between one LLLC 1:1 retrofit solution and the redesign retrofit solution that may suggest a select LLLC 1:1 retrofit solution shows a lower human factors' rating of fixture-borne discomfort.

### 3.3.2 Statistical correlation testing

A Pearson correlation was performed on the combined set of all collected data, including empirical, energy, and human factors questionnaires. There were few empirical metrics that stood out against the questionnaire data to any significant degree. No metrics were identified as common across all retrofit solutions as the correlation values fluctuated substantially among them. Table 11 shows selected metrics with top-performing squared correlation coefficients. The luminance-based metrics highlighted in gray have shown promise in previous studies [9, 10], although based on human factors rating of visual comfort with daylighting as the primary light source. And those highlighted in yellow are metrics that focus on the window area of each HDR image as shown by *Mask 02* in Figure 7.

**Table 11. Top 15 Squared Correlation Coefficients Across Systems and Questionnaire Items**

| ***System*** | ***Qu. item*** | ***Luminance-based metric*** | $_{adj}r^2$ |
|---|---|---|---|
| *Redesign System #5* | P4-P4Q6 | Average Luminance of Windows Glare Sources (Mask 02) | **0.51** |
| *LLLC System #4* | P4-P4Q3 | Experimental Unified Glare Rating of Windows (Mask 02) [11] | **0.44** |
| *LLLC System #2* | P2-P2Q11 | Daylight Glare Probability of Scene (Mask 01) | **0.42** |
| *LLLC System #2* | P3-P3Q5 | Standard Deviation of 60° Field of View Luminance (Mask 21) | **0.42** |
| *Redesign System #5* | P4-P4Q6 | Experimental Unified Glare Rating of Windows (Mask 02) [11] | **0.40** |
| *LLLC System #2* | P2-P2Q11 | Mean Luminance of 40° Horizontal Band (Mask 20) | **0.40** |
| *LLLC System #2* | P3-P3Q5 | Coefficient of Variation of 60° Field of View Luminance (Mask 21) | **0.38** |
| *LLLC System #2* | P2-P2Q11 | Mean Luminance of Scene (Mask 01) | **0.37** |
| *LLLC System #2* | P2-P2Q11 | Vertical Illuminance of 40° Horizontal Band (Mask 20) | **0.37** |
| *LLLC System #2* | P2-P2Q11 | Standard Deviation of 40° Horizontal Band Luminance (Mask 20) | **0.33** |
| *Redesign System #5* | P4-P4Q6 | Maximum Luminance of 40° Horizontal Band (Mask 20) | 0.32 |
| *LLLC System #4* | P4-P4Q2 | Experimental Unified Glare Rating of Windows (Mask 02) [11] | 0.32 |
| *LLLC System #2* | P3-P3Q5 | Mean Luminance of 60° Field of View (Mask 21) | 0.31 |
| *LLLC System #2* | P2-P2Q11 | Standard Deviation of Scene Luminance (Mask 01) | 0.30 |
| *LLLC System #1* | P4-P4Q2 | Coefficient of Variation of 40° Horizontal Band Luminance (Mask 20) | 0.30 |

*Notes:* Luminance-based metrics identified in previous visual comfort research are highlighted in gray.
Glare metrics based on the window area of the HDR data are highlighted in yellow.

The most common metrics primarily involved ratios of extreme luminance values for low light and bright light, which were often beyond the measured output capacities of the LED luminaires.

This could suggest that sky brightness may have indirectly influenced human factors' responses. The top two plot of Figure 12 show a pair of glare and brightness metrics calculated from the redesign solution subset of testing data and correlated to questionnaire item P4Q6, "*While you were working here, were the lighting fixtures a source of discomfort?*", that seem to support this assumption.

*Luminance of Window Glare Sources* is a glare metric derived from luminance-based HDR data by isolating the window area in each HDR image, see *Mask 02* in Figure 7, and focused on identifying potentially glaring sources via the glare calculation software *evalglare*. This metric is shown in the top-left plot of Figure 12 and correlated to questionnaire item P4Q6 with a relatively strong ${}_{adj}r^2$ value of 0.51.

