

CALiPER

Exploratory Study: Recessed Troffer Lighting

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Prepared by:

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Prepared for
the U.S. Department of Energy
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Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER relies on standardized photometric testing (following the Illuminating Engineering Society of North America [IES] approved method LM-79-08¹) conducted by accredited, independent laboratories.² Results from CALiPER testing are available to the public via detailed reports for each product or through summary reports, which assemble data from several product tests and provide comparative analyses.³ Since 2012, each CALiPER summary report has focused on a single product type or application.

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Products are selected with the intent of capturing the current state of the market—a cross section ranging from expected low to high performing products with the bulk characterizing the average of the range. The selection does not represent a statistical sample of all available products. To provide further context, CALiPER test results may be compared to data from LED Lighting Facts,⁴ ENERGY STAR® performance criteria,⁵ technical requirements for the DesignLights™ Consortium (DLC) Qualified Products List (QPL),⁶ or other established benchmarks. CALiPER also tries to purchase conventional (i.e., non-SSL) products for comparison, but because the primary focus is SSL, the program can only test a limited number.

For some product categories, CALiPER conducts additional investigations beyond the scope of LM-79-08 testing, such as with the troffers discussed in this report. As with standard reports, it is impossible for CALiPER to evaluate the full range of products available on the market. The selection process is intended to capture current trends, however, and the resulting observations are a valuable indicator of more widespread performance issues. With constantly changing product availability, there will always be products that perform better or worse than those examined by CALiPER.

It is important for buyers and specifiers to reduce risk by learning how to compare products and by considering every potential SSL purchase carefully. CALiPER test results are a valuable resource, providing photometric data for anonymously purchased products as well as objective analysis and comparative insights. However, LM-79-08 testing alone is not enough to fully characterize a product—physical attributes, compatibility with control(s), dimming performance, quality, reliability, warranty terms, and many other facets should also be considered carefully.

For more information on the DOE SSL program, please visit <http://www.ssl.energy.gov>.

¹ IES LM-79-08, *Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*, covers LED-based SSL products with control electronics and heat sinks incorporated. For more information, visit <http://www.iesna.org/>.

² CALiPER only uses independent testing laboratories with LM-79-08 accreditation that includes proficiency testing, such as that available through the National Voluntary Laboratory Accreditation Program (NVLAP).

³ CALiPER summary reports are available at <http://www.ssl.energy.gov/reports.html>. Detailed test reports for individual products can be obtained from <http://www.ssl.energy.gov/search.html>.

⁴ LED Lighting Facts is a program of the U.S. Department of Energy that showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The DOE LED Lighting Facts program is separate from the Lighting Facts label required by the Federal Trade Commission (FTC). For more information, see <http://www.lightingfacts.com>.

⁵ ENERGY STAR is a federal program promoting energy efficiency. For more information, visit <http://www.energystar.gov>.

⁶ The DesignLights Consortium Qualified Products List is used by member utilities and energy-efficiency programs to screen SSL products for rebate program eligibility. For more information, visit <http://www.designlights.org/>.

Report Summary

The recessed fluorescent troffer is ubiquitous in American commercial spaces, with 1×4, 2×2, and 2×4 troffers comprising more than 50% of the luminaires installed in commercial applications and using more than 87 Terawatt-hours (TWh) of electrical energy per year. Consequently, energy-efficiency improvements to this category of luminaire through the use of LED technology can potentially yield significant energy and environmental benefits.

This report describes an exploration of troffer lighting as used in office and classroom spaces, which was conducted by the CALiPER program. Twenty-four pairs of 2×2 and 2×4 troffers were procured anonymously, documented, tested for photometric and electrical performance, and installed in a mockup office space in Portland, Oregon. Three of the pairs were T8 fluorescent benchmark products, 12 were dedicated LED troffers, five were fluorescent troffers modified for LED lamps (sometimes referred to as “tubes”), and another four troffers were modified with LED retrofit kits. The modifications were performed by a commercial electrical contractor, following the instructions provided by the retrofit lamp or kit manufacturer. Once installed in the mockup facility, the converted luminaires were examined by a NRTL (Nationally Recognized Testing Laboratory) safety expert, who provided feedback on safety issues.

In September 2012, a group of lighting designers, engineers, and facility managers were brought in to observe the LED luminaires in comparison to fluorescent benchmarks. This report documents performance in measures that go beyond illuminance values or luminaire efficacy.

Dedicated LED troffers are ready to compete with fluorescent troffers in terms of efficacy (lumens per watt [lm/W]), and in many lighting quality issues such as glare, light distribution, visual appearance, and color quality. That is not to say that each one is stellar, but each one tested in this CALiPER study bested the fluorescent benchmarks in terms of efficacy, and almost all were rated highly in several categories—only one luminaire of twelve performed consistently poorly. One area of concern is that one third of the dedicated LED troffers were equipped with 0-10V dimming drivers that caused the LEDs to exhibit flicker when dimmed. It is important for the lighting industry to develop, adopt, and apply standards to limit flicker that may contribute to health concerns and reduced task performance.

Luminaires retrofitted with LED lamps performed in the same efficacy range as the fluorescent benchmarks, so it is not clear that they offer guaranteed energy savings when compared to fluorescent troffers equipped with 25 or 28 W high-performance lamps and electronic dimming ballasts. The color quality from these LED lamps ranged widely from very poor (CRI in the 60s) to very good (CRI in the upper 80s, which is slightly higher than typical high-performance T8 fluorescent lamps), so specifiers need to exercise care to ensure the new lamps are not reducing color quality compared to the incumbent fluorescent.

LED lamps that have exposed rows of bright LEDs are more likely to produce objectionable stripes and patterns in existing troffers than LED lamps that have a diffuse finish on the luminous half of the tube. Even diffuse LED lamps produced a more “stripey” troffer appearance and increased perceived glare, compared to fluorescent lamping. This was true whether K12 lensed troffers or parabolic louvered troffers were retrofitted.

LED retrofit kits hold some promise, but also face challenges. Each one of the four kits in this CALiPER study had issues: different colors delivered from the same fixture specification, odd or distracting brightness patterns produced on the lens, a poor-quality appearance, greater glare, and/or flicker when dimmed. However, these are engineering issues that can be solved by manufacturers, and a retrofit kit avoids some of the safety concerns

associated with LED lamps. Kits also offer the chance to provide a fresh appearance to the luminaire, rather than retaining the original lens or louver.

There is widespread concern about the performance and safety issues surrounding LED T8 replacement lamps and retrofit kits, and concerns were raised during an inspection of the modified fluorescent luminaires. As installed at the CALiPER mockup, more than half of the products would not have passed an electrical safety inspection because of labeling issues, poor installation instructions, poor mounting or construction, and other complications. This does not necessarily mean that the luminaires were unsafe, but it could trigger the inspector to require a site inspection. Manufacturers and installers should pay attention to the steps required to preserve NRTL certification and listing of the products.

To summarize the experience of the observers, “LEDs have not *improved* recessed troffers. But they *have* made them more efficient.”

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1 Introduction

Offices and classrooms have been principally lighted with fixtures using linear or U-shaped fluorescent lamps for decades. In fact, recessed 2×4s, 2×2s, and 1×4s—collectively known as troffers—comprise 50% of the luminaires used in the commercial market.⁷ The combination of T8 or T5 fluorescent lamps and electronic ballasts is a robust, mature technology that has been widely used and accepted as the norm. Maintenance is fairly easy—and although there is a wide range of lamp, ballast, and luminaire types—there is some consistency in installation methods, controls, and expected performance over time.

Enter the LEDs. The design team, facility manager, electrician, contractor, and user are all facing big changes in the “Type A recessed fixture” on lighting plans, and where the lighting needs a facelift for energy or appearance reasons in existing buildings. Three of the most widely available LED-based product types in the troffer genre include:

- *LED T8 lamps*, which may include an integral driver or may require swapping the existing fluorescent ballast(s) for a new LED driver.
- *Dedicated LED luminaires* with integral drivers. Some use a small number of high-output LEDs, and others use a larger number of mid-output LEDs.
- *LED retrofit kits*, where, in most cases, a fluorescent troffer’s housing is retained and the ballast is replaced with a driver that powers linear boards of LEDs. The kit either uses the luminaire’s existing optical system (e.g., lens, louver), or replaces it with a diffusing acrylic panel for a refreshed look.

These three product types, shown in Figure 1, are all available in multiple sizes (e.g., 2×4s, 2×2s) and match—or exceed—the performance of fluorescent troffers to varying degrees. For example, some LED products mimic the fluorescent products’ optical performance, but most simply deliver a cosine (or “blob”) distribution. This may or may not work in terms of luminaire spacing for ceiling or workplane uniformity, for visual comfort, or for reducing reflected glare on computer screens. At the same time, some of the LED products provide a higher luminaire efficacy than their fluorescent counterparts.



Figure 1. Diffuse and clear LED T8 tubes (left), the interior of a fluorescent troffer (center), and an LED retrofit kit (right) that includes the LED boards, driver, and a new diffuser for the aperture of the original troffer.

⁷ Statistic cited in BBA High-Efficiency Troffer Lighting Specification, December 19, 2012.
http://www1.eere.energy.gov/buildings/commercial/bba_troffer_spec.html

The architectural lighting industry is very familiar with fluorescent troffers, but now that LED options are available, a more complex set of choices has developed. Specifiers must evaluate how well LED products perform compared to conventional fluorescent troffers (and each other), which involves a wide range of criteria—much of which extends beyond the scope of LM-79-08 testing. Some important evaluation criteria include:

- Light output (lumens).
- Photometric distribution, direct glare, reflected glare, overhead glare, uniformity of light on task surface, and spacing criteria.
- Color quality, including color rendering and color appearance.
- Power quality, including total harmonic distortion (THD) and power factor (PF).
- Flicker, at full output and when dimmed.
- Dimming performance, including the smoothness and minimum light output.
- Ease of installation, including modification of existing fluorescent troffers with LED retrofit kits and LED T8 lamps.
- Maintaining electrical safety of troffers after they have been retrofitted with LED T8 lamps or retrofit kits.
- Energy efficiency, or specifically, the total luminaire efficacy and lighting power density of a typical installation.

This summary report describes a project that explores the performance of LED troffer products compared to fluorescent benchmarks—detailing the planning and preparation for a mockup of 24 pairs of troffers in a simulated office space. In September 2012, outside observers evaluated the products and completed a questionnaire, which then prompted discussion of many issues regarding LED troffers versus fluorescent troffers. Aside from typical CALiPER analysis, the subsequent enquiry focused on identifying which lighting issues are most critical, and which can be quantified.

2 Methods

This CALiPER exploratory study spanned the time period from product selection in March 2012 to final analysis in January 2013, including a key evaluation event held September 5–7, 2012. Complete details for each step in the process are provided in roughly chronological order.

Luminaire Selection

Beginning in March 2012, troffer products, including both LED versions and fluorescent benchmarks, were researched and evaluated by the CALiPER team. In selecting luminaires for this study, a set of criteria was established to ensure that—as much as possible—the luminaires served similar functions and were comparable. First, the products had to be a recessed 2×2 or 2×4 troffer luminaire—or one of the retrofit options previously described—designed for mounting in a 9 ft high acoustical tile/T-bar ceiling. A target correlated color temperature (CCT) of 4000 K and a minimum color rendering index (CRI) of 80 were chosen; although 3500 K is a more common CCT for fluorescent luminaires in the United States, more LED luminaires were available in 4000 K, so the criteria was shifted accordingly. Each luminaire had to be rated as producing between 2,500 and 6,000 luminaire lumens, use a 0-10V dimmable ballast(s) or driver(s), if available, and have a power factor greater than 0.90. The target minimum spacing criterion (SC) was 1.2 in both directions. Finally, for dedicated LED troffers, an LM-79 report for the specific version of the product had to be available.

In contrast with the fixed selection criteria, a goal for this study was to include products that spanned a range of optics, visual appearances, luminaire prices, and expected qualities. At least four samples of each type of LED product—T8 lamps, retrofit kits, and dedicated troffers—were included, as well as three fluorescent benchmarks. In total, 24 different products were selected. Although the sample is not comprehensive or statistically derived, it is generally representative of available products based on comparisons to LED Lighting Facts data.

Product Procurement

Selected products were ordered between May 18 and May 29, 2012. Importantly, the initial selected products list continued to evolve after product procurement began, due to difficulty in obtaining selected products within the necessary timeframe. In order to facilitate the mockup and evaluation process, products had to be delivered by July 31, 2012. The final list of installed products is provided in Table 1, and images of the installed products are shown in Figure 2. For clarity, in this report the products are referred to by their letter code instead of the CALiPER identification number. The CALiPER identification number can be used to find the detailed test data available in the online CALiPER database.

In summary, the 24 final installed products included:

- Three fluorescent benchmark products: one 2×2 troffer with two T8 U-lamps and a K12 prismatic lens; one 2×2 three-lamp troffer with 2 ft T8 lamps and a high-performance diffuser; and one 2×4 three-lamp troffer with a 3-inch deep cell, semi-specular 18-cell parabolic louver, and 4 ft T8 lamps.
- Five 2×4 lensed or parabolic-louvered troffers with LED T8 lamps. *Note that one of these was a prototype product included in order to evaluate LED lamps with separate drivers, and thus was not fully considered in the final data analysis.*
- Four 2×2 lensed troffers with LED retrofit kits.
- Twelve 2×2 or 2×4 dedicated LED troffer products, with a variety of lens/aperture designs.

Table 1. Product descriptions and classification.

Caliper ID	Tag	Product Type	Description	Size	Aperture Type
12-115	A	T8 LED Lamps ¹	Three Clean Light Green Light 342-SMD	2×4	K12 Lens
12-112	B	T8 LED Lamps ¹	Three Philips EnduraLED GA 22W	2×4	18 Cell Parabolic Louver
12-113	C	T8 LED Lamps ¹	Three Redbird L4-22W	2×4	K12 Lens
12-136	D	T8 LED Lamps ¹	Three Lumenor 17 W T8 LED lamps	2×4	18 Cell Parabolic Louver
12-107	E	LED Retrofit Kit	Acuity LE 2RTLEDRT	2×2	Partial Aperture Diffuser
12-106	F	LED Retrofit Kit	Albeo Technologies RK-V3D5-1U1	2×2	K12 Lens
12-109	G	LED Retrofit Kit	Envirobrite Dailite LED Restyle	2×2	Partial Aperture Diffuser
12-108	H	LED Retrofit Kit	LED Living Technology Claris CLA-34	2×2	K12 Lens
BK12-132	I	T8 Fluorescent	Two F32T8/SPX41/U6/WM/ECO lamps in Acuity Lithonia SP8 2x2 luminaire	2×2	K12 Lens
BK12-133	J	T8 Fluorescent	Two F17T8XL/SPX41WMEC lamps in Finelite HPR-A2x2DCO-3T8 luminaire	2×2	Diffuser with Linear Details
BK12-138	K	T8 Fluorescent	Three F28T8/XL/SPX41ECO lamps in Acuity Lithonia 2PM3N2x4-332-18LD luminaire	2×4	18 Cell Parabolic Louver
12-131	L	T8 LED Lamps ¹	Three prototype lamps with separate LED drivers	2×4	18 Cell Parabolic Louver
12-119	M	LED Troffer	Cree CR24-40L-40K 2x4	2×4	Partial Aperture Diffuser
12-120	N	LED Troffer	Finelite HPR-A-2x4-DCO-LED50	2×4	Diffuser with Linear Details
12-117	O	LED Troffer	Philips Lightolier Skyway SKS24-PK	2×4	Diffuser with Linear Details
12-118	P	LED Troffer	Cooper Corelite R2WL1L40	2×4	Partial Aperture Diffuser
12-123	Q	LED Troffer	Columbia Serrano LSER22-40-HL-G-C	2×2	Partial Aperture Diffuser
12-124	R	LED Troffer	Philips Ledalite Pique 9122-1-ST-L	2×2	Diffuser with Linear Details
12-125	S	LED Troffer	GE Lumination LED 2x2 edge-lit	2×2	Uniform Diffuser Panel
12-126	T	LED Troffer	MaxLite Direct Lit MLFP-22-D-45	2×2	Uniform Diffuser Panel
12-127	U	LED Troffer	Ringdale ActiveLED OL2-5538-C	2×2	K12 Lens
12-128	V	LED Troffer	Lunera 22-G3	2×2	Uniform Diffuser Panel
12-116	W	LED Troffer	Columbia e-Poc LEPC 24-40-44-G-LL	2×4	Partial Aperture Diffuser
12-122	X	LED Troffer	Acuity Lithonia VT-LED 2VTL4-48L-ADP-D47	2×4	Partial Aperture Diffuser

1. Lamps installed in 3L troffer having aperture as shown.

Initial Observations and Photometric Testing

Products and their arrival condition were documented once received by the CALiPER team at Pacific Northwest National Laboratory (PNNL). They were equipped with a mains voltage cord and plug, and wired for 0-10V dimming control (Lutron NTFTV with PP-120H relay). Products that were LED retrofit kits or LED T8 lamps were installed in two randomly assigned types of conventional T8 fluorescent troffers, also procured for this study. A commercial construction electrician from Richland, Washington was hired by PNNL to perform the retrofits with the manufacturer-supplied instructions. The install time and his comments on the ease of work were documented.

The assembled products were then taken to the PNNL photoelectric testing lab for measurement and evaluation of flicker and power quality, both at full output and dimmed conditions. Afterwards, they were either shipped to an independent, CALiPER-approved testing lab for LM-79-08 testing, or shipped directly to the evaluation host

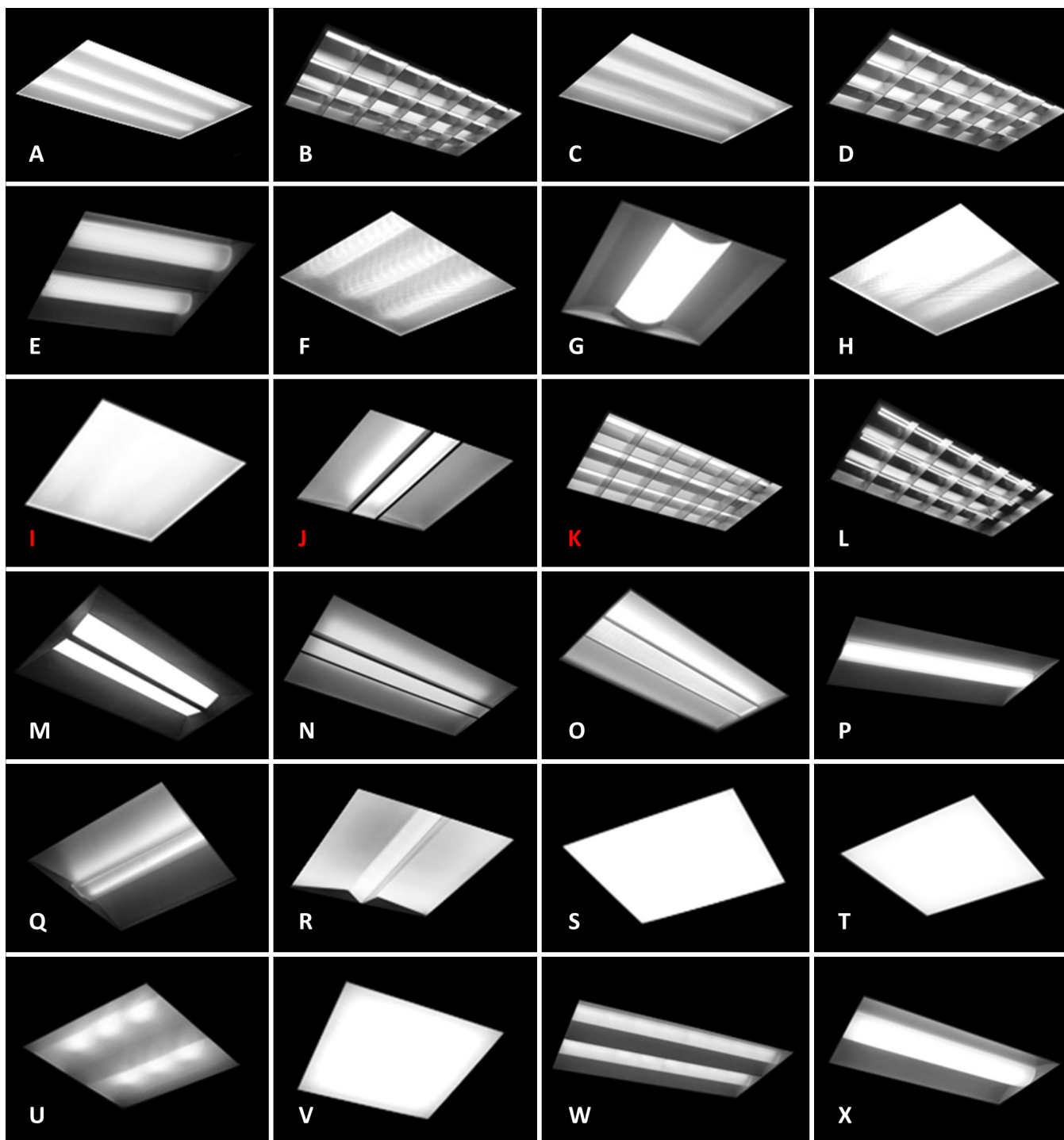


Figure 2. Photographs of the products installed for the study. The red letters indicate fluorescent benchmark products.