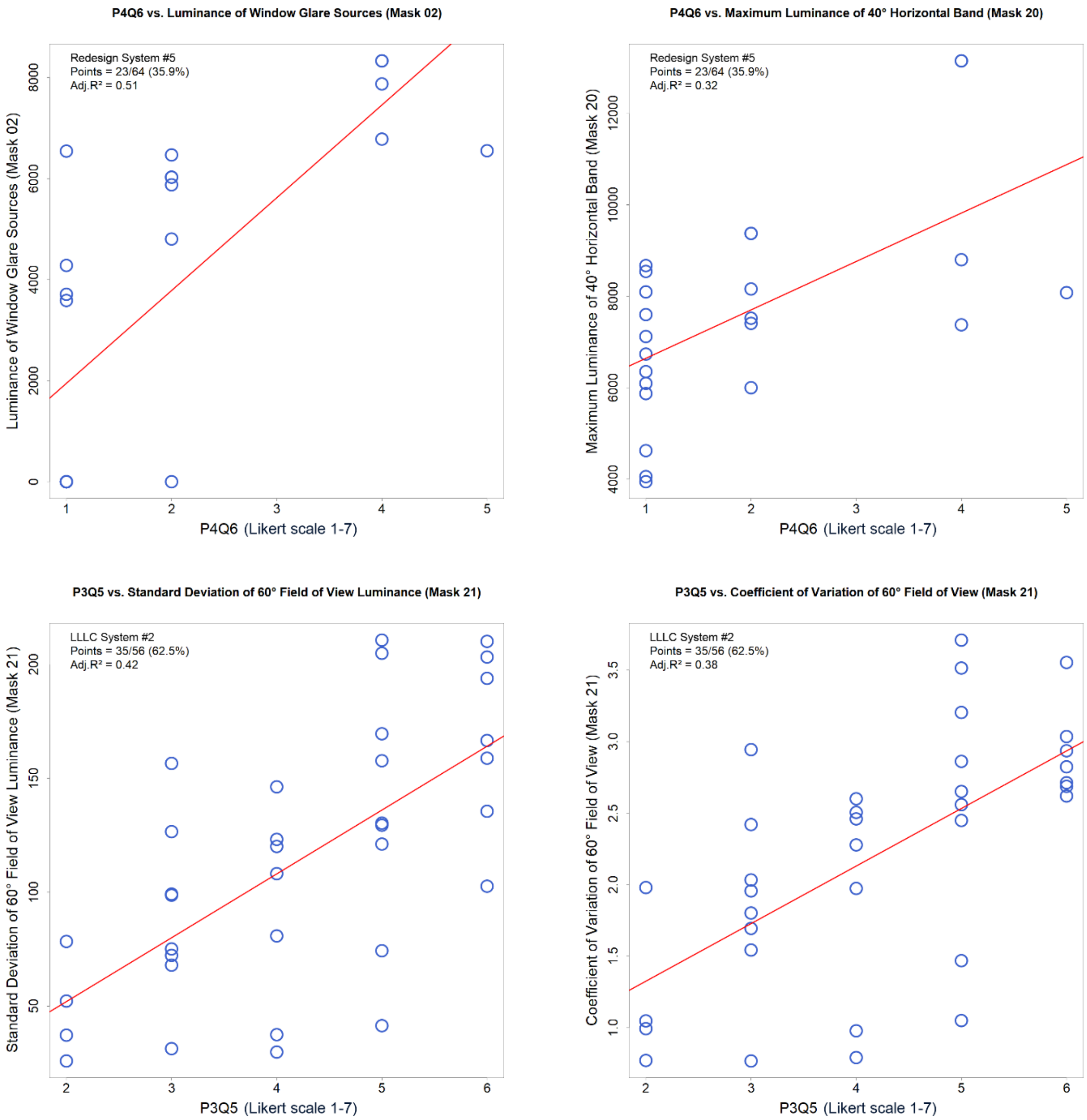
*Maximum Luminance of 40° Horizontal Band* is a simple brightness metric, also derived from luminance-based HDR data, that considers maximum luminance within the horizontal 40° band of human vision, see *Mask 20* in Figure 7. This metric is shown in the top-right plot of Figure 12 and correlated to questionnaire item P4Q6 with an ${}_{adj}r^2$ value of 0.32. It is worth noting that most recorded luminance values for both metrics are quite high compared to the output capacity of the LED luminaires used in this study.

The bottom two plots of Figure 12 show a pair of brightness metrics calculated from an LLLC 1:1 retrofit solution subset of testing data and correlated to questionnaire item P3Q5, "*How do you perceive the lighting quality in this space, choosing between [Dim - Bright]?*", which tracked human subjects' perception of light availability in 2-hour intervals over the course of their testing sessions. The brightness metrics were extracted from luminance-based HDR data by applying a 60° field of view mask, see *Mask 21* in Figure 7. This mask effectively excluded the north-facing windows, while including some of the lighting fixtures and focused on the front-facing 60° field of the human subjects' field of view from workstations #1 and #4. These metrics may provide some counterweight to the *Luminance of Window Glare Sources* and *Maximum Luminance of 40° Horizontal Band* metrics and the implication that daylight may have indirectly influenced human factors' responses.

*Standard Deviation of 60° Field of View Luminance* is a measure of the variation, or dispersion, of luminance within the 60° field of view. A high value indicates that there is a wide spread of luminance in the field of view and possibly an increase in contrast that may lead to glare issues. A low value indicates that the luminance spread is closer to the mean and likely reduces contrast glare. This metric is shown in the bottom-left plot of Figure 12 and correlated to questionnaire item P3Q5 with a relatively strong ${}_{adj}r^2$ value of 0.42.

*Coefficient of Variation of 60° Field of View* is derived as a ratio of the standard deviation and mean values that expresses luminance variability within the 60° field of view as a normalized percent value. This metric is shown in the bottom-right plot of Figure 12 and correlated to questionnaire item P3Q5 with an ${}_{adj}r^2$ value of 0.38.

**Figure 12. Linear Regression Analysis of Questionnaire Items P4Q6 and P3Q5**




*Notes:* Linear regression and adjusted $r^2$ values for the redesign solution (top) and questionnaire item P4Q6 "While you were working here, were the lighting fixtures a source of discomfort?"; an LLLC 1:1 retrofit solution (bottom) and questionnaire item P3Q5 "How do you perceive the lighting quality in this space, choosing between [Dim - Bright]?"; as correlated to metrics derived from luminance-based HDR data:
Top-left: "Luminance of Window Glare Sources" (Mask 02)" ${}_{adj}r^2 = 0.51$
Top-right: "Coefficient of Variation of 40-degree Horizontal Band" (Mask 20)" ${}_{adj}r^2 = 0.32$
Bottom-left: "Standard Deviation of 60-degree Field of View Luminance" (Mask 21)" ${}_{adj}r^2 = 0.42$
Bottom-right: "Coefficient of Variation of 60-degree Field of View" (Mask 21)" ${}_{adj}r^2 = 0.38$

### 3.4 Equipment and labor costs

A summary of costs is shown in Table 12. The retail quotes for hardware associated with each retrofit solution were provided by either a local electrical supplier in Eugene, OR, or the respective manufacturer. Each retrofit solution is based on 9 total fixtures. Labor costs are calculated based on UO personnel rates and account for equipment install, programming, and commissioning of each retrofit solution. Shipping costs are omitted as they are location specific.

**Table 12. Total Cost Comparison of All Retrofit Solutions**

| *System* | *Hardware total* | *Luminaire per unit* | *Labor* | *Design/ Specification* | *Total cost* | *Total cost/ft²* |
|---|---|---|---|---|---|---|
| *LLLC System #1* | $4,181.00 | $380.00 | $1,045.00 | $252.76 | **$5,383.76** | **$6.04** |
| *LLLC System #2* | $4,204.77 | $410.00 | $1,536.15 | $379.14 | **$6,120.06** | **$6.87** |
| *LLLC System #3* | $4,455.43 | $490.00 | $1,163.75 | $1,011.04 | **$6,630.22** | **$7.44** |
| *LLLC System #4* | $4,015.96 | $403.00 | $760.00 | $631.90 | **$5,407.86** | **$6.07** |
| *Redesign System #5* | $8,347.07 | $389.00 | $1,654.90 | $5,655.80 | **$15,657.77** | **$17.57** |