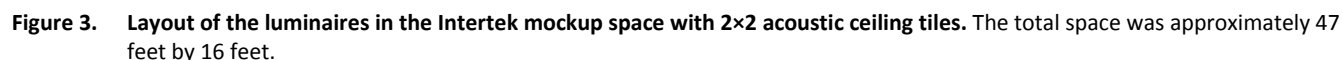
site—the Intertek Testing Laboratory in Fairview, Oregon—depending on timing. Those products shipped directly to the host site were sent for LM-79-08 testing after the evaluation event.

The Mockup Office Installation

The Intertek Testing Laboratory was contracted to install a temporary office mockup capable of housing 24 pairs of troffers at their facility. Intertek’s subcontractors built the mockup office space, installed the luminaires, and connected mains voltage.

The luminaires were equipped with interfaces for the Encelium⁸ Energy Management System™ (EMS), allowing individual luminaire control. These interfaces, referred to as Luminaire Control Modules (LCMs) within the EMS, decode the proprietary protocol delivered by the Encelium GreenBus II communication network, and create both an on/off control signal for the embedded relay and a 0-10V dimming signal for the driver or ballast. The GreenBus II communication network was formed by connecting luminaires together in daisy-chain fashion, and terminating the string in one of the channels of a central control gateway, referred to as an Energy Control Unit (ECU) within the EMS. Connections were made between LCMs using two-conductor cables equipped with compatible plug connectors.

Two movable partitions were created so that observers could position the “wall” at a typical distance from the luminaire. This allowed evaluation of the pattern of light created by each luminaire on vertical surfaces. Ceiling tile reflectance was approximately 80%, wall reflectance 70% (nominally white paint), and floor reflectance was approximately 30% (unfinished concrete). Two movable desks were located in the space, with laptop computers and paper tasks for evaluating visibility and reflections. Participants in the study provided several iPads®, which have highly specular screens, for evaluating reflected glare from the luminaires.



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An Intertek engineer, expert in field certification of luminaires, visited the mockup site the week before the evaluation event. He inspected the retrofitted products and provided feedback on the NRTL (Nationally Recognized Testing Laboratory) listing and certification status of the luminaires.

Observers and Evaluation Process

Eighteen people considered lighting experts were invited to attend a mockup event, held September 5–7, 2012, and evaluate the installed luminaires. Most of these observers were from independent lighting and engineering firms located across the United States, but the group also included one energy manager from a Portland-based healthcare organization, and a university professor teaching theatrical lighting.

The expert observers were divided into groups of six, and were presented with the room equipped with eight luminaires, equally spaced, to simulate an evenly lit office. The luminaires in a single presentation were all 2×2s or all 2×4s, four pairs of two identical luminaires at a time. The order of presentation to the groups was counterbalanced to mitigate order effects. After being presented with all six groups of luminaires at full output, the observers then saw the same groups of luminaires, in different order, in dimmed mode. As they were presented with different products, observers were asked to complete a questionnaire (see Appendix A) without communication among the group members. Photographs from the event are shown in Figure 4.

At the end of the evaluation session, all observers were brought together to discuss what they had seen, what they had learned, and what qualities were important to convey to the specifier and user. These observations were recorded and a summary is provided in this report.

In January 2013, a similar protocol was used to gather feedback from five Intertek employees with no lighting experience. These participants were considered naïve observers.

Data Analysis

The data was collated and analyzed from September 2012 to January 2013. When necessary, additional photometric data was collected in order to help identify metrics that might explain the observers' choices. Microsoft Excel 2012 and Minitab 16 Statistical Software were used to evaluate linear regression models. Both single variable and multi-variable models were fit to data comparing the mean survey response for a given question to a variety of relevant performance metrics. Best-subsets analyses were examined in some cases where no single variable provided reasonable correlation. Although post-hoc correlation analyses do not imply causation, they can help to alert specifiers and manufacturers to what metrics may lead to certain subjective responses. However, as the results suggest, subjective responses are often related to multiple variables as well as their interactions.



Figure 4. The installation at Intertek during the mockup event. Movable partitions and movable desks allowed for comprehensive evaluation of glare. A digital control system allowed for switching and dimming of the luminaires individually or in groups.

3 Results

The results from this work include both measured performance data and subjective evaluations completed by expert and naïve observers. For reference, complete luminaire performance data is tabulated in Appendix B. Summary tables of the questionnaire responses are available in Appendix C. As noted earlier, luminaire type L was a prototype LED T8 replacement product and is not included in all analyses, but is included in the analysis of color and flicker, for example, because it provides useful data points. Much of the discussion in this report focuses on the performance of the LED products, although all products were grouped together when investigating correlations between performance metrics and observers' ratings. This does not imply that fluorescent troffers are a perfect technology; they too have limitations.

The sample size was limited to ensure the feasibility of the in-person evaluation process. Further, LED T8 lamps were randomly assigned to a luminaire type, which may have affected performance and subsequent ratings. At the same time, this represents the real-world situation in which lamps are sold without knowing in which luminaire they will be installed. While the analysis included here is global in tone, there are undoubtedly products on the market that fall outside the listed range of performance. Plus, the performance of all types of LED products continues to change. Recommendations and conclusions are meant only as broad guidelines based on the analysis and observations of this study; specifiers should carefully evaluate the performance characteristics of all products in consideration.

Although the attributes listed below are evaluated individually, specifying lighting products often requires tradeoffs among many different factors. For example, efficacy and color quality are sometimes considered at odds, and cost and visual appearance almost always play a role in the decision. (Cost is not addressed in this CALiPER study.)

Luminaire Efficacy

Reducing energy consumption is often a primary goal when swapping existing fluorescent luminaires for LED products—or choosing an LED product over fluorescent in a new installation. Thus, efficacy is a critical attribute to evaluate, although not apparent to the mockup observers.

In terms of efficacy, the LED products performed as well as or better than the fluorescent products. Table 2 shows luminaire efficacies broken out by product type, and illustrates that the LED T8 lamps and LED retrofit kits performed in the same range or slightly higher than the fluorescent benchmarks, whereas the minimum efficacy of the dedicated LED luminaires was higher than the most efficacious fluorescent benchmark. Table 2 also shows

Table 2. Total luminaire efficacy by product type, and in comparison to data from LED Lighting Facts (February 6, 2013).

	Total Luminaire Efficacy (lm/W)		
	Minimum	Mean	Maximum
T8 Fluorescent Benchmarks	56.6	59.6	62.1
LED T8 Lamps	54.7	68.9	76.5
LED Retrofit Kits	60.1	66.2	76.5
LED Troffers	73.8	88.8	106.6
LED T8 Lamps on LED Lighting Facts ¹	35.0	62.1	87.4
LED Troffers on LED Lighting Facts	30.3	82.9	119.5

1. Values listed by LED Lighting Facts are for bare lamps. They have been multiplied by 0.70 to account for luminaire efficiency.

data from LED Lighting Facts, including LED T8 lamps that have been modified to estimate performance inside recessed troffers. In general, the performance range for the CALiPER-selected products is similar to or better than the performance range for products listed by LED Lighting Facts, which can be considered representative of the overall LED product market. Clearly, the dedicated LED troffers performed best in terms of efficacy. However, the discussion must continue with other performance attributes.

Input Power

Just because higher-efficacy LED products are used does not guarantee that power and energy will be reduced compared to baseline fluorescent troffers. In fact, total luminaire input power varied widely across the LED products, and energy savings would only result in some cases. For example, one of the 2×4 luminaires lamped with three LED T8s drew almost the same power as the highest wattage fluorescent 2×4 benchmark (79 W versus 83 W, as shown in Table 3). In contrast, some of the LED products provided more than a 30% reduction in power draw compared to the lowest wattage fluorescent benchmark. However, equivalency of lumen output must also be considered.

Light Output

In many retrofit applications, reducing light output is one way to reduce energy use. This can be accomplished by reducing the number of lamps in existing fluorescent troffers, switching to lower-output ballasts and/or lower wattage fluorescent lamps, or as part of the switch to LED products. The validity of this approach depends on the application and the existing hardware. In short, efficacy, input power, and lumen output should all be considered simultaneously.

The output of the LED products included in this study ranged from 2,138 lumens to 5,246 lumens, with a mean of 3,679 lumens. The three fluorescent products produced 2,638, 4,079, and 6,037 lumens for 2×2, 2×2, and 2×4 products, respectively. A wide variety of fluorescent products are available, both within and somewhat outside this range.

As expected, luminaire lumen output was correlated with the observers' rating of the appropriateness of light output from the luminaire ($R^2 = 0.69$), as shown in Figure 5 and based on the first item in the questionnaire. Additionally, multiple regression models suggest that increased output at higher vertical angles may also help increase the observers' rating on appropriateness of the light level. Luminaires with more high-angle output are less likely to result in a cave-like impression, but they also may be more glaring. This is a complex tradeoff.

Table 3. Input power by product type, and in comparison to data from LED Lighting Facts.

	Total Luminaire Input Power (W)		
	Minimum	Mean	Maximum
T8 Fluorescent Benchmarks	48.4	62.9	82.0
LED T8 Lamps (2 or 3)	48.0	62.4	79.4
LED Retrofit Kits	35.1	41.2	50.9
LED Troffers	26.1	42.3	57.5
LED T8 Lamps on LED Lighting Facts ¹	4.6	17.2	59.0
LED Troffers on LED Lighting Facts	9.0	46.0	131.0

1. The products tested in this study included two or three lamps; values shown are per lamp.

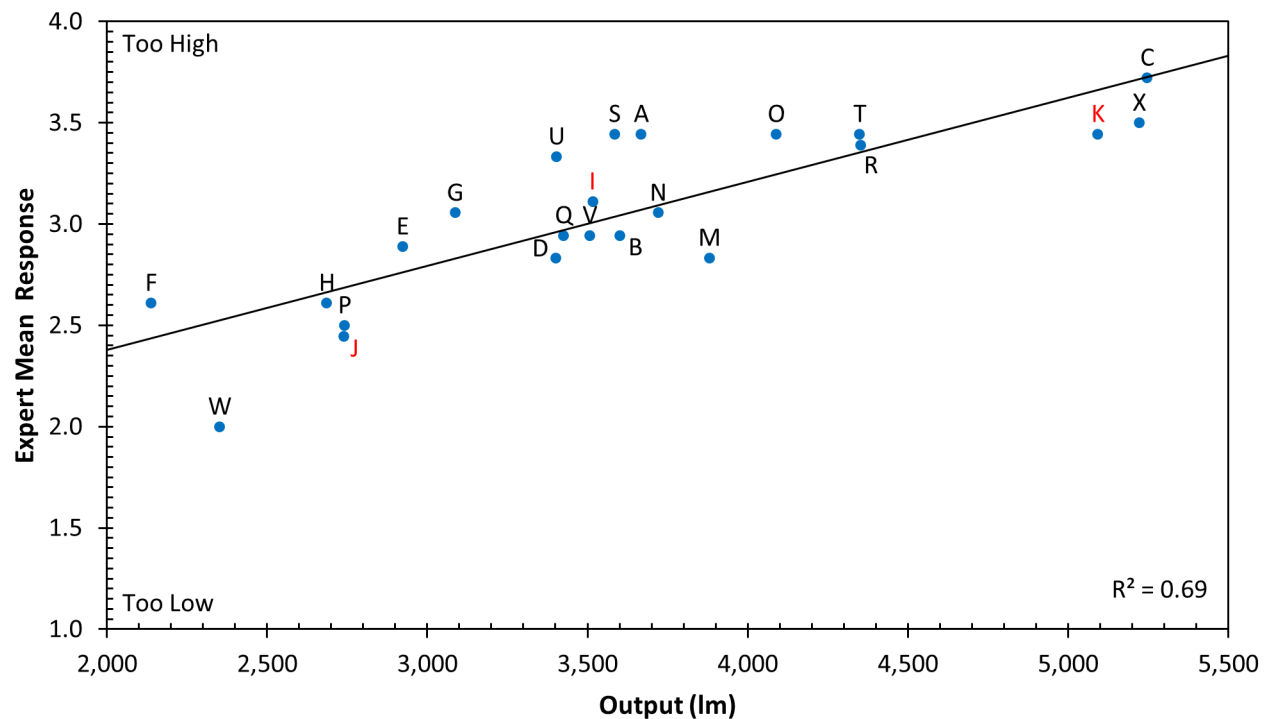


Figure 5. Mean expert ratings for *How appropriate is the light output from the luminaire for this application?* (Question 1) versus luminaire lumen output. A red label denotes a fluorescent benchmark product.

Observers were able to measure light levels as they evaluated groups of luminaires, and importantly, no products were considered to have output that was too low (either visually or numerically), based on their professional experience. The lowest rated product (type W) had a mean expert rating of 2.0, and was near the lowest measured output at 2,352 lumens.⁹ Many products had a mean observers' rating of 3.0 or greater, indicating that the products tended to provide too much light. Notably, none of the three products emitting more than 5,000 lumens had a mean observers' rating of less than 3.4. This may be a maximum threshold for acceptable lumen output, given the 9' ceiling height, luminaire spacing, and application represented in this mockup.

Visual Appeal

One attribute of luminaire performance that certainly cannot be captured by a numerical metric is visual appeal, which was probed with Question 10—*Do you like the appearance of this luminaire?* By dividing the products based on the type of aperture, very clear trends were apparent, as shown in Figure 6. Observers preferred the appearance of the diffuser surface with linear details best, smooth white diffuser and parabolic louver luminaires moderately well, and non-uniform lensed units least. The response in the top-rated products seemed to reflect current fashion and a desire for visual details on the diffuser surface, with a moderate rating given to visually indifferent products or mid-grade lensed and parabolic products, and a strong dislike of products with unexpected or distracting luminance patterns. Conventional luminaires using K12 lenses or parabolic louvers were the lowest rated, and those with odd patterns receive the lowest ratings within those groups. Despite

⁹ Notably, luminaire type W (as well as type P) was measured as emitting less than 80% of the lumen output claimed by the manufacturer. Two of the three fluorescent products (types I and K) were measured as emitting approximately 85% of the lumens claimed by the manufacturer. All other products were measured to be within $\pm 10\%$ of the claimed value.

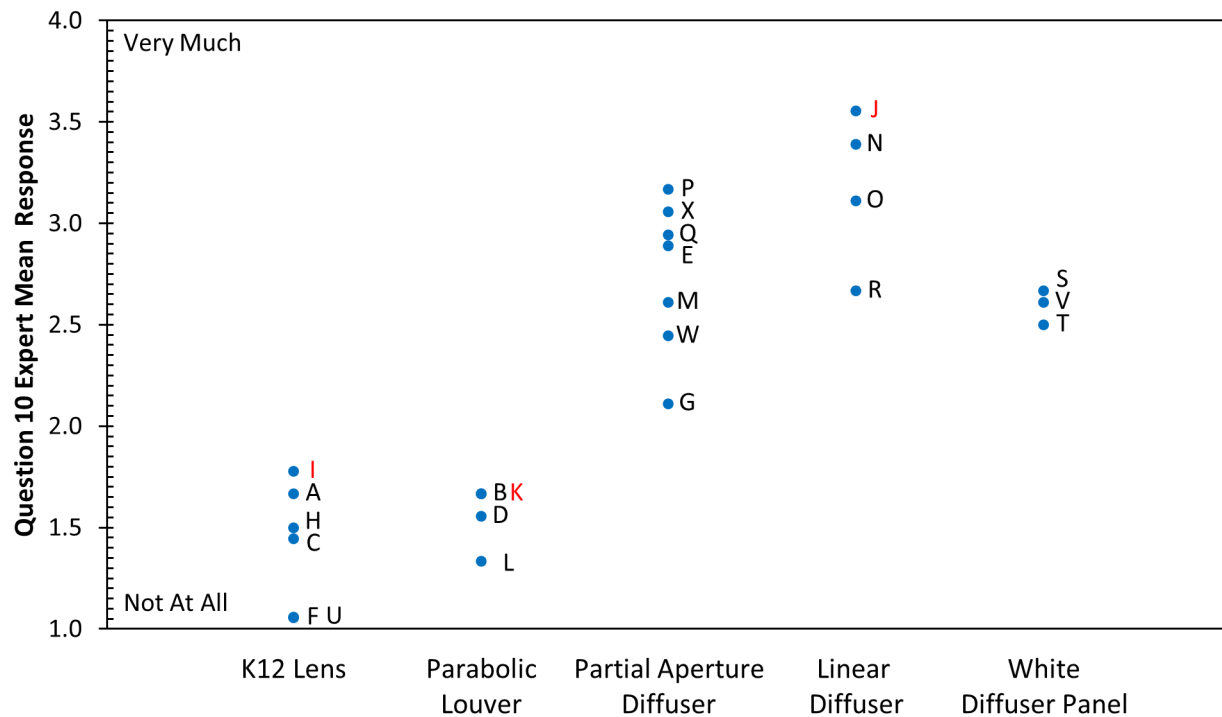


Figure 6. Figure 6. Mean expert ratings for *Do you like the appearance of this luminaire?* (Question 10) divided by the aperture type. A red label denotes a fluorescent benchmark product.

being visually similar, the fluorescent benchmarks were rated the highest within their respective category, although the difference between those and the LED products is unlikely to be statistically significant.

The observers' ratings on visual appearance weigh heavily in this study. Given that all of the questions asked for a subjective response, the participants' personal preferences likely affected their ratings even for seemingly unrelated questions. In many cases, the best multi-factor linear regression models for the questions included the ratings for visual appearance. However, it is also possible that better-performing products had attributes that the expert observers were able to identify, and which have come to influence their opinion of visual appearance.

Distribution of Light

Luminous intensity distribution and the luminance pattern on the face of a luminaire are very important aspects of performance that are related to many tangible qualities, such as illuminance uniformity, glare, and visual comfort. A substantial effort was made to find numerical quantities that correlated with the observers' impressions of these performance attributes. Polar plots of luminous intensity distribution for each luminaire can be found in Appendix D. Appendix E shows a photograph of each luminaire with the pattern of light produced on the adjacent wall.

When examining the polar plots of luminous intensity distribution, there are two distinct types of products. The majority of tested products had a cosine (or near-cosine) distribution, illustrated by the roughly circular pattern in the polar plot. There was some variation within this category, with a handful of products emitting less flux at higher vertical angles (expressed as a teardrop shape). The second type of distribution is the batwing, where more light is directed at a 45° angle rather than straight down. Luminaire types B, D, K, Q and R generally fall in this category. Three of those products, B, D, and K, utilized a parabolic louver. The remaining two were 2x2

dedicated LED products. Based on the questionnaire feedback, it is likely that impressions of glare and uniformity are affected by both the luminous intensity distribution and the pattern of light visible on the aperture surface, which can vary according to the type of troffer (parabolic louver or lens or diffuser, for example) and aperture construction. These impressions were not necessarily related to whether the luminaire used LED or fluorescent technology.

Workplane Uniformity

Spacing criterion (SC) is often used to estimate acceptable workplane illuminance uniformity. The minimum SC for the 2×2 luminaires procured for this study was 1.12, only slightly lower than the typical target SC for this simulated office application; a specifier would usually look for a minimum SC of 1.23 for an application where luminaires are mounted 6.5 ft above the workplane and are spaced 8 ft apart (i.e., 8 ft/6.5 ft = 1.23). The minimum SC for the 2×4 luminaires in this study was 1.20, but the target SC for this application would be 1.54 (i.e., 10 ft/6.5 ft = 1.54). Nine of the eleven 2×4 troffers had an SC less than 1.54. Given these numbers, it is surprising that none of the expert observers' mean ratings for Question 2 indicated that they felt the lighting was too uneven. In fact, the mean responses ranged between 2.3 and 3.1. This is probably because all of the luminaires provided a reasonably wide distribution of light, with a soft edge to the beam. The ratings may also have been affected by the surface finishes in the room—it was not a real office space—or the fact that the observers experienced only two adjacent luminaires of the same type.