# 4. DISCUSSION

### 4.1 Install and programming

Significant logistical issues were encountered during equipment acquisition, as noted in Section 2.2.7, which took substantial time to resolve due to communication complications and delays along the supply chain. Additionally, on two occasions, the LED fixtures did not match specifications and fixtures needed to be sent back to the manufacturer. However, once the fixtures and controls hardware were in-hand, no major issues were encountered during bench-testing and install. All components were in working order out of the box, but some did include specific defects. These issues were able to be addressed by the UO electrician and/or research staff on-site and included instances of plate separation of the LED fixture housing, dented sensor lenses, and missing screws.

Install of fixtures and controls hardware was completed without delays. Programming time varied since each control system uses different methods such as remote controls, mobile apps, and BAS-compatible NLC software that requires a PC or MAC. While each programming method was more than manageable, some difficulties were encountered. For example, using a remote control was relatively time-consuming since each fixture needed to be trimmed and adjusted individually. Scaling of this approach to larger spaces would be problematic. This is also applicable to mobile apps, but they tend to be more flexible depending on design and functionality. This study encountered two such examples. One app was effortless to use, without issues, and with expedient programming; and another that suffered from interface issues/bugs, lacked technical/troubleshooting documentation, and required a substantial amount of time to complete system programming. LLLC System #2 was an example of the latter case and required a multi-day effort by the UO electrician to troubleshoot the associated app software and programming sequence. This process consisted mainly of a trial and error methodology while simultaneously reaching out to the manufacturer technical support. As shown in Table 3, this was reflected in the programming time with System #2 taking roughly 2 hours and 45 minutes to complete, while the other three LLLC 1:1 systems ranged between 30-45 minutes and the Redesign System #5 required 2 hours and 35 minutes. The BAS-compatible NLC software was relatively complex compared to the other control systems with a steeper learning curve and required a moderate amount of programming time, partly because lighting fixtures and controls components needed individual attention for trimming, zoning, and calibration. Even so, the software was reliable, well-supported, and came partially pre-programmed by the manufacturer.

Connectivity was consistent for all systems without major issues. In each case, fixtures were able to recognize and reliably communicate with one another, as well as any additional controls peripherals like communication hubs. The only minor exceptions include the remote-control programming tool that needs specific proximity and orientation to fixtures it is engaging with, and the redesign solution's BAS-compatible NLC software that requires a wired ethernet or secured Wi-Fi connection to access the software interface. This may also apply to the mobile apps, though mobile phones tend to have access to mobile networks as well.

### 4.2 Cost comparison

The cost difference is well in favor of the LLLC 1:1 retrofit solutions, ranging from $\$6.04/ft^2$ to $\$7.44/ft^2$, compared to $\$17.57/ft^2$ for the redesign retrofit solution. This includes hardware costs and labor consisting of design, specification, and install costs. Design costs were based on consulting provided by a third-party lighting design firm along with internal design work by research staff with considerable design and research experience in this area.

### 4.3 Fixture energy consumption statistics

The introduction of high-efficiency LED fixtures outperformed the existing baseline T8 fixtures, as expected, reducing the lighting energy consumption. The reported savings are well within the range found in previous research that shows savings ranging from 43% to 82% in an office environment. [12] It is worth noting that the occupancy patterns of the ESBL and its test space are unique as a research lab and may deviate from a typical open office space type.

It is also important to note that luminaire tuning introduces modest variance in the power draw on a per-fixture basis. This was necessary to equalize the horizontal illuminance at the work plane of the workstations among the different retrofit solutions.

### 4.4 Energy savings statistics

The energy savings statistics confirm that LLLC LED fixtures can net significant savings over fluorescent T8 fixtures across the four LLLC 1:1 solutions and the redesign solution. The four LLLC 1:1 systems reported savings ranging from 70% to 77% while the redesign system reported savings of 63%. Additionally, the per-fixture calculations can be used for a more detailed analysis, such as isolating the perimeter fixtures from the core zone. In this instance we see savings between 85% and 92% near the north-facing facade, while the core shows savings between 28% and 87%. This gives some insight into the savings potential of daylight harvesting in addition to the high-efficiency lamp upgrades.