Figure 7 illustrates that the perceived uniformity was moderately correlated with the number of lumens emitted between 60° and 90° per unit area ($R^2 = 0.58$), indicating that luminaires emitting the most lumens in that zone were more likely to be considered “somewhat too uniform.” In contrast, there was almost no correlation between the observers' impressions of uniformity and the luminaires' SC. In general, 2×2 luminaires spaced 8' on center tended to be perceived as producing more workplane uniformity than 2×4 luminaires with 10' spacing.

Light Distribution on Adjacent Walls

The experts' mean responses to Question 3—*Is the light distribution on the adjacent wall appropriate for the application?*—ranged from 1.7 to 3.7, showing some division based on the luminaire type. Luminaire types B, D, and K, which were the three deep-cell parabolic louvered products, received the lowest ratings. The two parabolic luminaires lamped with LED T8s received lower mean ratings than the fluorescent-lamped product, suggesting that the patterns of light produced on the walls were harsher and left the upper wall in relative shadow because there was no indirect component (or “backlight”) from the LED lamps to soften the pattern. This is illustrated in Figure 8.

As with workplane uniformity, the observers' responses to Question 3 are moderately correlated with the percent of lumens emitted between 60° and 90° per unit area, as shown in Figure 9 ($R^2 = 0.52$). Luminaires delivering 10% or more of their lumens in this zone received average ratings of 3.0 or higher. A better model (R^2 greater than 0.80) can be achieved by including more luminous intensity distribution variables, such as the candela at several angles and the total lumen output.

Visual Comfort (Overhead Glare)

Two of the observer questions (4 and 5) were aimed at understanding more about overhead glare; that is, the visual discomfort that is sensed when luminaires are situated above the normal field of view, usually from 55° to 85° above a horizontal gaze. Figure 10 illustrates the angles producing overhead glare. For both questions, the most highly correlated metric was the maximum luminaire spot luminance as measured at a steep angle of 10° from vertical ($R^2 = 0.46$). Although this metric is not necessarily an intuitive predictor, the correlation between the observers' ratings and other measurements of luminous intensity distribution, such as intensity (candelas) at

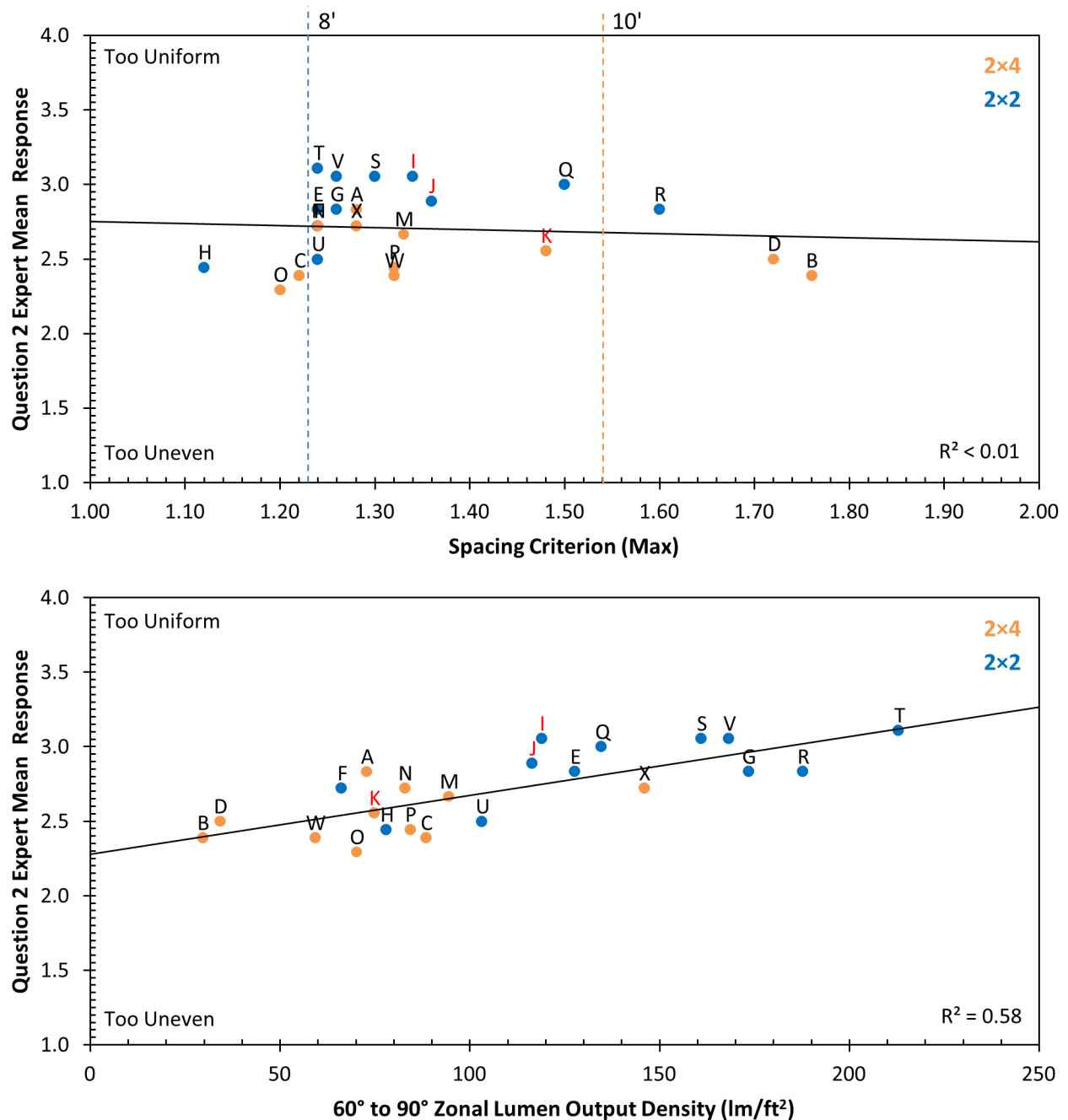


Figure 7. Mean expert ratings for *Is the light distribution on the workplane between luminaires appropriately uniform for this application?* (Question 2) versus spacing criterion (top) and output in the 60° to 90° zone per square foot. A red label denotes a fluorescent benchmark product.

a given angle, were weak. Notably, the correlation of the spot luminance metric is heavily influenced by the measurement for luminaire type U ($55,320 \text{ cd/m}^2$), which was much higher than all the others (with U removed, $R^2 = 0.26$).

Those products with maximum spot luminance higher than $20,000 \text{ cd/m}^2$, such as U, L, D, B, G, and C, generally received poorer ratings. The luminaires that the observers rated as the most glaring were U, C, and F, all of

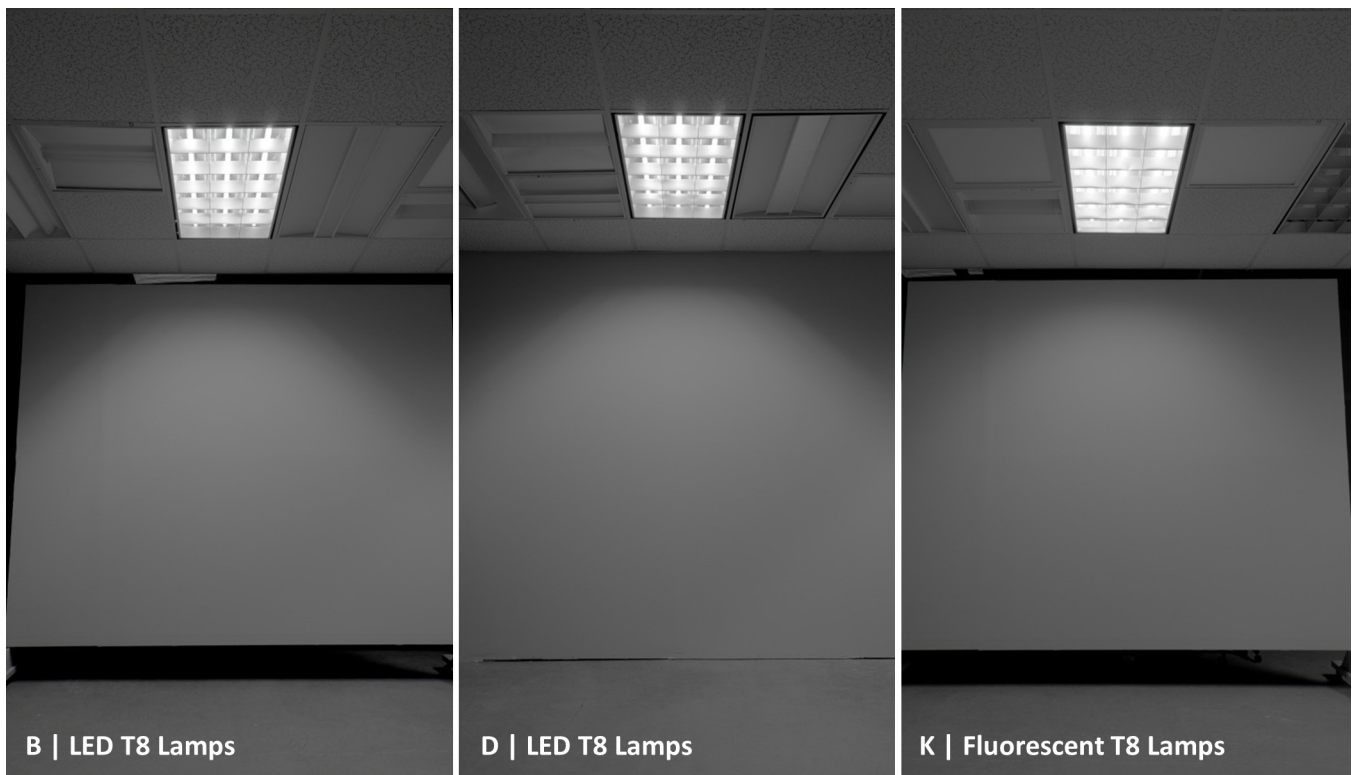


Figure 8. Example comparison of the pattern of light created on the wall by three different troffers with the same parabolic louver. The patterns created by the LED T8 lamps have a more distinct edge that observers did not like.

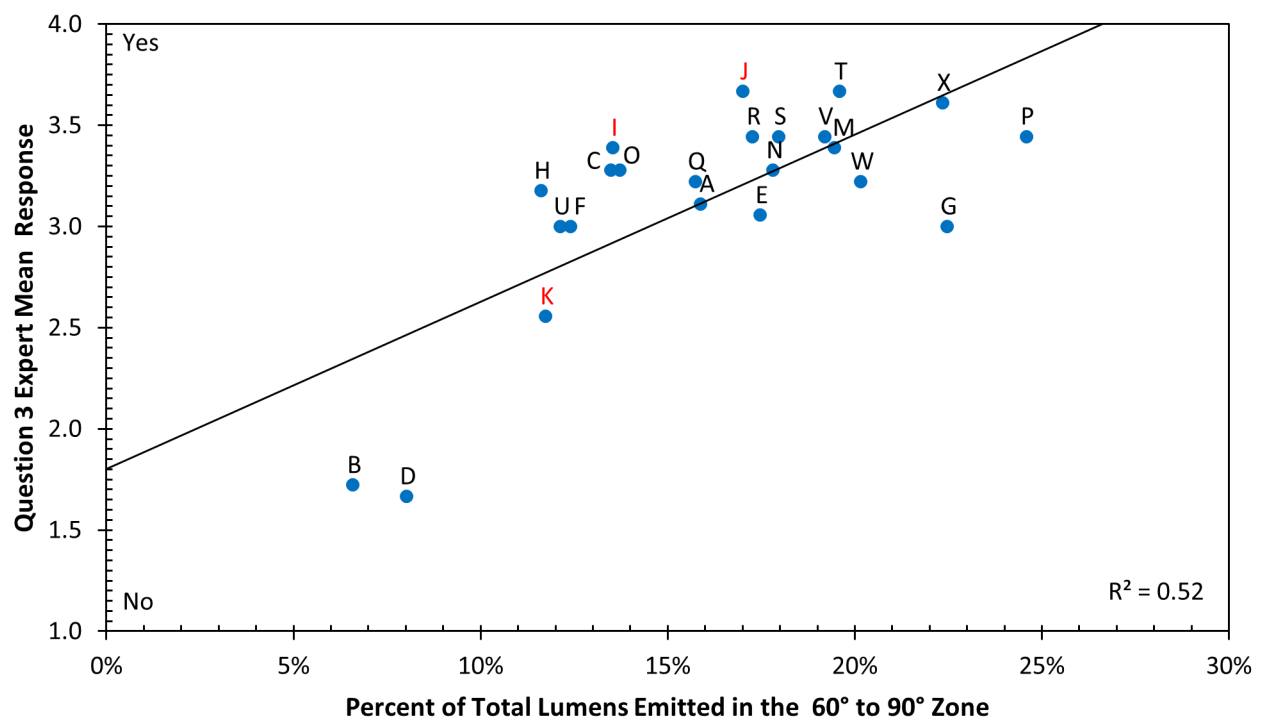


Figure 9. Mean expert ratings for *Is the light distribution on the adjacent wall appropriate for the application?* (Question 3) versus the percent of total lumens emitted in the 60° to 90° zone. A red label denotes a fluorescent benchmark product.

which are prismatic lensed products that were retrofitted with LED T8 lamps or retrofit kits (see Figure 11). All three had strong, odd, and/or distracting luminance patterns on the lens.

Luminaire types D, B, and K (all parabolic louver luminaires with bare lamps visible between the cells of the louver) were the next lowest rated group in terms of overhead glare, but they were surprisingly rated at approximately the same level as type T, a smooth, flat-panel 2x2. Luminaire types N, O, and J were the top-rated luminaires for visual comfort, and all of them are 2x4s with a diffuser panel with linear details, producing a smooth gradient of light across the diffuser. The maximum measured lens luminance among these three luminaires was 12,480 cd/m².

Discomfort (Direct-view) Glare

Similar to overhead glare, troffers U, F, and C were rated lowest for discomfort glare, and types N, J, and W were rated as the least glaring (Question 6). U, F, and C are the lensed fixtures with pronounced luminance patterns noted previously, but not all lensed troffers received similarly low ratings. For example, luminaire types A (using an LED T8 lamp) and I (using fluorescent U-lamps) both received higher, more neutral ratings.

In an effort to find a metric to predict discomfort glare problems, observer responses were compared to a range of quantities derived from photometric reports or from in-situ luminance measurements. None of the following metrics produced a reliable correlation (R^2 values were less than 0.18):

- Maximum spot luminance measured on the surface of the luminaire from a measurement angle of 25° above horizontal (65° from the luminaire nadir), measured in the luminaire's 90° plane.
- Ratio of maximum to minimum spot luminance measured across the surface of the luminaire from the same 25° above horizontal.
- Ratio of maximum luminance to adjacent ceiling tile luminance, measured from the same angle.
- Maximum luminaire candela value at 55°, 65°, 75° or 85° luminaire elevation angles.
- Average luminaire luminance at 55°, 65°, 75° or 85° luminaire elevation angles.
- Percent lumens emitted between 60° and 90°, or absolute lumens emitted between 60° and 90°.
- Total luminaire lumen output.

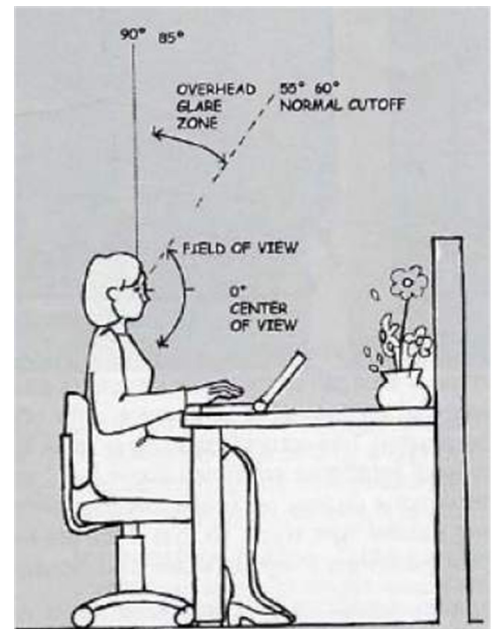


Figure 10. Illustration of overhead glare zone for office worker. Source: IES DG-18-08, *Light + Design: A Guide to Designing Quality Lighting for People and Buildings*



Figure 11. Observers found the luminance patterns for LED luminaire types U, C, and F to be distracting.

However, as with overhead glare, maximum luminaire spot luminance values measured 10° from vertical showed promise as a metric for discomfort glare ($R^2 = 0.48$). However, as previously noted, luminaire type U exhibited a very high maximum spot luminance which becomes an extreme data point that may be exaggerating the appropriateness of this metric. Notably, the ratings for Questions 5 and 6 (overhead glare and direct-view glare) were highly correlated ($R^2 = 0.91$). Additional investigation is warranted.

Reflected Glare in Computer Screen

Question 7—*Would you consider the luminaire's reflection in the computer screen to be a concern?*—resulted in mean responses between 1.5 and 2.8; none of the luminaires were rated as especially good for reflected screen glare. Several of the observers submitted separate scores for a standard diffuse LCD laptop screen and the highly-specular Apple iPad® tablet screen, and it was clear that *all* luminaires produced highly conspicuous reflections in the iPad® screen. The two screen types are shown in Figure 12. Looking at mean ratings for both screen types, luminaire types N, J, P, and W produced the best ratings of 2.5 or higher. All have diffuse lenses and seem to have fairly uniform luminance (“brightness”) gradients across the lens.

The lowest rated luminaires for Question 7 were U, T, C, G, and S. Luminaire types U and C are both LED-based lensed troffers with high spot luminances and distracting patterns on their lenses, and luminaire type G is a retrofit kit using a small-area diffuser that has a very high surface luminance. The biggest surprises in this lowest-rated group are luminaire types S and T, which are both 2x2 LED troffers with smooth white diffuser panels. Luminaire type V is also a diffuse flat-panel LED product, but it may have performed better on this question because its lumen output was approximately 20% lower than that produced by luminaire T.

Since 2000, the IES has used luminous intensity values (candelas) as a metric to identify recessed luminaires that are potentially problematic for producing computer screen glare. In this CALiPER study, candela values at 65°, 75°, and 85° did not explain why some luminaires received higher ratings than others. Figure 13 shows a typical lack of correlation between the observers’ ratings of reflected screen glare and candela values at 65°.

The strongest explanation for reflected glare came from a combination of factors, identified through a multiple regression model. The maximum surface luminance measured at 10° from vertical, combined with the number of lumens emitted between 60° and 90° per square foot of troffer area, plus the rating of the luminaire appearance, together produced an R^2 of 0.78. This merits further study. It may be that maximum spot luminance

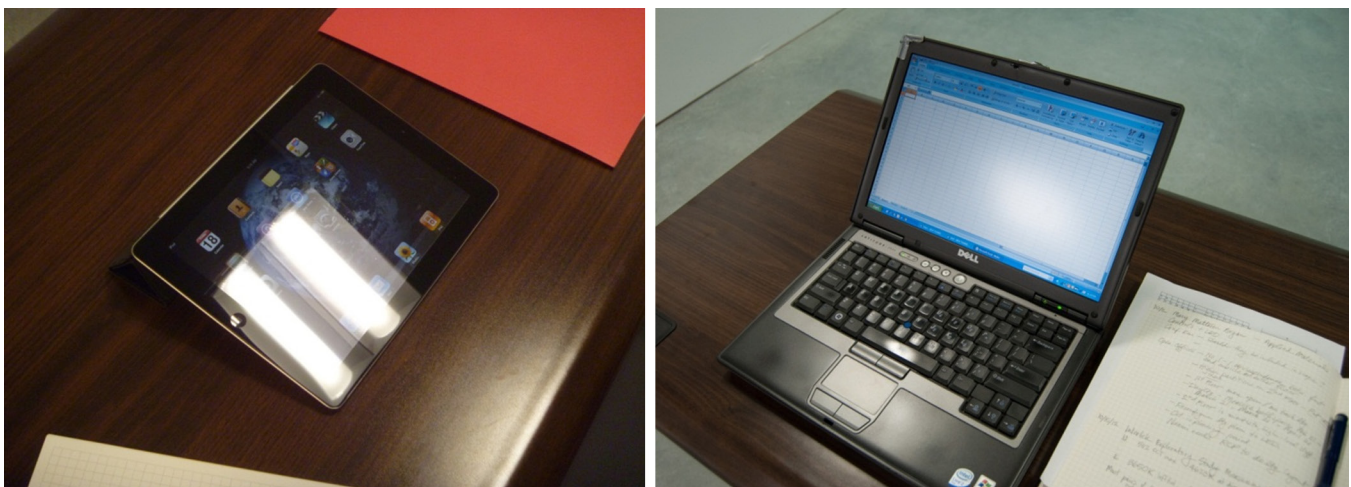


Figure 12. Reflected glare from recessed troffer on iPad® tablet screen (left) and laptop computer screen (right).