Annualized estimated lighting energy savings confirm the same trends as the monitored data when compared against the baseline, with total savings ranging from 70% to 75% for the LLLC 1:1 solutions and 59% for the redesign solution. Looking at the per-zone savings shows that the perimeter and middle zones had comparable performance between the LLLC 1:1 and redesign solutions. The perimeter zones ranged from 85% to 90% savings for the LLLC 1:1 systems, while the redesign system showed 84%. The middle zones ranged from 66% to 70% savings for the LLLC 1:1 systems, while the redesign system showed 65%. On the other hand, the core zones show a significant difference in favor of the LLLC 1:1 solutions, with the LLLC 1:1 systems ranging from 56% to 70% savings, while the redesign system showed 28%. This is partly due to the fact that the redesign solution employed a zoning strategy that did not include a third daylight harvesting zone for the luminaires furthest from the north facade (the core zone), as daylight harvesting zoning was not considered beyond a section depth of 2x the head-height of the perimeter windows for the redesign of the test space.

Additional energy savings were estimated that focus specifically on the annual energy savings attributed to controls performance. These calculations were based on the maximum, pre-tuning energy consumption of each LLLC 1:1 and redesign solution to quantify the daylight harvesting, occupancy switching, and high-end trim savings of each system. Considering all three controls measures the System #5 redesign solution showed 67% savings with System #2 as the only 1:1 system to show higher savings of 74%. However, it is important to note the savings impact of the high-end trim, which varied by system due to specification differences between systems and luminaires, as shown in Table 1. This effect is particularly evident when comparing the core and middle zone savings of all controls measures, as seen in Table 7 (*Left*), versus the savings of only the active controls portions (daylight harvesting and occupancy switching), as seen in Table 7 (*Center*). For example, high-end trim accounts for 40% of System #2 core zone savings (71% to 31%) and 40% of System #5 redesign core zone savings (47% to 7%). Likewise, high-end trim accounts for 51% of System #2 middle zone savings (74% to 23%) and 50% of System #5 redesign middle zone savings (73% to 23%). While these are the highest instances, the remainder of systems and zones are certainly not insignificant, as seen in Table 7 (*Right*).

To get a better sense of the active portion of the controls, savings attributed to daylight harvesting and occupancy switching were separated in Table 7 (*Center*) and show a pattern like the measured estimated total energy savings in Table 6. The LLLC 1:1 solutions range from 40% to 45% savings while the redesign solution shows 32% savings. Looking at the per-zone savings, the perimeter and middle zones were relatively close and consistent between the LLLC 1:1 and redesign solutions. The 1:1 perimeter zone savings ranged from 71% to 80%, with 71% for the redesign. The 1:1 middle zone savings ranged from 23% to 37%, with 23% for the redesign. Meanwhile, the 1:1 core zones ranged from 15% to 31%, while the redesign showed 7%. The wider range of savings among the LLLC 1:1 systems is attributable to the unique programming and operation of each system. However, the lower value of the redesign solution is also influenced by its different luminaire zoning/grouping strategy. Each 1:1 luminaire is individually controlled with integrated daylight harvesting and occupancy sensors, while the redesign approach uses a comprehensive NLC system that allows for grouping of multiple luminaires and assignment of those groups to individual daylight harvesting and occupancy sensors. As such, the redesign solution included a core zone of three luminaires that were beyond the defined daylit perimeter, as seen in Figure 3. This difference in core zone savings highlights the potential of employing daylight harvesting beyond the daylit perimeter.

### 4.5 Human factors comfort responses

We interpret that satisfaction with light level responses may have been influenced by the LLLC systems being tuned to IES standards. This raises the issue that because LED fixtures are easily tunable and many LLLC systems are capable of providing building owners and operators with control of high-end trim, it needs to be understood that if given the opportunity users may change the trim to increase illumination, thus negating one of the energy-saving features of LLLC systems. Similar logic may apply to occupancy switching and daylight dimming. For this study participants were not allowed access to manual switching.

The LLLC 1:1 retrofit solutions showed consistent improvement over the baseline condition across eight different human factors' questionnaire items, which dealt with a range of factors as presented in Section 3.3.1. Overall spatial brightness was found to be lower because the luminaires were trimmed to satisfy the recommended IES standard for open office horizontal illuminance at the work plane (300 Lux). This was also the case for ceiling brightness. LLLC 1:1 light quality was also rated more calming and subdued than the baseline, while subjects also reported feeling a higher sense of alertness. They also reported higher satisfaction with light distribution at the workstation and the amount of light available for the intended work, which was defined as computer and/or paper tasks. The redesign system followed a similar trend with five of these same factors, while significant differences were not found for level of alertness, distribution of light at the workstation, and satisfaction with the amount of light available for the intended work.

The comparison between LLLC 1:1 retrofit solutions and the redesign solution did not provide definitive evidence of significant difference. However, there were three singular instances for three questionnaire items and two instances for a fourth questionnaire item that showed some contrast, as seen in Table 10. The three singular instances showed that (1) the redesign solution showed a higher rated level of participant alertness, while (2) an LLLC 1:1 solution showed higher satisfaction with the amount of light available for paper-based tasks and (3) another LLLC 1:1 solution showed lower rating of lighting fixtures as a source of discomfort during testing. And lastly, two LLLC 1:1 solutions showed higher ratings of satisfactory lighting distribution at the workstation.

### 4.6 Statistical correlation

The statistical analysis revealed that the HDR data was the main source of significant correlations against the human factors questionnaire items. Metrics that isolated the glazing area of the HDR images suggest that the north-facing windows may have had an influence on the participants' discomfort ratings during testing. However, when considering metrics that *exclude* the glazing areas, such as the front-facing 60° field of view (see *Mask 21* in Figure 7), a correlation between measured light intensity in the space and human factors rating of brightness remains relatively strong. While this did not rule out the luminaires as a source of discomfort, the correlations did not suggest it either.

# 5. CONCLUSIONS

The energy analysis showed significant overall savings provided by the LLLC 1:1 and redesign retrofit solutions compared to the baseline, while the LLLC 1:1 solutions also showed 7% to 14% more savings compared to the redesign solution. The estimated annual lighting energy savings, as compared to the baseline, also showed LLLC 1:1 solutions with 11% to 16% more savings. However, the difference in luminaire zoning/grouping strategy between the LLLC 1:1 and redesign solutions contributed to this difference, where the redesign core zone was beyond the daylit perimeter and did not include daylight harvesting. Likewise, it could be argued that the LLLC 1:1 solution was inherently a more suited approach given the scale of the test space used in this study.

The estimated annual savings attributed to all controls measures was relatively even. As previously discussed, this included daylight harvesting, occupancy switching, and high-end trim. One LLLC system showed 7% more savings than the redesign solution, while the remaining four systems ranged between 4% and 17% less. However, the high-end trim did introduce significant variability due to the varied nature of equipment specification for each system and set of luminaires. Therefore, additional savings were calculated to account for only the active controls portions of each system (daylight harvesting and occupancy switching). These values showed LLLC systems with consistently higher savings compared to the redesign, ranging from 8% to 13% more savings. It is worth restating that the difference in luminaire zoning/grouping strategy contributed to this difference as well. Though it is also worth pointing out the implicated value of daylight harvesting beyond the daylit perimeter, which is often left unrealized and in this case amounts to an additional 8% to 24% savings.

The human factors data do not show a distinct difference between LLLC 1:1 and redesign retrofit solutions. The fact that both are performing on relatively even terms when compared to the baseline condition provides, at minimum, reasonable confidence in equity of overall light and controls quality.

The statistical analysis did not reveal consistent and comparable metrics that applied across all retrofit solutions, but there are some that showed correlations between measured light variance in the test space and the human factors' rated discomfort and variation in lighting during testing. The strongest of these correlations showed that the window luminance variance corresponded with human factors ratings of discomfort taken at the end of a subject's test session. As such, even though potential glare was indicated it is unlikely that the luminaires were the source.

Overall, these findings support the value of LLLC systems as cost-competitive 1:1 retrofit alternatives that provide comparable performance to more comprehensive NLC redesign solutions. However, since this study was performed in a single space representative of an 891ft$^2$ open office we recommend a larger study to confirm these findings are valid at larger scale and sample size. This is also dependent on the scope of the LLLC system and its compatibility with more comprehensive building automation and/or building management systems. In this case the "*clever*" and "*smart*" classifications were used to distinguish input/output and feedback capabilities between these systems (one-way or two-way communication).