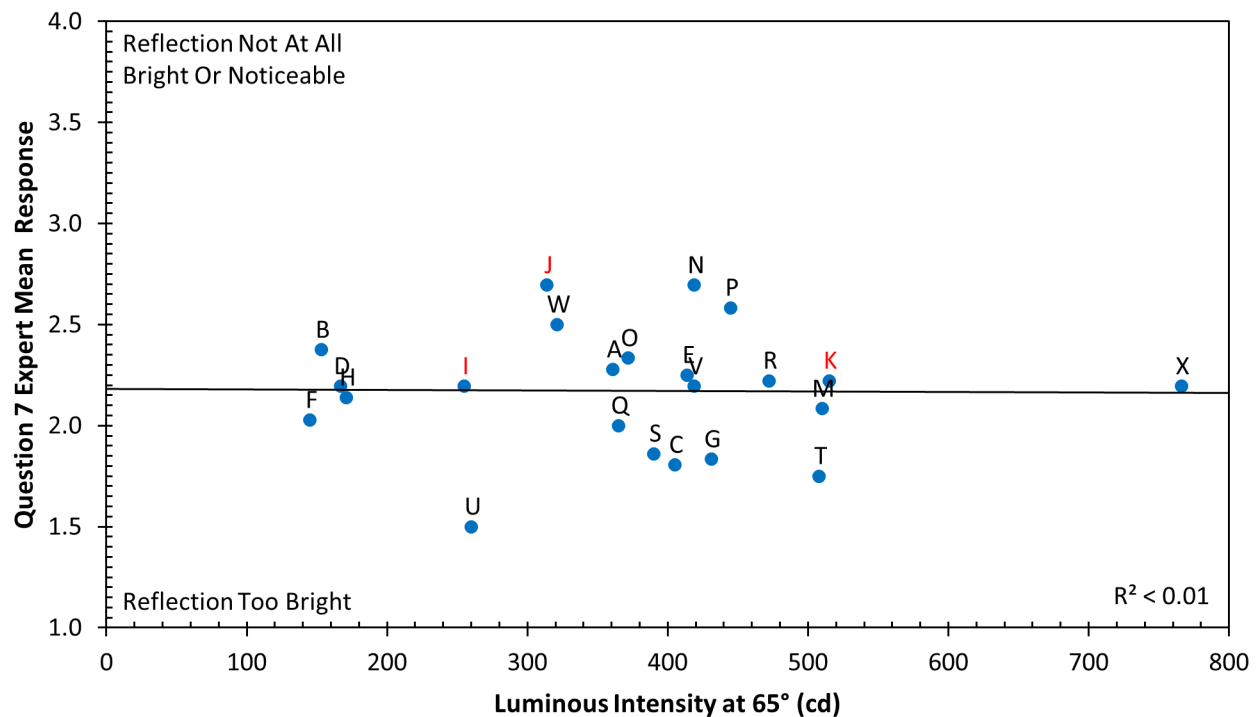


Figure 13. Mean expert ratings for *Would you consider the luminaire's reflection in the computer screen to be a concern?* (Question 7) versus luminous intensity at 65° from nadir. There is no correlation between the ratings and any luminous intensity value. A red label denotes a fluorescent benchmark product.

affects visibility of screens, especially when they are laptops or tablets, since they are tilted further back than many office monitors, and so are reflecting the overhead luminaire.

Glare and Preference

For all questions related to glare, it is notable that the experts' mean responses were correlated with their rating for the overall appearance of the luminaire, oftentimes more so than any other single metric. It is likely that glare perception is related to a more complex picture of luminous intensity distribution than can be captured with a single number. It is difficult to say, however, if glare is a driving factor behind overall preference, or if the observers' feelings towards each luminaire led to bias in certain areas, like glare, which can be more difficult to conceptualize.

Color Quality

Because of the selection criteria, a vast majority of products had a nominal CCT of 4000 K, with actual measured CCTs¹⁰ between 3937 K and 4329 K. Three products nominally listed as 4000 K had average measured CCTs outside the ANSI-defined range (3616 K, 4365 K, and 4424 K for luminaire types E, A, and T, respectively). In the case of luminaire type E, a retrofit kit, the two products that arrived had nominal CCTs of 3500 K and 4000 K, based on the printing on the circuit board. The disparity likely was a manufacturing error. Two product types, G and U, were not available with a nominal 4000 K CCT, so they were ordered at 3500 K (3233 K measured) and 5000 K (5184 K measured).

Given the above consideration, especially the notable outliers, the observers' responses to Question 8— *Would you consider the color appearance of the emitted light to be appropriate for this application?*— must be

¹⁰ Measured CCTs are reported as the mean of all tested samples.

evaluated piecemeal. Almost all of the products had a mean rating between 2.5 and 3.5, indicating the color appearance was generally appropriate. However, luminaire types U (1.56) and E (2.17) received substantially lower ratings. These were the 5000 K and mismatched products, respectively.

During a debriefing session after the questionnaires were completed, all but one observer commented that although 4000 K is an acceptable color of light for office use, they prefer 3500 K lamps to make office environments appear more appealing and comfortable. However, one designer noted that some high-tech clients prefer CCTs from 4000 K up to 5000 K.

Although it was not directly addressed in the questionnaire, color rendering is another important component of color quality. Table 4 provides a summary of CRI values based on product type. Three of the five LED T8 products and one of the dedicated LED troffers had a CRI less than 73; this level is below what is specified today for most office and classroom applications (CRI greater than 80). Specifiers should be aware that some LEDs have color attributes that are poorer than the majority of fluorescent options, although some LEDs also deliver *better* color rendering than their fluorescent counterparts. Scrutiny of LED color data is an important task for the lighting specifier.

Power Quality

ANSI C82.77-2002 provides power quality recommendations for lighting equipment. Commercial indoor hard-wired ballasts or luminaires are recommended to have a minimum PF of 0.9 and a maximum line current THD (fundamental) of 32%. CALiPER testing showed that under the same specified conditions, line current THD was measured to be below 12% for all luminaires except two LED T8 lamps, types A and C, which were measured at 37.4% and 46.4%, respectively.

Dimming

Participants in the mockup event answered additional questions when the luminaires were dimmed, which were related to several characteristics such as flicker, color quality, and the dimming performance itself. Notably, six of the LED luminaires (types A, B, C, D, F, and O) were not dimmable. Additionally, one product (type U) did not have a 0-10V dimming option, and instead was dimmed with a proprietary 256 step digital control.

Observers were shown each type of dimmable luminaire at full output, then slowly dimmed to its lowest level using the Encelium EMS, and then raised back to full output. They were also shown the dimming performance from the off state, raising the output from minimum to maximum. The questionnaire (Question 11) asked them to rate the dimming performance by observing “maximum output, rate of change, range over which it dims, minimum level, instability, etc.,” using a scale of one (poor) to four (excellent).

Table 4. Color rendering index (CRI) by product type, and in comparison to data from LED Lighting Facts.

	Color Rendering Index		
	Minimum	Mean	Maximum
T8 Fluorescent Benchmarks	83	85	87
LED T8 Lamps	68	75	87
LED Retrofit Kits	82	83	84
LED Troffers	68	83	92
LED T8 Lamps on LED Lighting Facts	56	79	89
LED Troffers on LED Lighting Facts	63	84	94

Different aspects of dimming performance are impacted by different system components. For 0-10V control, the luminaire performance (including the amount of flicker present) at a stable dimmed level and the minimum achievable dimmed level are determined by the luminaire alone. However, the dimming curve and dimming smoothness are determined by the interaction between the control device and the luminaire. In this installation, the Encelium EMS generated and delivered a dimming control signal over the GreenBus II communication network, where it was then decoded and translated by an LCM into a 0-10V control signal that was fed to the luminaire. The luminaire driver or ballast then converts the 0-10V control signal into a relative dimmed light level. Since different drivers or ballasts may convert a given 0-10V control signal to different relative dimmed light levels, it was difficult to directly compare the dimming performance and dimming curves of different luminaires at a given level, as set by the lighting control system. Furthermore, the dimming smoothness during a high-to-low or low-to-high transition is dependent on the resolution of the control signal origin (the Encelium EMS) and destination (luminaire), and how well the luminaire driver or ballast is able to translate the transition (i.e., through software or interpolation).

The mean responses from the questionnaire indicate that the LED dimming performance was roughly equivalent to fluorescent. Notably, neither fluorescent nor LED sources have yet achieved the dimming smoothness and range benchmarks set by incandescent lamps. The mean responses to Question 11 for all luminaires except one were between 2.1 and 3.1, indicating dimming performance was neither remarkably good nor bad. Only luminaire type U differed, with a mean rating of 1.28. As previously noted, this product used a different dimming system, and the “stepping” during dimming was very apparent and widely considered distracting and unacceptable. In fact, many observers interpreted this stepping behavior as producing visible flicker, and the luminaire rated poorly in the flicker questions even though the frequency was very high (estimated at greater than 2,000 Hz) and modulation should not have been visible when the luminaire was in a fixed dimmed state.

For many luminaires, observers disliked the transitional instability from one level to the next, particularly when raising the light level from the off state to a low level of output. Some of the luminaires flashed during this transition, and several participants asked if there was a way for dimmer and luminaire manufacturers to profile this behavior. They also observed that the dimming curves for some luminaires were different than others. As a result, one product could exhibit most of its dimming during the control signal transition from 100% to 50%, while another might dim only between the control signal transition from 75% to 25%. This could make the dimming of different make and/or model luminaires appear inconsistent within a single room or auditorium, for example. A small number of LED luminaires showed color shifts when dimmed to low levels, but this was not considered a major issue—among the 21 LED or 3 fluorescent luminaires examined—for the commercial office lighting application.

The minimum measurable illuminance for each luminaire type varied somewhat from session to session, but Table 5 shows the approximate minimum level achieved through dimming. Note that luminaire types Q and U could be dimmed so low that a glow was detected visually from the luminaire, but there was no measurable difference from the ambient illumination.

Flicker

Photometric flicker has been shown to be related to migraines, headaches, autistic behaviors, reduced visual performance, and comfort, along with other possible neurological health issues.¹¹ With the introduction of LED

¹¹ IEEE PAR 1789 report, *“Recommending practices for modulating current in High Brightness LEDs for mitigating health risks to viewers.”* <http://grouper.ieee.org/groups/1789/public.html>

products to the marketplace, flicker has reemerged as a consideration, partly because the time-modulation of LED light output has been frequently observed to be greater than the modulation seen with fluorescent or HID sources. For LED sources, flicker is predominantly determined by the LED driver. Some driver designs produce little to no detectable flicker at full or dimmed outputs, others result in flicker noticeable at both full and dimmed output, while still others produce little to no flicker at full output but objectionable flicker when dimmed.

All light sources flicker to some degree, usually as a consequence of drawing power from AC mains sources (i.e., 60 Hz AC in North America). However, large variations in light output can be visible to some individuals, and may affect some populations even if not visible. Four factors characterize flicker: amplitude modulation of light output (i.e., the peak versus minimum light output in a cycle), the average light output in a cycle (also called the DC component), the shape or duty cycle of light output during a cycle (or, roughly, the percentage of time the light output is high or on during the cycle), and the frequency. At this point in time, the research community does not have a precise model of how combinations of the four factors render the light modulation hazardous or harmless.

At present, a standard procedure for measuring luminous flux modulation does not exist. Flicker measurements for the products were made in the PNNL laboratory using a test setup consisting primarily of a light-impermeable box, an analog photosensor with matching transimpedance amplifier and digital oscilloscope, together with digital signal processing software. This allowed the capture of even very high-frequency luminous flux modulation. Appendix F shows the light output waveforms for the luminaires at full output (both when operated by a switch and when operated by a 0-10V dimming control) and dimmed at an approximate setting of 25% on the dimming control. Only the switched waveform is shown for non-dimming luminaires.

As measured by PNNL, none of the mockup luminaires exhibited dramatic flicker in either switched operation or full-output in dimming operation. Most of them produced a steady or effectively DC output, defined here by 3% flicker or less. Table 5 provides the flicker attributes for each dimmable product.

Based on several questionnaire items that dealt with the subject, the observers varied widely in their ability to detect flicker, as is typical among human observers. None of the participants were able to reliably detect flicker when luminaires were at their full output, as controlled by the Encelium EMS. The most objectionable flicker was seen in luminaire types N, B, and L. However, when dimmed, some drivers produced a greater modulation depth, and almost all observers were able to pick up flicker through the stroboscopic effect produced by hand motion or pencil movement in the area lit by the troffer. Several observers needed no motion more than their normal eye movement to register the flicker. In the dimmed state, the observers most easily identified luminaire types X, G, and E as producing flicker. From the flicker waveforms, it appears that these three LED drivers all use pulse-width modulation (PWM) as a technique to reduce the average light output, producing 100% flicker at a PWM frequency of around 250 Hz. The mean rating for luminaire type N was also moderately low, and was potentially influenced by the lower 120 Hz modulation.

It is notable that flicker was detectable from luminaire type M by approximately one third of the observers when dimmed. Probably a consequence of its higher PWM frequency, it received higher average ratings (indicating less noticeable flicker) than luminaires with higher values of flicker index and percent flicker. This includes luminaire type N at its dimmed setting, even though type M's flicker metrics are higher (i.e., worse) than type N's. Anecdotally, this shows the effect of frequency on flicker detection, although it does not indicate whether invisible flicker is without physical or neurological consequences.

Table 5. Flicker and minimum output characteristics for each luminaire type. Yellow highlighting indicates products that observers indicated exhibited mild flicker, whereas orange highlighting indicates products deemed to have moderate to bad flicker.

Tag	Product Type	Full Output			Dimmed			Minimum Output ¹
		Percent Flicker	Flicker Index	Frequency (Hz)	Percent Flicker	Flicker Index	Frequency (Hz)	
A	T8 LED Lamps	1.8%	0.00	DC	-	-	-	-
B	T8 LED Lamps	16.5%	0.05	120	-	-	-	-
C	T8 LED Lamps	1.1%	0.00	DC	-	-	-	-
D	T8 LED Lamps	12.9%	0.04	120	-	-	-	-
E	LED Retrofit Kit	0.3%	0.00	DC	100.0%	0.77	270	4.2%
F	LED Retrofit Kit	0.4%	0.00	DC	-	-	-	-
G	LED Retrofit Kit	0.4%	0.00	DC	100.0%	0.76	260	10.9%
H	LED Retrofit Kit	0.3%	0.00	DC	0.4%	0.00	DC	10.2%
I	T8 Fluorescent	0.6%	0.00	DC	3.0%	0.00	DC	5.5%
J	T8 Fluorescent	0.6%	0.00	DC	2.9%	0.00	DC	9.2%
K	T8 Fluorescent	0.6%	0.00	DC	2.9%	0.00	DC	4.1%
L	T8 LED Lamps	21.6%	0.07	120	16.3%	0.05	120	18.5%
M	LED Troffer	0.4%	0.00	DC	100.0%	0.59	480	3.6%
N	LED Troffer	23.6%	0.07	120	13.2%	0.04	120	10.8%
O	LED Troffer	1.3%	0.00	DC	-	-	-	-
P	LED Troffer	1.0%	0.00	DC	0.4%	0.00	DC	6.6%
Q	LED Troffer	11.2%	0.03	120	6.9%	0.02	120	0.4%
R	LED Troffer	7.5%	0.02	120	16.1%	0.05	120	11.5%
S	LED Troffer	0.3%	0.00	DC	0.6%	0.00	DC	13.2%
T	LED Troffer	0.1%	0.00	DC	0.9%	0.00	DC	11.5%
U	LED Troffer	1.3%	0.00	DC	55.7%	0.15	2,000	0.0%
V	LED Troffer	0.6%	0.00	DC	0.5%	0.00	DC	4.9%
W	LED Troffer	0.8%	0.00	DC	0.7%	0.00	DC	9.1%
X	LED Troffer	0.3%	0.00	DC	100.0%	0.77	250	4.0%

1. Minimum output in dimmed state relative to full output.

Note that luminaire type U received very poor ratings for flicker, for reasons that likely have nothing to do with flicker. Its color was poor and bluish in contrast with the other luminaires, its stepped dimming was widely considered unacceptable and interpreted as “flickering,” and its appearance was not well liked. For these reasons, U was not included in the regression analysis of flicker metrics.

Figure 14 shows about the same high correlation between the mean expert response for the question on flicker detectability in the dimmed state to the two most common flicker metrics, with $R^2 = 0.71$ for flicker index and $R^2 = 0.72$ for percent flicker. Neither of these metrics describes flicker perception completely, since neither accounts for frequency.

Installation Concerns

Installing LED T8 lamps and retrofit kits can sometimes be baffling or challenging for the electrical contractor. CALiPER wanted to capture the perspective of the installer, so a commercial construction electrician from the Richland, Washington area was hired to convert the fluorescent troffers to LED. The installation process was

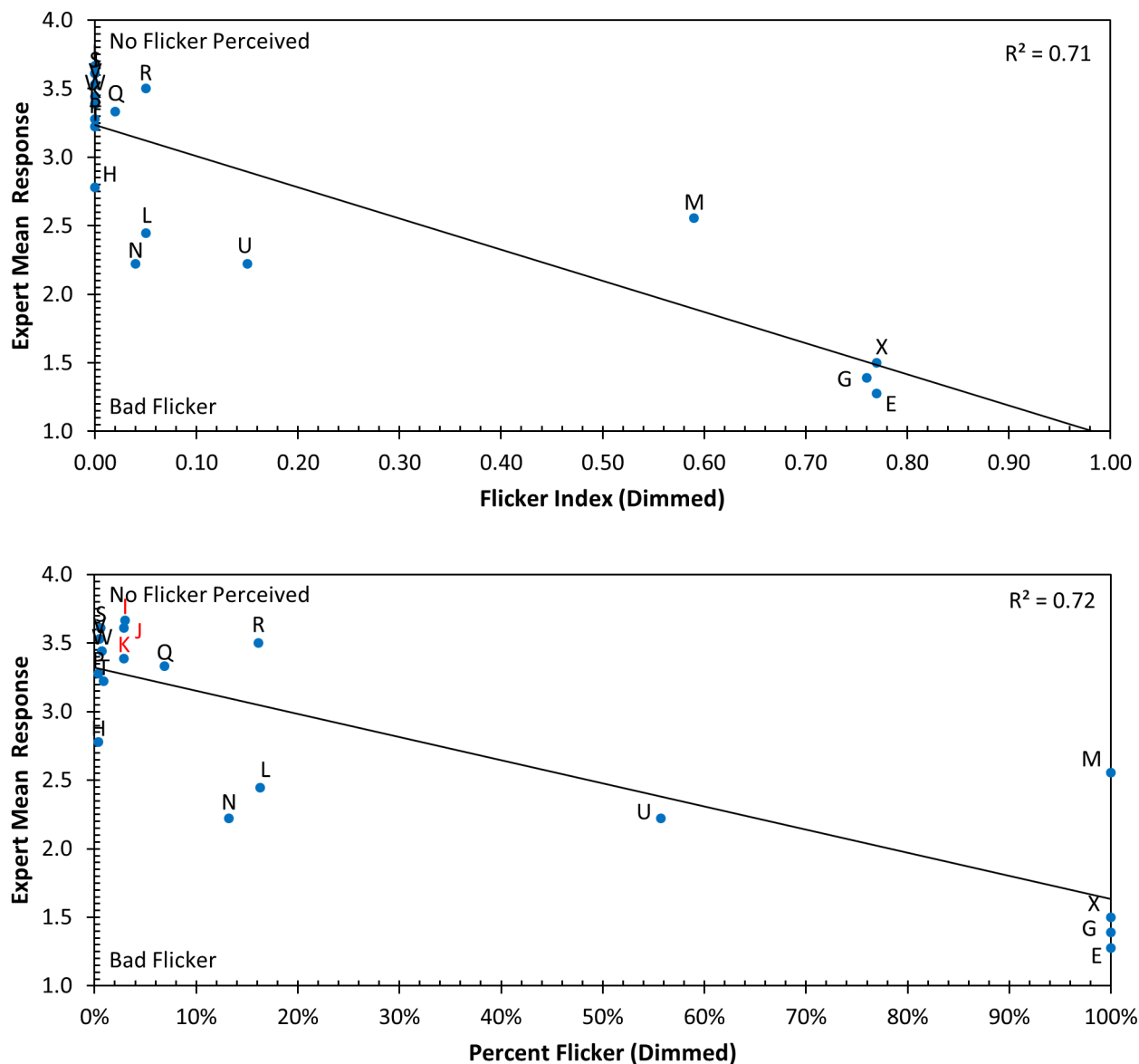


Figure 14. Mean expert ratings for *While dimmed, do you detect any flicker or stroboscopic effect from this luminaire or the area lighted by the luminaire?* (Question 14) versus flicker index (top) and percent flicker (bottom). These ratings and measured values are for the luminaire in a dimmed state.

monitored and his comments and recommendations documented. This anecdotal evidence is intended to provide examples of what to consider when evaluating various LED troffer retrofit products and estimating the ease of installation.