Standardized cognitive testing was not included in this study and could be a valuable part of further study.

## 6. FUNDING

Funding for this project is provided by the Northwest Energy Efficiency Alliance.

## 7. ACKNOWLEDGEMENTS

The authors would like to acknowledge the efforts of the University of Oregon Facilities and Maintenance in providing consulting and assistance with installation and wiring of the tested LLLC systems. We would also like to thank the wider lighting and controls industry and key organizations for supporting this project and lab personnel by contributing their valuable time, expertise, and equipment for this study. Lastly, we would like to thank the Energy Studies in Buildings Laboratory and Biology in the Built Environment staff and students for supporting the human factor data collection.

# 8. REFERENCES


[1] Galasiu, Anca D., Guy R. Newsham, Cristian Suvagau, and Daniel M. Sander. "Energy Saving Lighting Control Systems for Open-Plan Offices: A Field Study." *LEUKOS* 4, no. 1 (July 1, 2007): 7–29. https://doi.org/10.1582/LEUKOS.2007.04.01.001.

[2] Meugheuvel, Niels van de, Ashish Pandharipande, David Caicedo, and P. P. J. van den Hof. "Distributed Lighting Control with Daylight and Occupancy Adaptation." *Energy and Buildings* 75 (June 1, 2014): 321–29. https://doi.org/10.1016/j.enbuild.2014.02.016.

[3] Pandharipande, Ashish, and David Caicedo. "Smart Indoor Lighting Systems with Luminaire-Based Sensing: A Review of Lighting Control Approaches." *Energy and Buildings* 104 (October 1, 2015): 369–77. https://doi.org/10.1016/j.enbuild.2015.07.035.

[4] Shen, Eric, Jia Hu, and Maulin Patel. "Energy and Visual Comfort Analysis of Lighting and Daylight Control Strategies." *Building and Environment* 78 (August 1, 2014): 155–70. https://doi.org/10.1016/j.buildenv.2014.04.028.

[5] Yun, Geun Young, Hyo Joo Kong, Hyoin Kim, and Jeong Tai Kim. "A Field Survey of Visual Comfort and Lighting Energy Consumption in Open Plan Offices." *Energy and Buildings*, Sustainable and healthy buildings, 46 (March 1, 2012): 146–51. https://doi.org/10.1016/j.enbuild.2011.10.035.

[6] Illuminating Engineering Society of North America. (2011). The lighting handbook: Reference and application (Tenth ed.) (D. DiLaura, Ed.). New York, NY: Illuminating Engineering Society of North America.

[7] R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/

[8] Fraunhofer. (2016). https://www.radiance-online.org/learning/documentation/manual-pages/pdfs/evalglare.pdf/view.

[9] Van Den Wymelenberg, K., & Inanici, M., (2016). Evaluating a New Suite of Luminance-Based Design Metrics for Predicting Human Visual Comfort in Offices with Daylight. *Leukos*. 12(3), 113-138. https://doi.org/10.1080/15502724.2015.1062392.

[10] Mahić, A., Galicinao, K., & Van Den Wymelenberg, K. (2016) A pilot daylighting field study: Testing the usefulness of laboratory-derived luminance-based metrics for building design and control. *Building and Environment*, v. 113, pp. 78-91. https://doi.org/10.1016/j.buildenv.2016.11.024.

[11] Fisekis K., Davies M., Kolokotroni M., Langford P. "Prediction of discomfort glare from windows." *Lighting Research & Technology* 35 (December 1, 2003): 360-369. https://doi.org/10.1191/1365782803li095oa.

[12] Kisch, Teddy, Eric Rubin, Thomas Tu, Kelly Sanders, Jason Huffine, and Brittany Luntz. "Energy Savings from Networked Lighting Control NLC Systems." *DesignLights Consortium*, September 21, 2017. https://www.designlights.org/default/assets/File/Lighting%20Controls/DLC-Report_Energy-Savings-from-Networked-Lighting-Control-NLC-Systems.pdf.