Installing LED T8 Lamps

The following are the most common comments or observations regarding the electrician's process of installing the LED T8 lamps in the typical troffers. Each bullet point usually applies to more than one product.

- Most of the LED T8 lamps were sold as a universal product, with no stated requirements in the specification sheets for the types of fluorescent sockets that would work. Some instructions omitted any details about the bi-pin fluorescent sockets, which could be a serious safety hazard. Some LED T8 lamps were designed for shunted sockets, whereas some were expressly *not* designed for shunted sockets and

require the sockets to be changed out to rapid start sockets. The wiring for the different T8 products was not consistent, and incorrectly wiring the socket could easily result in a short circuit. The electrician suggested that in all cases the LED T8 lamp manufacturers should provide all new sockets of the proper wiring configuration, since the older sockets could easily be worn or broken anyway. Also, extracting wires from older sockets and rewiring them differently was tedious and time-consuming.

- Some LED T8 lamps came with stickers to be mounted inside the modified luminaire to warn users not to reinstall T8 fluorescent lamps; however, if the instruction sheet made no mention of the label, the electrician did not always install it.
- The instructions said to install a supplied plastic lens sheet in the "frame of existing housing," but it was not clear whether the lens sheet was to be used in lieu of the existing troffer lens, or in addition to it. If the lens sheet were to be added to the prismatic lens, was it to be added loose in the door frame, or sandwiched in the lens frame flush with the lens? After powering the luminaire, it was clear both were needed to reduce the odd pattern produced by the LEDs, and the least distracting pattern was produced with no gap between the K12 lens and the diffusing panel.
- The instruction sheets referred to sleeving or other bits that were supposed to be included in the packaging for the retrofit kit, but were not.
- The electrician commented that removing ballasts and rewiring sockets in the existing fixture in order to accommodate the LED T8 lamps was easier to understand, but more work and more time-consuming than installing an LED retrofit kit.
- In some troffers, there was not enough wire to reach across the fixture once the ballast was cut out. Extra wires had to be added, adding time to the process.
- Two LED T8 lamp manufacturers' products had rotatable pins on the socket, for orientation of the lamps inside the troffer. The electrician found it very challenging to get these lamps seated and rotated in the fluorescent socket, even before he took the step of orienting the lamps.

Installing LED Retrofit Kits

The following are the most common comments or observations regarding the electrician's process of retrofitting fluorescent troffers with LED retrofit kits. Each bullet point usually applies to more than one retrofit product.

- Some of the retrofit kits needed to be installed in deeper troffer housings (e.g., "deeper than 4.5 inches"), but it was easy to miss that note on the product cut sheet.
- The electrician commented that the kits that direct the installer to throw away the tombstones and install bars of LEDs instead of T8 lamps are a lot less labor. He said, "If I was the manufacturer, I would throw that [fluorescent socket] technology out. It is totally outdated and requires more work and twice as many wire nuts to reuse the tombstones."
- LED retrofit kits where the driver used the same holes and clips as the ballast were easier to install. Not all kits fit conveniently in conventional fluorescent troffer products because there are variations in the basic form factor. In one case, the cover for the access door in the chassis interfered with the retrofit kit's ability to lay flat in the housing.
- Several retrofit kits were poorly engineered, requiring the electrician to adapt the product to the existing troffer by locating LED drivers off-center or bending reflectors and metal panels, for example. Further, some instructions provided no guidance on attaching mounting brackets, a power drill was often needed, and adhesive mounting strips on the back of LED boards meant there was no room for error in placing the strips.

- One of the retrofit kits required throwing the existing doorframe away, replacing it with a new diffuser and splayed trim. The electrician liked the appearance of the new surface; however, that kit was only held in place by its flange, sandwiched between the troffer housing's flange and the T-bar. The electrician was nervous that it would not be secure and it would be difficult to service the driver once the unit was installed in the ceiling grid.
- One LED retrofit kit provided stranded wire for push connectors, when the electrician thought solid wire would be easier to install and provide a more secure electrical connection.
- With optical systems where a paper-thickness diffuser was provided in addition to the prismatic lens, the electrician was not clear whether that diffuser was just protective material for shipping, or whether it should remain in the completed fixture. The instructions were not explicit.
- Protective films were provided on some lenses and surfaces to minimize scratching, but instructions suggested removing them long before the risk of scratching the surface was over.
- Instructions for some LED retrofit kits and T8 lamps made no mention of the importance of installing a label on the modified fixture. In one case, the "label" was printed on the instruction sheet paper itself, and the manufacturer expected the installer to cut out the paper label and tape it to the inside of the modified fixture.

Time Required to Relamp or Retrofit Troffers

The commercial construction electrician retrofitted five troffers with LED T8 lamps, all of which required disconnecting the fluorescent ballast. Most required additional work with the sockets. Although the electrician had no previous experience rewiring for LED T8 lamps, he had a better idea of what to expect for the later products, so it took less time. There was a learning curve for the four LED retrofit kits as well, but less consistency among the four kits. The following times are for modifying two identical troffers:

- LED T8 lamps: 105 minutes, 95 minutes, 65 minutes, 55 minutes, and 30 minutes (for one troffer only; the second had already been retrofitted for its laboratory testing).
- LED retrofit kits: 100 minutes, 90 minutes, 85 minutes, and 45 minutes.

Given these measurements, there does not appear to be a clear advantage in terms of installation time for either type of retrofit product. Nonetheless, specifiers should carefully consider ease-of-installation, as labor can substantially increase payback period for retrofit projects.

Electrical Safety and Certification of Retrofitted Troffers

There is ongoing concern in the lighting industry over the safety of fluorescent troffers when they are converted using LED T8 lamps or retrofit kits. Specifically, the issue is whether or not the retrofitted luminaires maintain existing safety certifications. The national testing laboratories for electrical safety may apply marks including UL, ETL, and CSA, and the authorized laboratories are collectively called the National Recognized Testing Laboratories (NRTL). The three levels of NRTL listing are as follows:¹²

- **NRTL Classified.** This indicates the product has been evaluated by the laboratory, but only with respect to specific properties, a limited range of hazards, or suitability for use under limited or special conditions. LED retrofit kits and LED T5 or T8 lamps that require disconnection of the original ballast, and reflector kits, are products that usually fall into the classified category.

¹² Information provided by Carl Bloomfield of Intertek Testing Laboratories.

- **NRTL Recognized.** This mark is used with components that are intended to be installed as part of a specific larger system, such as an LED driver, where the fixture housing may provide protection from heat. The components are intended to be installed at a factory, not in the field. A luminaire can be rated to use a variety of recognized components, without requiring re-testing for re-listing. However, the rules for recognition are not consistent among testing laboratories, so a driver that is recognized for use in one luminaire may not be interchangeable with one recognized for use in another luminaire. LED drivers can only be given a NRTL recognized label if they are temperature tested, unlike Class P (thermally-protected) fluorescent ballasts. Because Class P ballasts are thermally protected, they can be used in a luminaire housing that has not undergone specific temperature testing. Most fluorescent luminaires are temperature-exempt unless they are used in insulated ceilings, mounted in cooking hoods, are gasketed for use in wet locations, and/or a variety of other conditions that necessitate special temperature testing.
- **NRTL Listed.** This indicates that the laboratory found that a representative group of product samples met ANSI/UL's safety requirements, usually based on published UL standards. The typical listed product is a complete system meant to be "plug and play," meaning nothing else needs to be done to the product other than connecting power, either with a cord-and-plug or by hard-wiring. T5 or LED T8 lamps can fall into this category if they are designed as a straight fluorescent lamp replacement, with no ballast change or disconnection. Unlike fluorescent ballasts, LED drivers cannot be listed because there is not yet consensus in the industry on how to test drivers for consistent performance, given the wide variation in potential connected loads (e.g., number, type, make/model, and configuration of LEDs).

When a specifier or client is considering an LED T8 lamp or LED retrofit kit installation, they should ask the product manufacturer:

1. Is the lamp or kit NRTL approved? If this is an LED lamp, it must comply with UL1598C and the UL1993 standard. LED lamps that use a separate driver (i.e., the driver is not built into the lamp itself) must comply with UL1598C only.
2. Is there any limitation on which manufacturers' troffers it can be used with?

A local electrical inspector can disapprove any retrofit kit or LED T8 lamp that has no label installed in the troffer. Labels are an essential piece of information for a retrofitted product because they transfer responsibility of the retrofitted product from the original manufacturer to the LED product manufacturer. For this reason, it is essential that the label be sufficiently prominent, so that a future maintenance person knows how to contact the manufacturer and how to describe the installed product (i.e., the catalog number). This label should also carry the NRTL approval mark.

Inspection of the installed LED retrofit kits and T8 lamps at the mockup site, performed by Carl Bloomfield of Intertek Testing Laboratories, resulted in the following comments, warnings, and observations:

- Most of the products appropriately exhibited NRTL Classified testing labels on their instruction sheets or on the products.
- The most common issue was a lack of stickers/labels mounted inside the retrofitted troffer to change responsibility of the product, provide contact information, and warn users and maintenance people about the permanent changes made to the luminaire. Of the eight products inspected (not including type L, which was not inspected because it was a prototype product), four were missing stickers and a fifth had a label that provided no new contact information for the manufacturer.

- It was not easy to see how the ground wire was wired in two of the luminaires.
- One retrofit kit had different manufacturers' names on the instruction sheets and the kit hardware. The two must match.
- One retrofit kit was installed with self-tapping screws, which are not allowed because they can pierce a jacketed electrical wire. It was not known whether these were supplied in the kit, or provided by the electrician.
- One LED T8 lamp manufacturer had multiple stickers and markings on their product, with conflicting catalog numbers. This would pose a problem with product reordering.
- One LED retrofit kit utilized LED strips that were screwed directly to the fluorescent troffer housing. Unfortunately, because fluorescent luminaires are temperature-exempt, there is no way to know whether this combination of metal housing and LED is safe, without complete temperature testing of the retrofitted system.

The inspection showed that for more than half of the installed LED lamps and kits, an electrical inspector could have disqualified the installation of luminaires due to safety documentation or poor assembly. This does not necessarily mean that the luminaires were unsafe, but it could trigger the inspector to require a site-inspection and safety certification by a recognized safety testing body. Manufacturers should ensure proper compliance with established safety protocols and labeling requirements, in order to avoid costly site certifications.

Lighting Control

This study was intended as an evaluation of lighting performance, not lighting control performance. However, the subjective evaluations were greatly aided and facilitated by the availability of the lighting control system provided by OSRAM SYLVANIA/Encelium. Many observers were interested in the impact of the control system on the lighting performance of the luminaires and the capabilities of the lighting control system. These inquiries revolved around several themes: 0-10V dimming; system architecture; and ease of installation, commissioning, and use. As discussed earlier, the 0-10V dimming protocol does not guarantee uniform dimming ranges or smoothness. The Encelium EMS did not offer the ability to customize how it generated its control signal, but it did offer the ability to normalize the dimming range and linearize the dimming curve for a given luminaire make and model if the user was willing and able to take a series of illuminance measurements at varying control signal inputs. The Encelium EMS uses a hybrid architecture, in that the communication network consists of channels of series-connected luminaires communicating control instructions via a proprietary protocol, but the dimming signal was delivered to individual luminaires via the "standardized" 0-10V protocol. This approach greatly simplifies the design and installation of such a system, without requiring any specialized or proprietary interface in the luminaire.

The cable construction was simple, and daisy-chain installation goes extremely fast. However, attaching the LCM to each luminaire can be a laborious process. Installation is seemingly simple; each LCM has a threaded mount designed to be inserted through one of the knockouts available in the driver or ballast compartment. Variations in knockout number and location, as well as available space within the driver or ballast compartments, slowed the process at times. A normal office lighting installation would have fewer luminaire makes and models, which would reduce the installation challenge, but these are barriers to ideal plug-and-play installation. Commissioning the system proved to be a relatively straightforward process, and once the entire system was up and running, operation and performance were extremely reliable.

4 Discussion

Comparison of Knowledgeable and Naïve Observer Responses

Following the workshop with 18 lighting-knowledgeable observers, a similar questionnaire and protocol was given to five Intertek employees with no lighting experience. Although the sample size was too small to make precise comparisons, the data supported the informal observations shown in Table 6. In general, the responses did not seem remarkably different; a more complete analysis would require larger sample sizes.

Verbal Feedback from Observers

After the observation data had been collected, participants were invited to contribute comments and suggestions in a group debriefing. In many ways, this feedback was just as valuable as the numerical results of the questionnaire. Several areas of concern over LED (and fluorescent) troffers were identified:

- There is color inconsistency among LED products that were ordered to be “4000 K” white. Multiple LED products installed in a single interior space could exhibit sufficiently different color appearances that occupants could find it distracting. As with metal halide and fluorescent technologies, the project specifier must do mockups to ensure color compatibility.
- Observers could identify flicker under dimmed conditions for some (but not all) LED products, although some needed a demonstration of how to test for it since their visual systems were not sensitive to flicker. All were frustrated with the wide variation in flicker found in LED sources, and the difficulty in correlating any flicker measurements with risk levels for the various flicker hazards.
- They were also frustrated that metrics are not reported to help them identify products with more or less flicker. Flicker metrics and guidelines for using them are needed.
- Compared to fluorescent lamps, LED T8 lamps installed in troffers increased the contrast of the lamp against its background in all cases. The fact that the evaluated lamps emitted no backward light changes both the photometric distribution and the appearance of the luminaire, resulting in brighter stripes of light in the lens or louver.
- The computer tablet screens were especially reflective of all recessed troffers in the space, whether fluorescent or LED, and none of the luminaires were effective at rendering that mirror-like reflection less conspicuous. Because of the superimposed reflection, an iPad screen was very difficult to read without adjusting its tilt.

Table 6. Comparison of responses from the naïve and expert observers.

Performance Area	Relative Reaction of Naïve Observers
Appropriateness of light level	Overall, the naïve observers thought amount of light was less appropriate (i.e., too low) for an office application
Overhead glare	Overall, the naïve observers found glare less objectionable
Discomfort glare	The naïve observers found direct view glare less objectionable, but had similar response to high spot luminances on troffers
Reflected glare	The naïve observers were less sensitive to screen glare, but responses were similarly related to high spot luminances on troffers
Flicker at full output	Like the experts, the naïve observers were unable to see any flicker
Flicker when dimmed	Responses almost identical to those of experts
Appearance of luminaire	As with the expert ratings, the lowest rated products also had lowest CRI and R ₉ values

- Computer and tablet manufacturers do not always publish whether the screen finish is matte or shiny, so it is difficult for the specifier to modify the lighting for electronic display devices in an office or classroom—much less for the technology that will be prevalent in five years. Similarly, the specifier cannot anticipate ink colors, screen types, font sizes, etc.; thus, the IES Handbook office lighting recommendations are difficult to apply. The observers noticed a market trend toward troffers that deliver a cosine distribution of light (see the round polar plots of luminaires G, M, P, S, T, and V in Appendix D). They wondered whether batwing distributions (see polar plot of luminaires Q and R in Appendix D) would help reduce reflected glare and discomfort glare.
- LED dimming performance from 0-10V dimming drivers was about as smooth and predictable as that seen in fluorescent troffers with 0-10V dimming ballasts. Observers disliked the flash that occurred when raising the output from off to a minimum dimming level for some LED luminaires. Although neither fluorescents nor LEDs have achieved the dimming smoothness and range of incandescent sources, the approximate minimum values achieved by the luminaires as a whole were considered acceptable for most applications, including daylight dimming.
- There was widespread concern about the performance and safety issues surrounding LED T8 lamps and retrofit kits. Intertek’s post-conversion inspection of the fluorescent luminaires modified with retrofit kits provided invaluable information for the study’s participants on the conditions for preserving NRTL certification and listing of the products.
- “The fluorescent troffer did not get better with LEDs.” The efficacy may be higher, but the light distribution, appearance, direct and reflected glare, and other issues have not necessarily improved compared to fluorescent.

Comparison of Product Types

Combining the measured performance values and the subjective responses of the participants, observations can be made regarding each type of LED troffer product included in this evaluation. Notably, the included products are not an exhaustive representation of the market. However, the performance trends are clear. As always, any given product should be evaluated on its own merit.

First, dedicated LED troffers are already ready to compete with fluorescent troffers in terms of efficacy and in many lighting quality issues such as glare, light distribution, visual appearance, and color quality. That is not to say that every one is stellar, but each one tested in this CALiPER study bested the fluorescent benchmarks in terms of efficacy, and almost all were rated highly by the observers in several categories. Only one LED troffer was consistently rated poorly. One area of concern is that one-third of the dedicated LED troffers were equipped with 0-10V dimming drivers that caused the LEDs to exhibit objectionable flicker when dimmed. It is important for the lighting industry to develop, adopt, and apply standards to limit flicker.

LED T8 lamps performed in the same efficacy range as the fluorescent benchmarks, so it is not clear that they offer guaranteed energy savings compared to fluorescent troffers with 25 or 28 W high-performance lamps and electronic dimming ballasts. However, LED T8 lamps could be an energy-efficiency improvement compared to older, low-efficiency T8 systems. It was clear to observers that LED T8 lamps that have exposed rows of bright LEDs are more likely to produce objectionable stripes and patterns in existing troffers than LED T8 lamps that have a diffuse finish on the lens. The color quality of the included lamps ranged widely from very poor (CRI in the 60s) to very good (CRI in the upper 80s).

LED retrofit kits hold some promise, but also face challenges. Every one of the kits in this CALiPER study had issues, such as different colors delivered from the same fixture specification, odd or distracting bright patterns

produced on the lens, poor-quality appearance, glare, and objectionable flicker when dimmed. However, these are engineering issues that can be solved by manufacturers, and a retrofit kit avoids some of the safety concerns associated with LED T8 lamps. Kits also offer the chance to provide a fresh appearance to the luminaire, rather than retaining the original lens or louver.

Relating Subjective Evaluations to Numerical Metrics

In addition to the global evaluations of each product type, the subjective evaluations of the entire group helped to identify key performance attributes that help or hinder the effectiveness of the product. Specific observations include:

- LED and fluorescent troffers emitting more than 4,800 lumens per luminaire were considered excessive (i.e., emitting too much light) for normal office use, given the nine-foot ceiling heights and the luminaire spacing used in this study. Luminaire lumens as low as 2,100 were considered acceptable. This may suggest that since there are varying office and classroom types, dimensions, visual tasks, and user ages, a specifier should be able to choose from a range of troffer lumen values.
- All of the troffers studied were judged to produce acceptable uniformity on the workplane, and this seemed unrelated to spacing criterion. However, it is important to note that there were no workstation partitions in the mockup room that could block the spread of light, plus all the surfaces were a neutral gray or white color.
- Light distribution on adjacent office walls is a factor that seems to be related to the percent of light emitted from 60° to 90°. Troffers that emitted more than 10% of their lumens in that zone produced better—meaning higher and “softer”—wall patterns. Parabolic louver troffers lamped with LED T8 lamps were rated lower than those lamped with fluorescent lamps, probably because the back light from the fluorescent tube (the indirect component) helps soften the pattern of light on the adjacent wall.
- Strong patterns created on lensed fixtures (pronounced stripes, swirls, circles, etc.) were disliked. The appearance of troffers with LED T8 lamps and some retrofit kits evoked strong negative reaction, compared to dedicated LED or fluorescent troffers. This strongly suggests that retrofit products need to be mocked up and visually evaluated before ordering the product for a large installation.
- Glare remained an enigma. Whether overhead glare or direct (discomfort) glare, only one measured or calculated photometric quantity proved to be a promising predictor. That metric was maximum spot luminance measured across the face of the troffer from a steep angle of 10° from vertical. The lowest rated troffers for glare were those LED products (new or retrofit) with prismatic lenses and odd or distracting patterns (types U, F, and C), along with an LED retrofit kit with extremely high lens luminance (type G). In general, fluorescent lensed troffers, diffuse flat panel troffers, and parabolic louver troffers received average ratings, and products with diffuse lenses and simple visual details (types N, J, W, P, and X) received the most favorable ratings for glare.
- Reflected glare on electronic display screens is a concern for tablets and other products with shiny glass, but less of an issue for laptops and monitors with matte displays or other low-reflectance screen technology. No troffer earned an average score as high as three (moderately noticeable but not problematic). This is an issue that warrants further study since the electronic screen is ubiquitous in American culture.
- Dimming performance of the LED products was deemed about the same as that of the fluorescent benchmarks; the dimming was neither dramatically smoother or more consistent. The “stepped” dimming provided by one dedicated LED troffer product (type U) was considered unacceptable for office

and classroom applications. Observers suggested that dimming profiles would be useful information for the specifier.

- Flicker was not an issue for any of the fluorescent or LED troffers operating at full output, nor for the fluorescent troffers when dimmed. However, four of the LED troffers were identified as producing moderate to bad flicker when dimmed to low output. This appeared to be related to the modulation depth and/or PWM frequency of the dimming driver's output to the LED, but currently neither metric is commonly published by manufacturers, thereby limiting the ability of specifiers to identify in advance whether a product will exhibit objectionable flicker. The flicker waveforms published in this study may be a useful industry tool.
- There is widespread concern about the performance and safety issues surrounding LED T8 lamps and retrofit kits, and concerns were raised in the post-conversion inspection of the fluorescent luminaires modified with LED lamps and retrofit kits. Manufacturers and installers should pay attention to the steps required to preserve NRTL certification and listing of the products.
- Installation problems were common. Manufacturers of LED T8 lamps or retrofit kits would do well to observe electricians at work with their products as they are installed in a range of existing troffer types, and improve their products and instruction sheets to make them easier and more intuitive for the installer, as well as more easily reviewed and approved by the electrical inspector.

Future Steps

This exploratory study of troffers represents the first complete CALiPER subjective evaluation to be undertaken. In addition to the numerical test results, it has raised issues that warrant future investigation. Flicker and glare, which seemed to be the most enigmatic attributes, are particularly worthy of future investigation. Work to improve dimming drivers is needed to reduce flicker and provide smoother dimming performance with lower minimum output levels. Further, it seems possible that a change in LED troffer light distribution could reduce perceived glare for users and reflected glare on electronic display screens. Planned future CALiPER work includes more comprehensive testing of LED T8 lamps in troffers with various aperture types. This work will include both laboratory testing and subjective assessments in an attempt to evaluate the interaction of the luminous intensity distribution of the LED lamps with the optical system of the installed luminaires. The goal is to establish guidelines to help specifiers choose appropriate product combinations to ensure lighting systems that deliver expected lighting performance without compromising occupant comfort and satisfaction.

5 Conclusions

This CALiPER study examined recessed LED troffers for office and classroom use, as a snapshot of how the lighting industry is progressing in developing energy-efficient, good-quality alternatives to conventional fluorescent troffers. It also helped identify ways to evaluate LED products for ambient lighting. From this, it is expected that luminaire manufacturers can learn what features make their products more desirable in the marketplace, and that lighting specifiers and facility managers and their colleagues and clients will gain a better idea of how to evaluate LED products, as well as which tradeoffs are acceptable and which are non-negotiable for their specific applications. The subjective responses collected for this study are likely related to a combination of performance attributes, and correlation between any single metric and a mean rating was often not very strong. Luminaires must be evaluated holistically, and there are often tradeoffs among different attributes.

In general, the dedicated LED luminaires provided the highest level of performance for LED troffer products. Notably, they may have a higher initial cost, so they may not necessarily be the best choice for all situations. In new installations, they should be a primary choice. LED retrofit kits and LED T8 lamps had a similar level of performance, with LED T8 lamps experiencing more difficulty in producing acceptable distributions and color quality given their interaction with existing optical systems. In any of the three categories discussed here, there may be effective products for a given application. Each product should be evaluated on its own merit.

As a whole, the performance of LED products in the troffer category is as follows:

- Total luminaire efficacy covers a wide range, from approximately 50 lm/W to more than 100 lm/W. There are several very high efficacy products, but actual energy savings versus the incumbent fluorescent technology ultimately depends on the total power needed to deliver effective lighting for the application. For any technology being considered, this is driven by the lumen output, input power, and light distribution.
- Distracting luminance patterns within the luminaire aperture seemed to be particularly concerning to the expert observers. These usually result from the interaction of existing optics with new LED T8 lamps or retrofit kits.
- There is a wide range of LED product quality reflected in this study: color, efficacy, light output, appearance, glare, and flicker. Many of these factors cannot be evaluated from a manufacturer's specification sheet, so it is incumbent on the specifier and client to see and compare products in person, and in mockups.

Appendix A: Questionnaire

Table A1. Questionnaire (luminaires at full output).

Question Number	Question Segment	Question	Response Range
1	Full	How appropriate is the light output from the luminaire for this application?	1 = Too low 2 = Moderately low 3 = Moderately high 4 = Too high
2	Full	Is the light distribution on the workplane between luminaires appropriately uniform for this application?	1 = Too uneven 2 = Moderately uneven 3 = Somewhat too uniform 4 = Too uniform
3	Full	Imagine the luminaire installed 2' or 3' from the walls. Is the light distribution on the adjacent wall appropriate for the application?	1 = No 2 = Somewhat inappropriate 3 = Somewhat appropriate 4 = Yes
4	Full	Is the luminaire comfortable (not glaring) to sit under in a heads-down-type visual task (office)?	1 = Not comfortable 2 = Moderately uncomfortable 3 = Moderately comfortable 4 = Very comfortable
5	Full	Is the luminaire comfortable (not glaring) to sit under in a heads-up-type visual task (classroom)?	1 = Not comfortable 2 = Moderately uncomfortable 3 = Moderately comfortable 4 = Very comfortable
6	Full	Is the direct view of the luminaire comfortable (not glaring) for normal office tasks?	1 = Very uncomfortable 2 = Moderately uncomfortable 3 = Moderately comfortable 4 = Very comfortable
7	Full	Would you consider the luminaire's reflection in the computer screen to be a concern?	1 = Reflection too bright 2 = Reflection moderately bright 3 = Moderately noticeable but not problematic 4 = Reflection not at all bright or not noticeable
8	Full	Would you consider the color appearance of the emitted light to be appropriate for this application?	1 = Poor 2 = Moderately poor 3 = Moderately good 4 = Excellent
9	Full	Do you detect any flicker or stroboscopic effect from this luminaire or the area lighted by the luminaire?	1 = Bad flicker 2 = Moderate flicker 3 = Almost no flicker 4 = No flicker perceived
10	Full	Do you like the appearance of this luminaire?	1 = Not at all 2 = Moderate dislike 3 = Like somewhat 4 = Like very much

Table A2. Questionnaire (luminaires dimmed).

Question Number	Question Segment	Question	Response Range
11	Dimming	Please describe the dimming performance: Maximum output, rate of change, range over which it dims, minimum level, instability, etc. Then, please give it a rating for this application.	1 = Poor 2 = Moderately poor 3 = Moderately good 4 = Excellent
12	Dimming	Would you consider the color appearance of the emitted light to be appropriate for this application?	1 = Poor 2 = Moderately poor 3 = Moderately good 4 = Excellent
13	Dimming	At maximum output, do you detect any flicker or stroboscopic effect from this luminaire or the area lighted by the luminaire?	1 = Bad flicker 2 = Moderate flicker 3 = Almost no flicker 4 = No flicker perceived
14	Dimming	While dimmed, do you detect any flicker or stroboscopic effect from this luminaire or the area lighted by the luminaire?	1 = Bad flicker 2 = Moderate flicker 3 = Almost no flicker 4 = No flicker perceived

Appendix B: Luminaire Measurement Results

Table B1. Basic performance characteristics. All measurements were taken by independent photometric testing laboratories according to LM-79-08. Only one sample of each product was tested. All measurements are for in-situ performance, if applicable; refer to Table 1 for luminaire configurations.

Tag	Initial Output ² (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	THD	CRI	R ₉	CCT (K)	D _{uv}
A	3,667	48	76	0.92	37%	68	-44	4355	0.0063
B	3,600	66	55	1.00	6%	87	36	4094	-0.0027
C	5,246	69	76	0.90	46%	73	-16	4114	0.0022
D	3,402	50	68	0.99	10%	72	-16	4184	0.0012
E	2,924	43	68	0.99	12%	84	39	3616	-0.0006
F	2,138	36	60	0.99	10%	84	25	4137	-0.0016
G	3,088	51	61	0.99	9%	83	21	3233	-0.0034
H	2,686	35	77	0.99	7%	82	2	3991	0.0037
I	3,516	58	60	1.00	5%	85	9	3959	0.0069
J	2,740	48	57	0.99	11%	87	11	3874	0.0053
K	5,093	82	62	1.00	7%	83	11	4092	0.0042
L ¹	-	79	-	0.98	10%	83	22	3815	0.0015
M	3,880	42	93	0.99	6%	92	64	4019	0.0000
N	3,721	36	105	0.97	9%	83	13	4022	0.0030
O	4,089	52	78	0.99	6%	85	45	3959	0.0010
P	2,742	35	79	1.00	3%	87	51	4016	0.0013
Q	3,425	34	100	1.00	12%	83	8	4019	0.0025
R	4,352	58	76	0.99	7%	83	23	3973	0.0011
S	3,585	49	74	0.99	7%	82	18	4057	-0.0049
T	4,349	47	92	1.00	4%	84	23	4424	0.0002
U	3,404	40	85	1.00	6%	68	-41	5184	0.0070
V	3,507	40	87	1.00	12%	82	18	3937	-0.0016
W	2,352	26	90	0.99	11%	84	22	3825	0.0028
X	5,222	49	107	0.98	10%	82	6	4144	0.0030

1. Product L did not undergo full LM-79 testing via an independent laboratory. Information listed was measured by PNNL.

2. CALiPER testing for the following luminaires showed significantly lower luminaire lumens than expected from the manufacturer-provided photometric files: type I (86%), type K (84%), type P (78%), and type W (56%). Types I and K are fluorescent benchmarks, and this may reflect a difference between relative photometry and absolute photometry. CALiPER has seen reductions up to 15% in past evaluations for fluorescent luminaires. The differences for LED luminaires P and W were not explained. All other CALiPER test results were within 10% of expected values.

Table B2. Attributes of luminous intensity distribution. Luminance values were measured by the CALiPER team for in-situ luminaires. All other values were derived from independent LM-79 results.

Tag	60°–90° Zone				Spacing Criterion	Luminous Intensity (cd)				Luminance (10° Angle) cd/m ²
	Output Density ¹ (lm/ft ²)	Output (lm)	Output Density (lm/ft ²)	Percent Total Output		55°	65°	75°	85°	
A	556	582	73	16%	1.28	650	361	206	91	9,711
B	545	237	30	7%	1.76	789	153	26	3	25,390
C	795	707	88	13%	1.22	774	405	223	82	21,920
D	515	273	34	8%	1.72	716	167	43	17	27,430
E	956	511	128	17%	1.24	631	414	167	17	17,020
F	699	265	66	12%	1.24	267	145	99	31	18,940
G	2,782	694	174	22%	1.26	580	431	278	75	21,440
H	878	312	78	12%	1.12	304	171	117	35	10,990
I	1,134	476	119	14%	1.34	487	255	159	59	12,990
J	685	466	117	17%	1.36	523	314	137	26	9,755
K	782	598	75	12%	1.48	966	515	147	35	9,058
L	-	-	-	-	-	-	-	-	-	31,700
M	1,492	755	94	19%	1.33	756	510	264	35	10,610
N	539	663	83	18%	1.24	662	419	210	53	5,536
O	590	561	70	14%	1.20	621	372	185	45	12,480
P	1,443	674	84	25%	1.32	550	445	322	153	11,160
Q	4,964	539	135	16%	1.50	613	365	173	32	19,330
R	1,299	751	188	17%	1.60	775	472	255	65	10,260
S	1,358	644	161	18%	1.30	614	390	210	66	5,869
T	1,389	852	213	20%	1.24	750	508	265	61	5,609
U	1,038	413	103	12%	1.24	512	260	166	69	55,320
V	993	673	168	19%	1.26	619	419	210	33	3,787
W	800	474	59	20%	1.32	505	321	156	41	3,863
X	1,826	1,167	146	22%	1.28	1,013	766	482	157	11,850

1. Measured as lumen output per nominal unit area.

Appendix C: Summary of Survey Responses

Table C1. Mean responses from expert observers.

Tag	Question													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	3.44	2.83	3.11	2.78	2.61	2.50	2.28	2.67	3.78	1.67	-	-	-	-
B	2.94	2.39	1.72	2.56	2.44	2.39	2.38	2.78	3.06	1.67	-	-	-	-
C	3.72	2.39	3.28	2.06	2.00	1.83	1.81	2.67	3.22	1.44	-	-	-	-
D	2.83	2.50	1.67	2.44	2.44	2.11	2.19	2.72	2.89	1.56	-	-	-	-
E	2.89	2.83	3.06	3.06	2.50	2.67	2.25	2.17	3.67	2.89	2.22	2.06	2.56	1.28
F	2.61	2.72	3.00	2.17	1.89	1.61	2.03	2.44	3.11	1.06	-	-	-	-
G	3.06	2.83	3.00	2.83	2.11	1.89	1.83	2.72	3.61	2.11	2.50	2.56	2.72	1.39
H	2.61	2.44	3.18	2.94	2.67	2.56	2.14	2.50	3.56	1.50	2.50	2.83	3.83	2.78
I	3.11	3.06	3.39	2.78	2.61	2.44	2.19	2.89	3.56	1.78	3.11	2.67	3.89	3.67
J	2.44	2.89	3.67	3.61	3.50	3.33	2.69	3.44	3.65	3.56	2.94	3.11	3.94	3.61
K	3.44	2.56	2.56	2.50	2.44	2.28	2.22	3.17	3.83	1.67	2.83	2.78	3.61	3.39
L	3.11	2.12	2.00	2.22	2.06	1.56	2.19	2.92	2.89	1.33	2.61	3.22	2.72	2.44
M	2.83	2.67	3.39	3.22	2.89	2.61	2.08	3.22	3.61	2.61	3.11	2.78	3.39	2.56
N	3.06	2.72	3.28	3.72	3.67	3.83	2.69	3.17	3.11	3.39	2.06	2.67	2.89	2.22
O	3.44	2.29	3.28	3.56	3.28	2.89	2.33	3.17	3.33	3.11	-	-	-	-
P	2.50	2.44	3.44	3.50	3.17	3.00	2.58	3.33	3.44	3.17	2.72	3.00	3.56	3.28
Q	2.94	3.00	3.22	3.28	2.72	2.50	2.00	3.17	3.56	2.94	2.94	3.17	3.50	3.33
R	3.39	2.83	3.44	3.17	2.83	2.39	2.22	3.06	3.39	2.67	3.06	3.00	3.89	3.50
S	3.44	3.06	3.44	2.83	2.39	2.17	1.86	3.00	3.56	2.67	3.06	2.94	3.83	3.61
T	3.44	3.11	3.67	2.50	2.00	2.22	1.75	2.67	3.50	2.50	2.33	2.67	3.53	3.22
U	3.33	2.50	3.00	1.61	1.39	1.11	1.50	1.56	3.22	1.06	1.28	1.56	2.89	2.22
V	2.94	3.06	3.44	3.17	3.06	3.06	2.19	2.94	3.44	2.61	2.41	2.65	3.71	3.53
W	2.00	2.39	3.22	3.44	3.39	3.17	2.50	2.67	3.67	2.44	3.06	2.72	3.67	3.44
X	3.50	2.72	3.61	3.22	2.83	3.06	2.19	2.83	3.56	3.06	2.50	2.72	2.83	1.50

Table C2. Mode (most frequent) responses from expert observers.

Tag	Question													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	4	3	3	3	3	3	2	3	4	1	-	-	-	-
B	3	3	1	3	3	2	3	3	4	1	-	-	-	-
C	4	2	3	2	2	1	1	3	3	1	-	-	-	-
D	3	3	1	2	3	2	3	3	4	2	-	-	-	-
E	3	3	3	3	3	3	2	3	4	3	2	2	4	1
F	3	3	3	3	2	1	2	2	4	1	-	-	-	-
G	3	3	3	2	2	2	2	3	4	2	2	3	3	1
H	3	3	3	3	3	3	2	3	4	1	2	3	4	4
I	3	3	3	3	2	2	3	3	4	2	3	3	4	4
J	2	3	4	4	4	4	3	3	4	4	3	3	4	4
K	3	3	2	2	3	2	2	3	4	2	3	3	4	4
L	4	2	1	2	2	1	3	3	2	1	3	3	2	2
M	3	3	3	3	3	2	2	3	4	3	3	3	4	1
N	3	3	3	4	4	4	3	3	4	4	2	3	4	3
O	4	2	4	4	3	3	2	3	4	3	-	-	-	-
P	2	3	3	4	3	4	3	3	4	4	2	3	4	4
Q	3	3	3	3	2	2	2	3	4	3	3	3	4	3
R	3	3	4	3	3	2	2	3	4	3	3	3	4	4
S	4	3	3	3	2	2	2	3	4	2	3	3	4	4
T	3	3	4	3	2	2	2	3	4	3	2	2	4	4
U	3	3	3	1	1	1	1	1	4	1	1	1	4	1
V	3	3	4	3	3	4	3	3	4	3	2	3	4	4
W	2	2	4	4	3	3	3	3	4	3	3	3	4	4
X	3	3	4	3	3	3	2	3	4	3	3	3	4	1

Table C3. Mean responses from naïve observers.

Tag	Question													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	2.80	-	3.40	-	2.80	3.00	3.00	2.40	3.80	2.20	-	-	-	-
B	2.20	-	3.20	-	2.60	2.60	2.40	2.80	4.00	2.00	-	-	-	-
C	3.20	-	3.40	-	2.60	2.80	2.40	3.00	4.00	1.80	-	-	-	-
D	2.60	-	2.60	-	2.60	2.60	2.20	2.40	3.80	1.80	-	-	-	-
E	2.80	-	2.60	-	2.40	2.40	1.60	3.00	4.00	3.20	-	-	-	2.20
F	2.00	-	2.80	-	3.00	2.20	2.40	2.80	4.00	1.80	-	-	-	-
G	2.20	-	3.00	-	2.80	2.60	2.80	2.40	4.00	2.60	-	-	-	1.50
H	1.80	-	2.60	-	2.40	2.60	2.80	2.80	4.00	2.20	-	-	-	3.60
I	2.00	-	2.40	-	2.60	3.20	2.40	2.40	4.00	2.60	-	-	-	3.40
J	2.40	-	3.00	-	3.20	3.40	2.60	2.80	4.00	2.80	-	-	-	3.40
K	2.80	-	3.00	-	2.20	2.40	2.80	2.00	3.80	1.60	-	-	-	3.20
L	3.00	-	2.40	-	2.80	2.40	2.00	2.20	4.00	1.60	-	-	-	3.25
M	2.60	-	3.00	-	2.80	3.00	2.40	2.60	4.00	3.60	-	-	-	2.00
N	2.40	-	2.80	-	3.00	3.00	2.60	2.60	4.00	3.20	-	-	-	3.40
O	3.40	-	3.40	-	2.60	2.80	2.20	3.20	4.00	3.80	-	-	-	-
P	1.80	-	2.60	-	2.20	2.80	2.60	2.40	3.80	2.60	-	-	-	3.40
Q	2.75	-	3.25	-	2.60	2.80	2.60	3.00	4.00	3.20	-	-	-	3.00
R	3.00	-	3.20	-	3.40	3.20	3.00	3.20	4.00	3.20	-	-	-	2.80
S	3.00	-	3.20	-	3.40	3.00	2.60	2.80	4.00	3.20	-	-	-	3.80
T	3.20	-	3.40	-	3.40	3.60	3.00	3.20	4.00	3.40	-	-	-	3.00
U	2.40	-	2.80	-	2.00	2.40	2.20	2.00	4.00	2.00	-	-	-	3.20
V	2.80	-	3.40	-	3.80	3.00	2.80	2.40	4.00	3.00	-	-	-	3.20
W	2.00	-	2.80	-	2.60	3.00	2.80	2.20	4.00	2.80	-	-	-	2.80
X	2.80	-	3.40	-	3.00	2.40	2.60	2.40	4.00	3.40	-	-	-	1.40

Table C4. Mode (most frequent) responses from naïve observers.

Tag	Question													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	3	-	3	-	4	2	3	1	4	1	-	-	-	-
B	2	-	4	-	3	3	3	2	4	1	-	-	-	-
C	3	-	4	-	4	2	2	2	4	1	-	-	-	-
D	3	-	3	-	3	3	3	2	4	1	-	-	-	-
E	3	-	3	-	3	2	2	3	4	3	-	-	-	3
F	2	-	2	-	3	2	2	3	4	1	-	-	-	-
G	2	-	3	-	2	2	3	2	4	3	-	-	-	1
H	2	-	3	-	3	3	2	3	4	2	-	-	-	4
I	2	-	2	-	3	4	3	3	4	1	-	-	-	3
J	2	-	3	-	3	3	3	3	4	3	-	-	-	3
K	3	-	3	-	3	2	3	1	4	2	-	-	-	4
L	3	-	2	-	2	2	1	1	4	2	-	-	-	4
M	3	-	3	-	3	4	3	3	4	4	-	-	-	2
N	3	-	3	-	4	2	3	3	4	3	-	-	-	4
O	3	-	3	-	2	4	3	3	4	4	-	-	-	-
P	2	-	2	-	2	3	3	3	4	3	-	-	-	4
Q	3	-	3	-	3	2	3	2	4	3	-	-	-	3
R	3	-	3	-	3	3	3	3	4	3	-	-	-	2
S	3	-	3	-	4	2	3	3	4	4	-	-	-	4
T	3	-	3	-	4	4	2	4	4	3	-	-	-	3
U	3	-	3	-	2	2	2	1	4	1	-	-	-	3
V	3	-	4	-	4	4	3	1	4	3	-	-	-	4
W	3	-	4	-	2	4	3	2	4	3	-	-	-	3
X	3	-	4		2	1	3	2	4	3	-	-	-	1

Appendix D: Polar Plots of Luminous Intensity Distribution

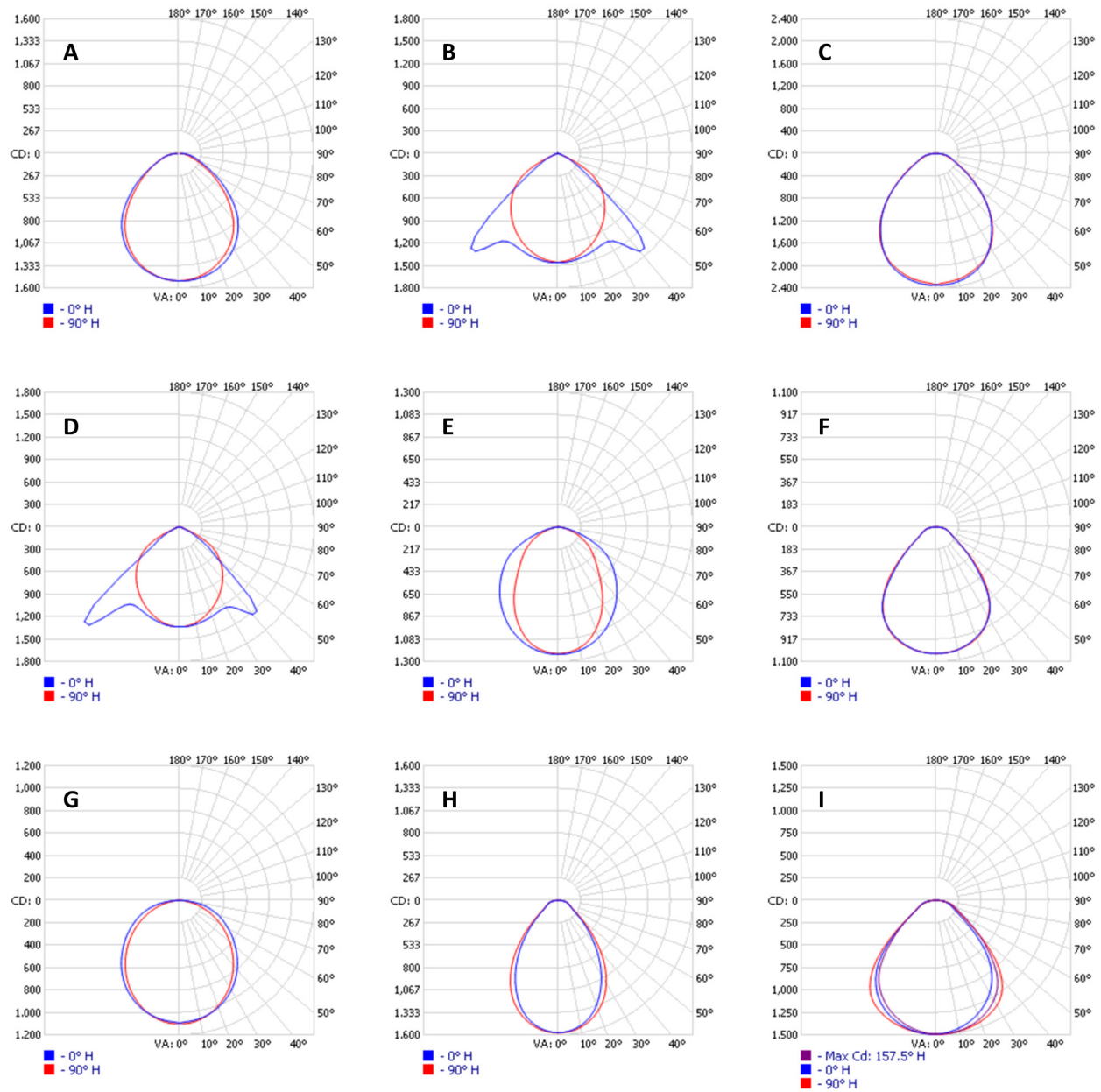


Figure D1. Polar plots of luminous intensity for product types A through I. Plots are not to scale.

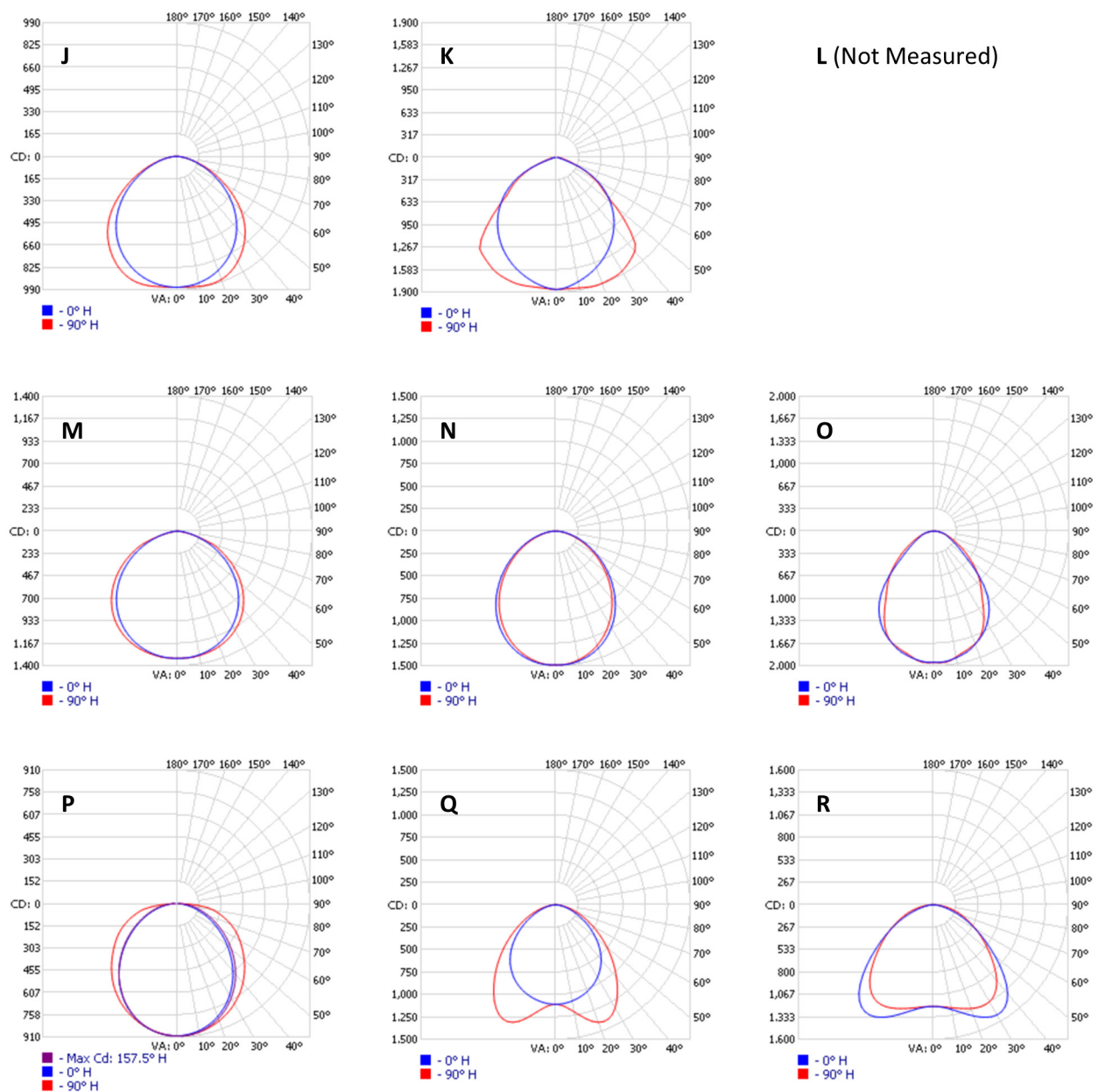


Figure D2. Polar plots of luminous intensity for product types J through R. Plots are not to scale.

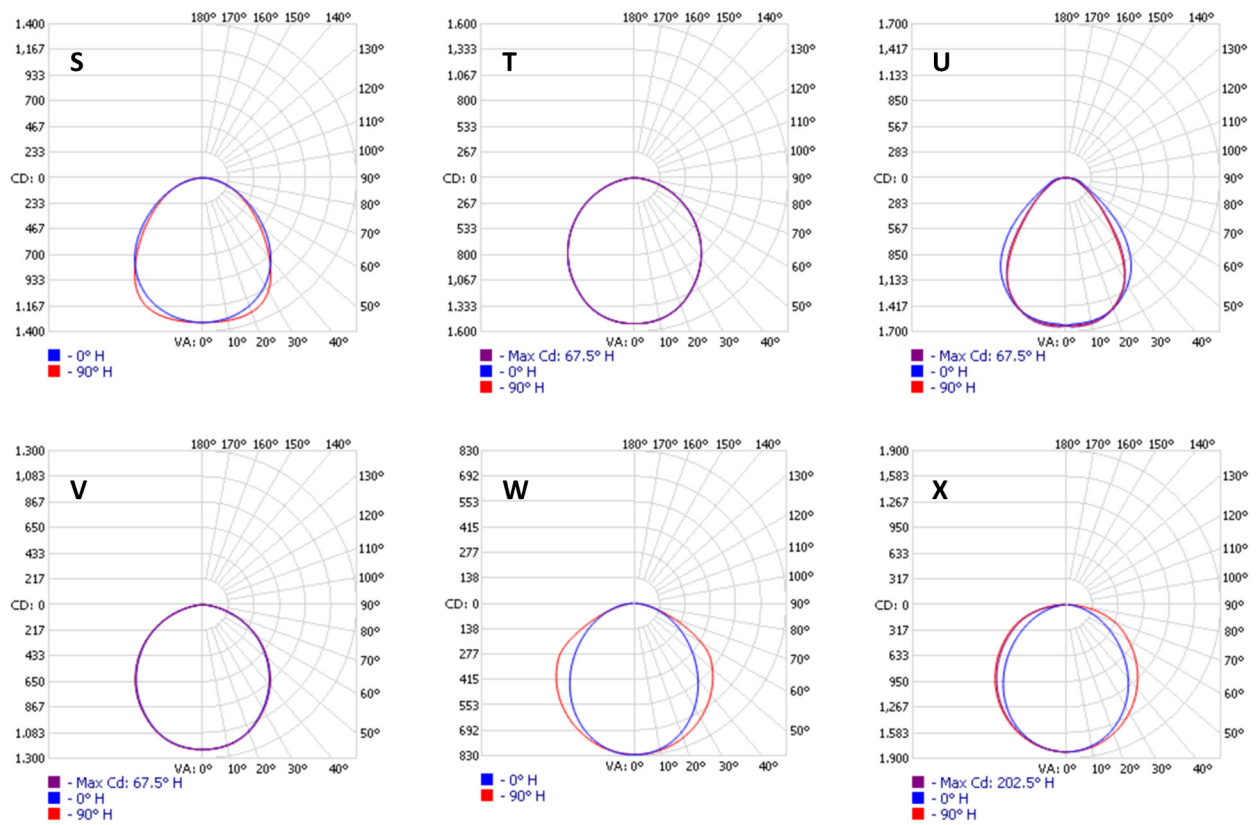
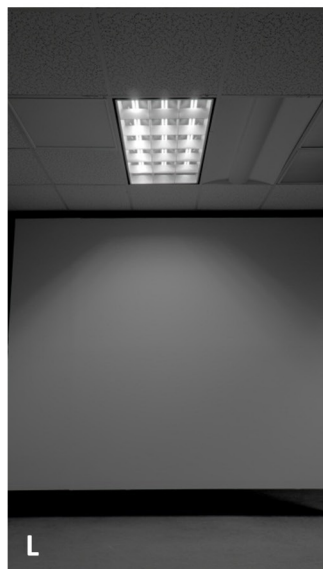
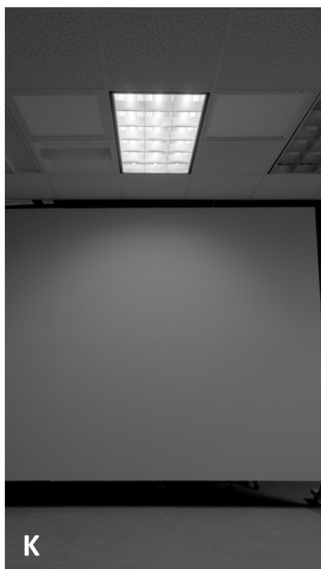
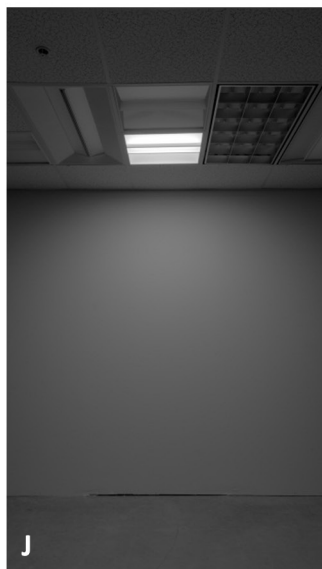
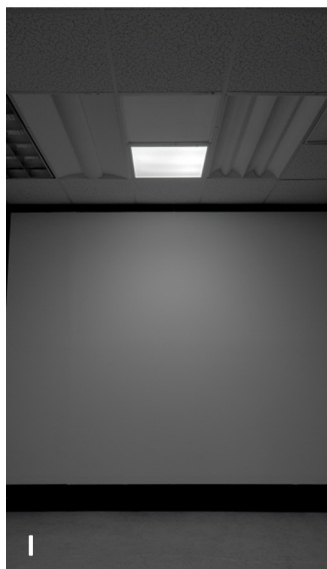
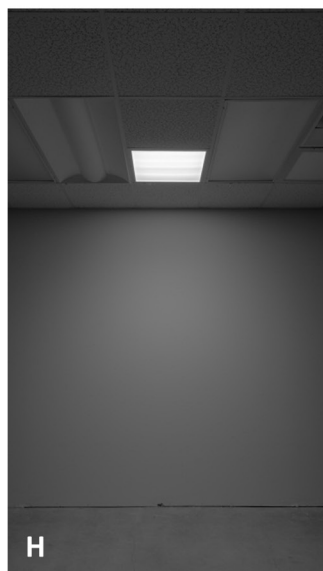
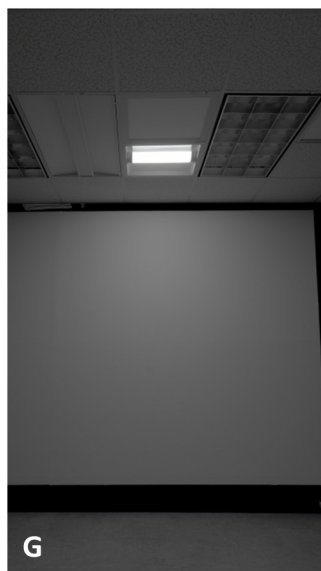
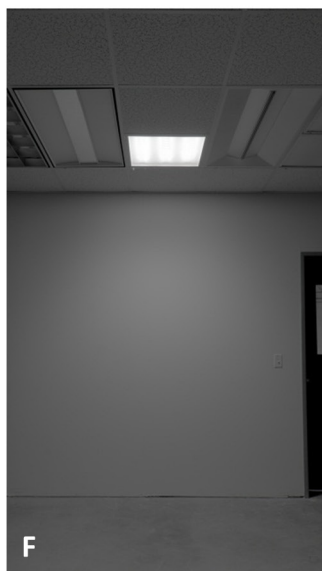
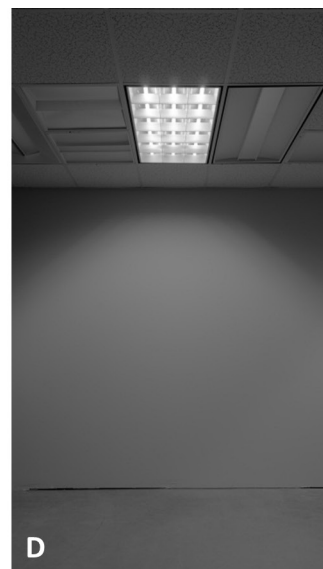
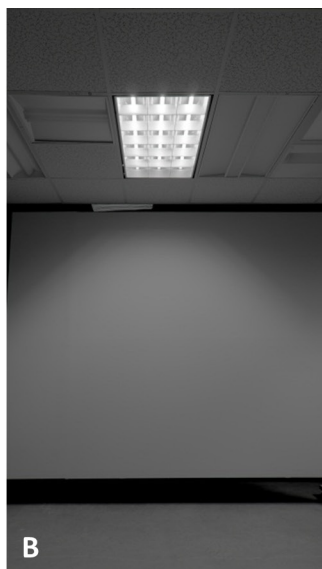
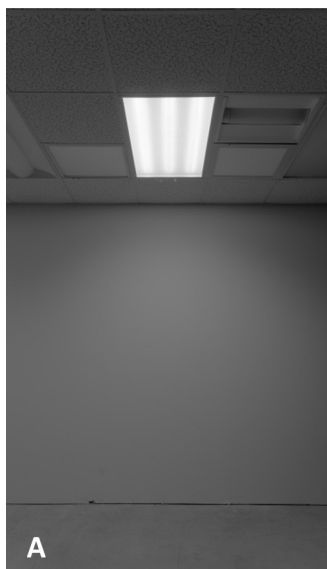
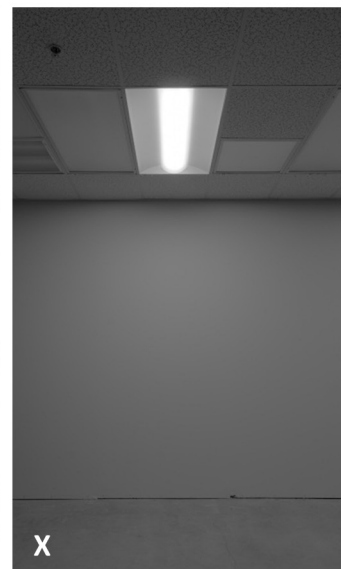
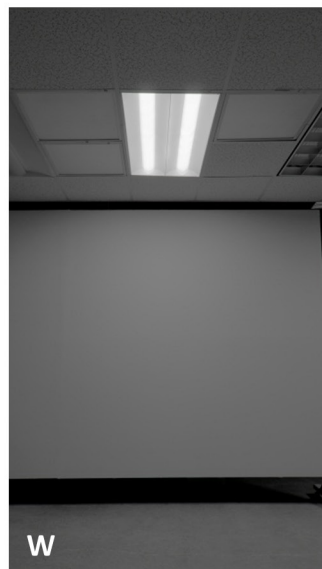
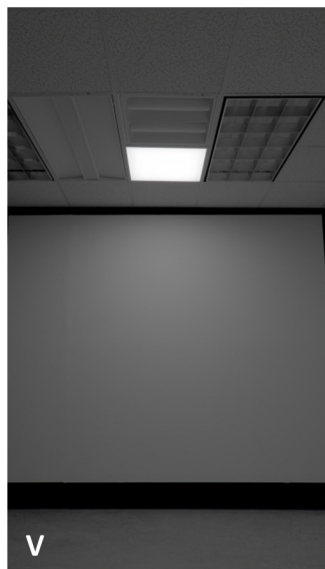
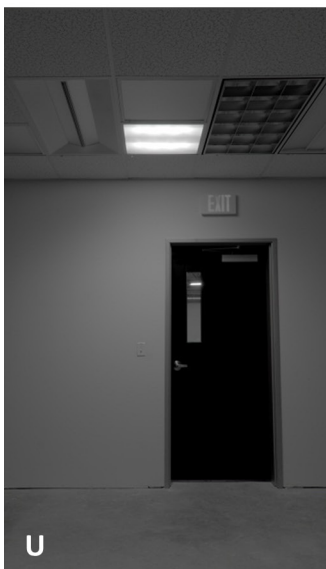
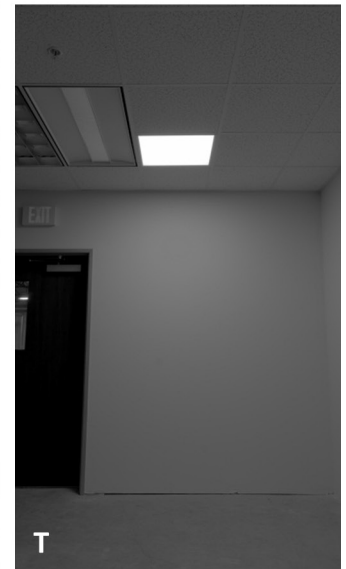
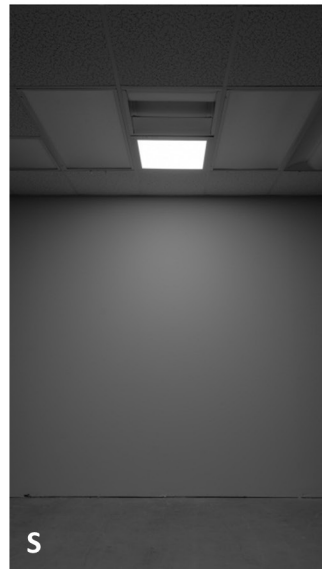
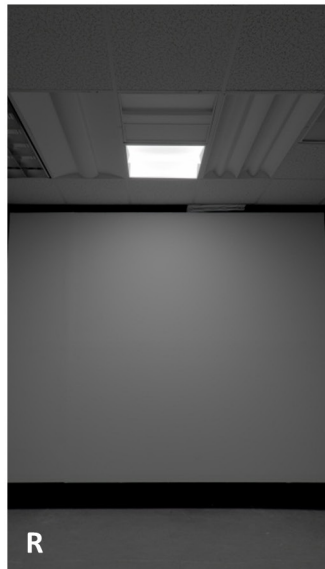
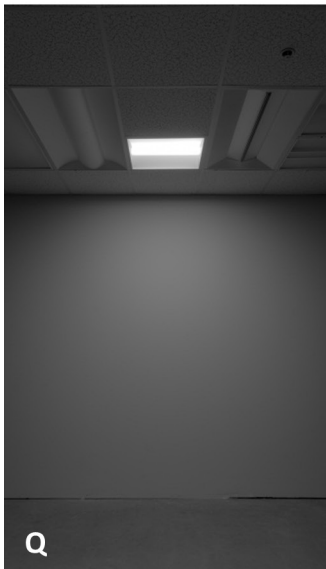
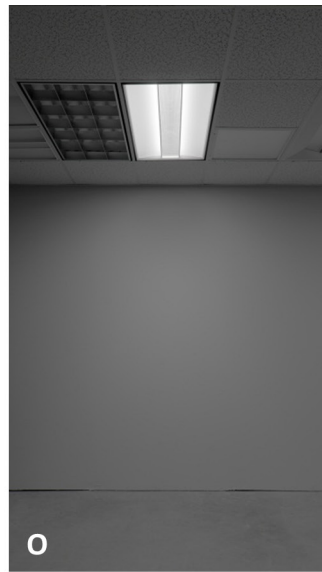
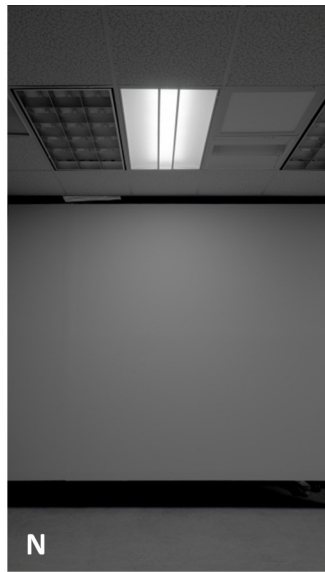
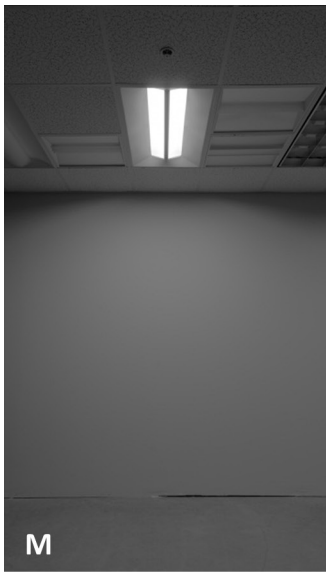


Figure D3. Polar plots of luminous intensity for product types S through X. Plots are not to scale.

Appendix E: Luminaire Distribution Photographs





Appendix F: Flicker Waveforms

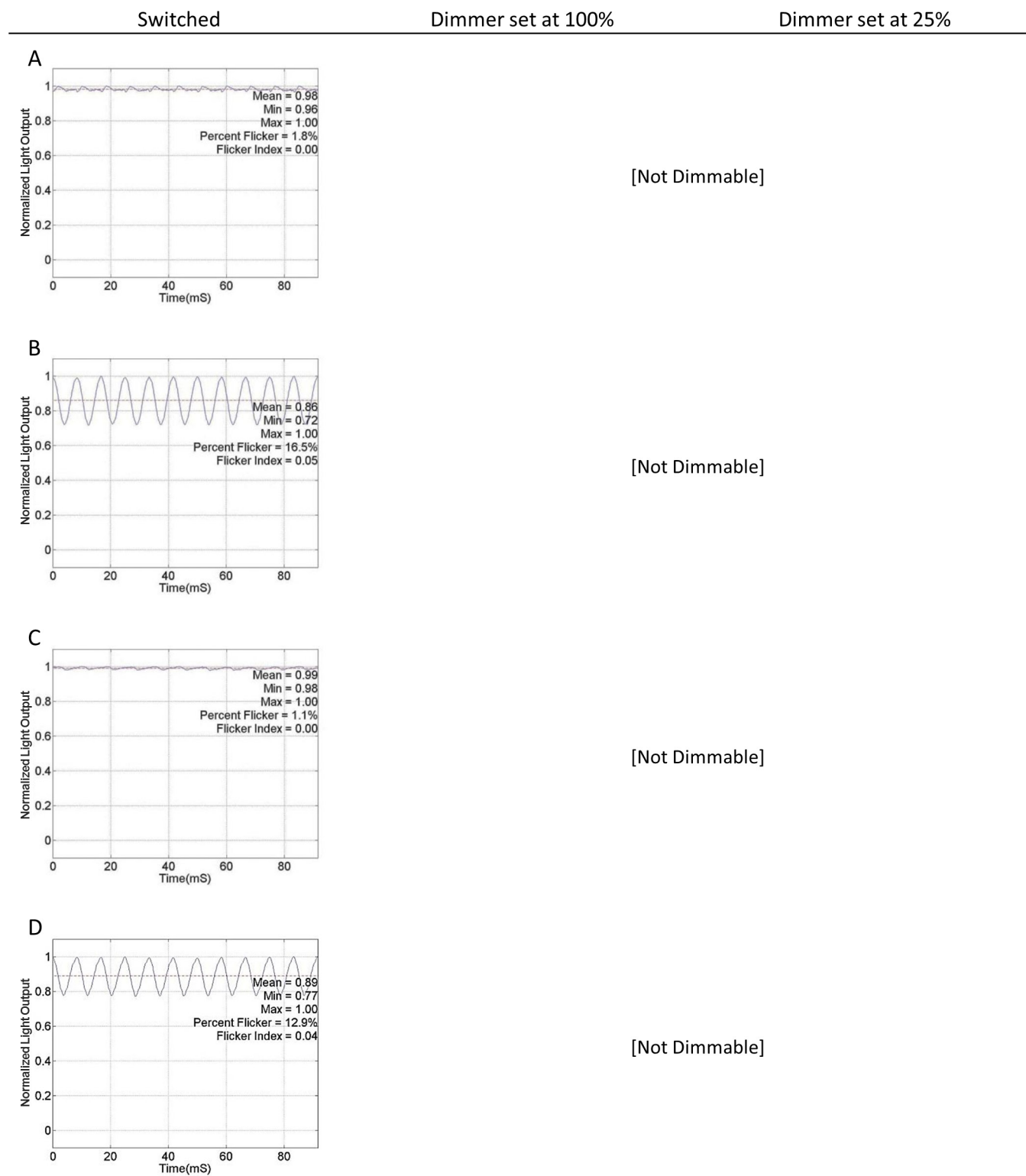


Figure F1. Dimming and flicker characteristics for product types A through D.

Dimmer set at 25%



47

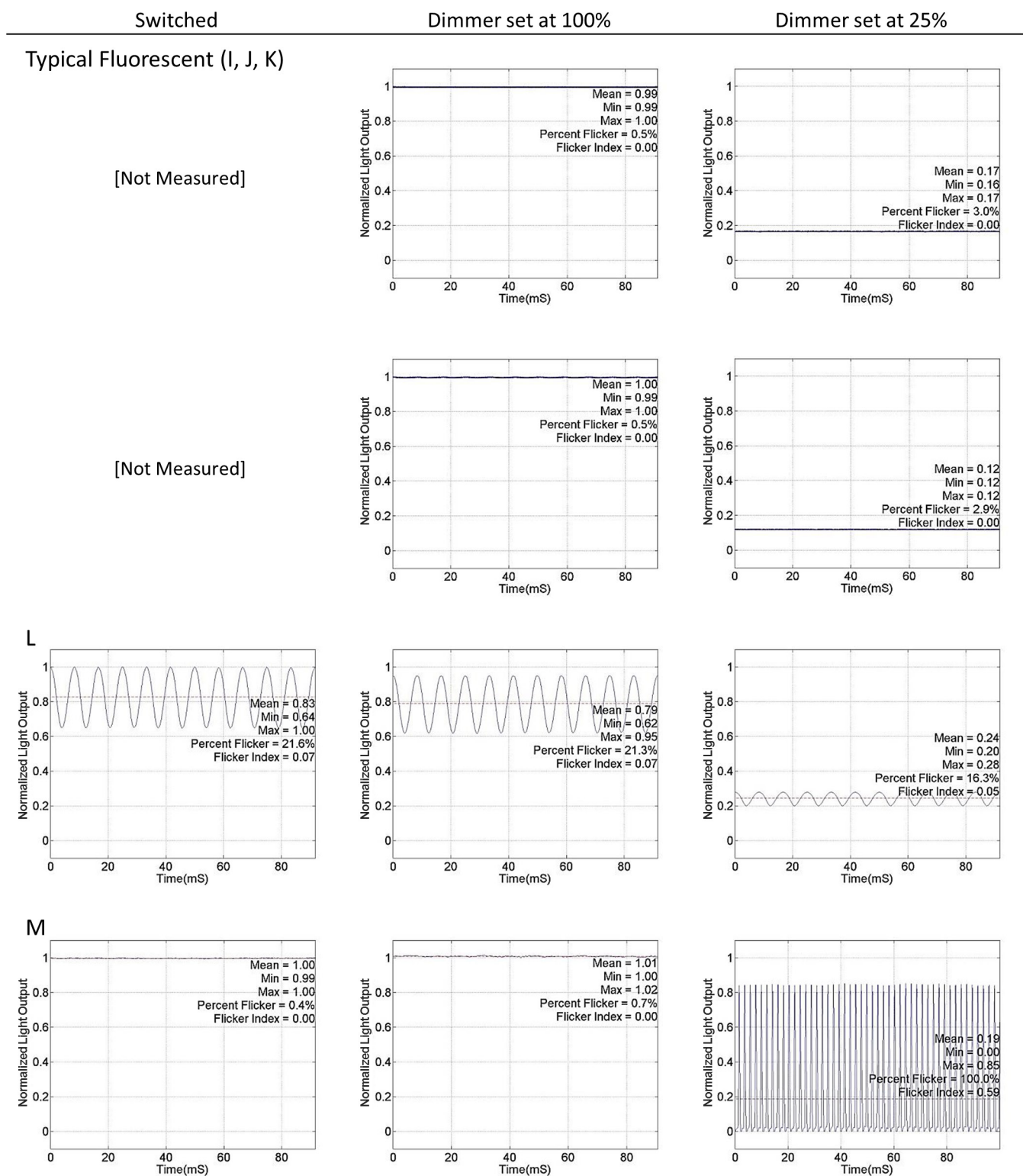


Figure F3. Dimming and flicker characteristics for product types I through M.

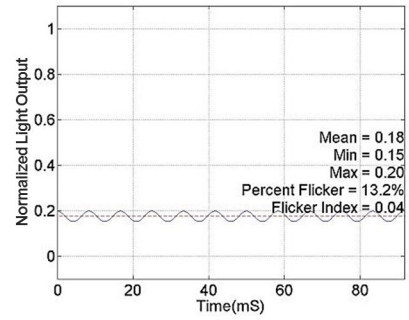
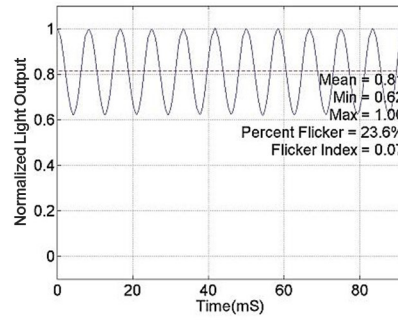
Switched

Dimmer set at 100%

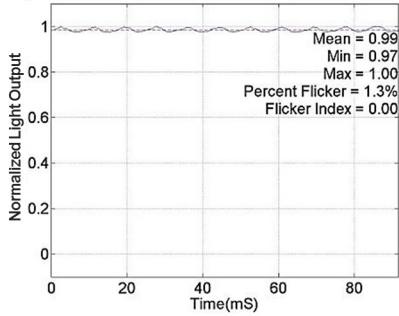
Dimmer set at 25%

N

[Not Measured]

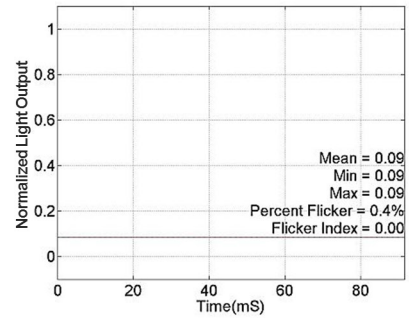
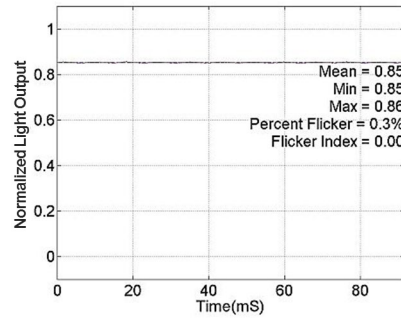
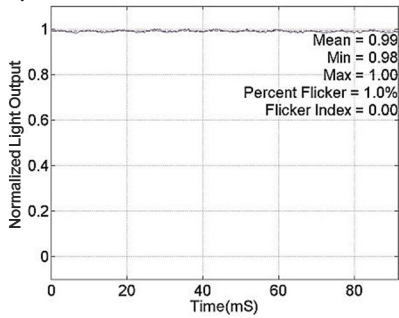


O



[Not Dimmable]

P



Q

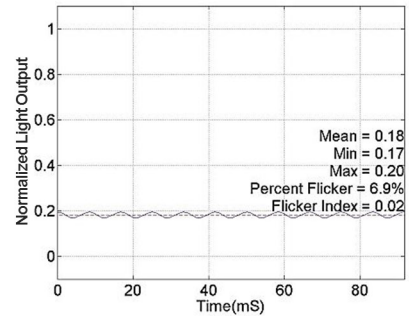
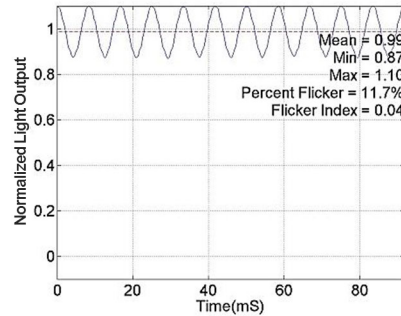
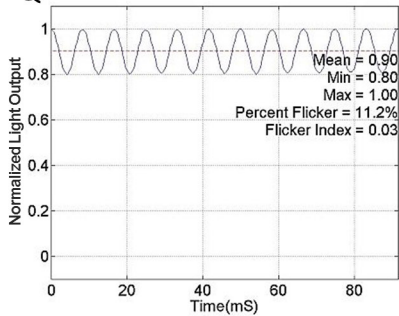


Figure F4. Dimming and flicker characteristics for product types N through Q.

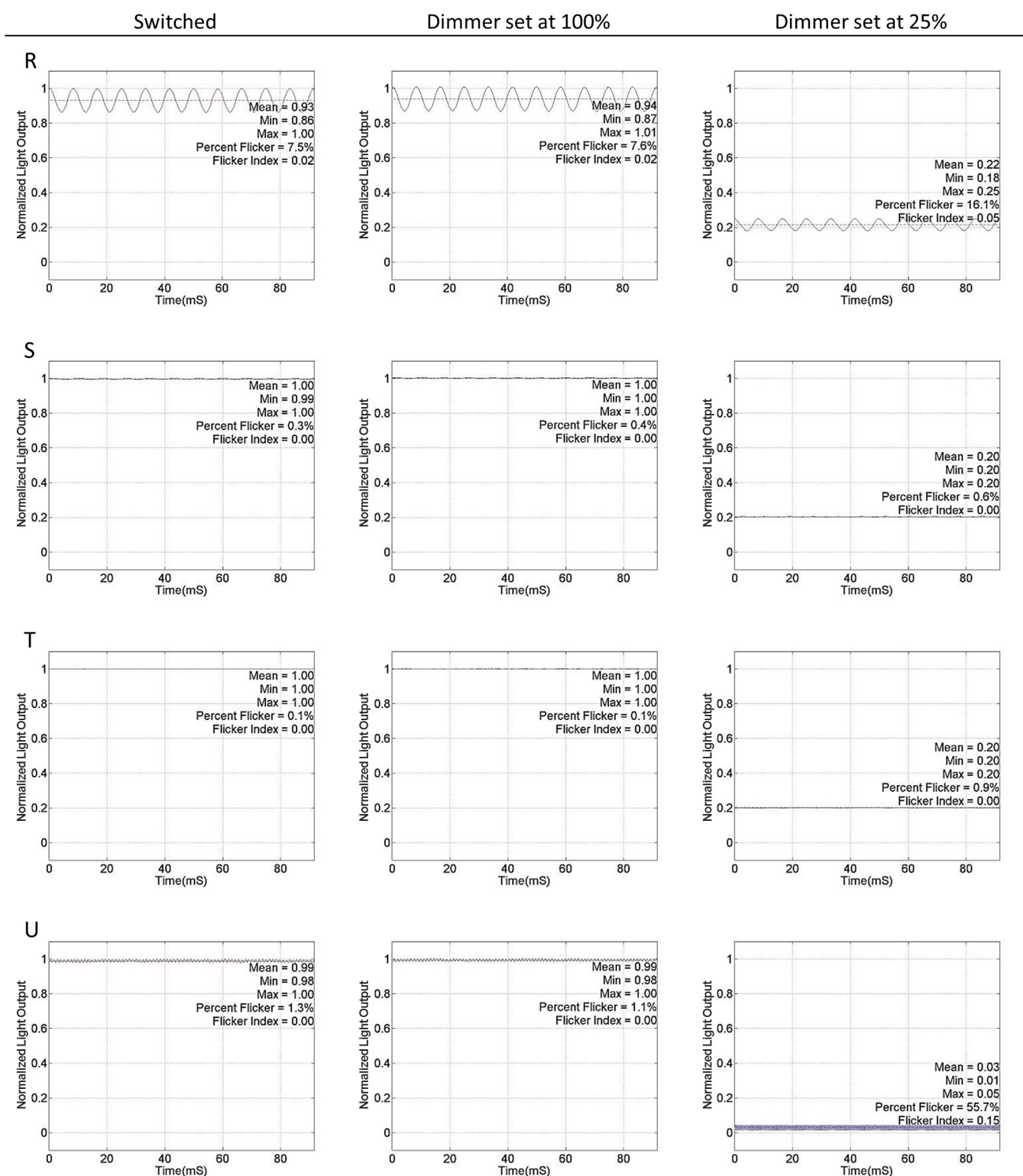


Figure F5. Dimming and flicker characteristics for product types R through U.

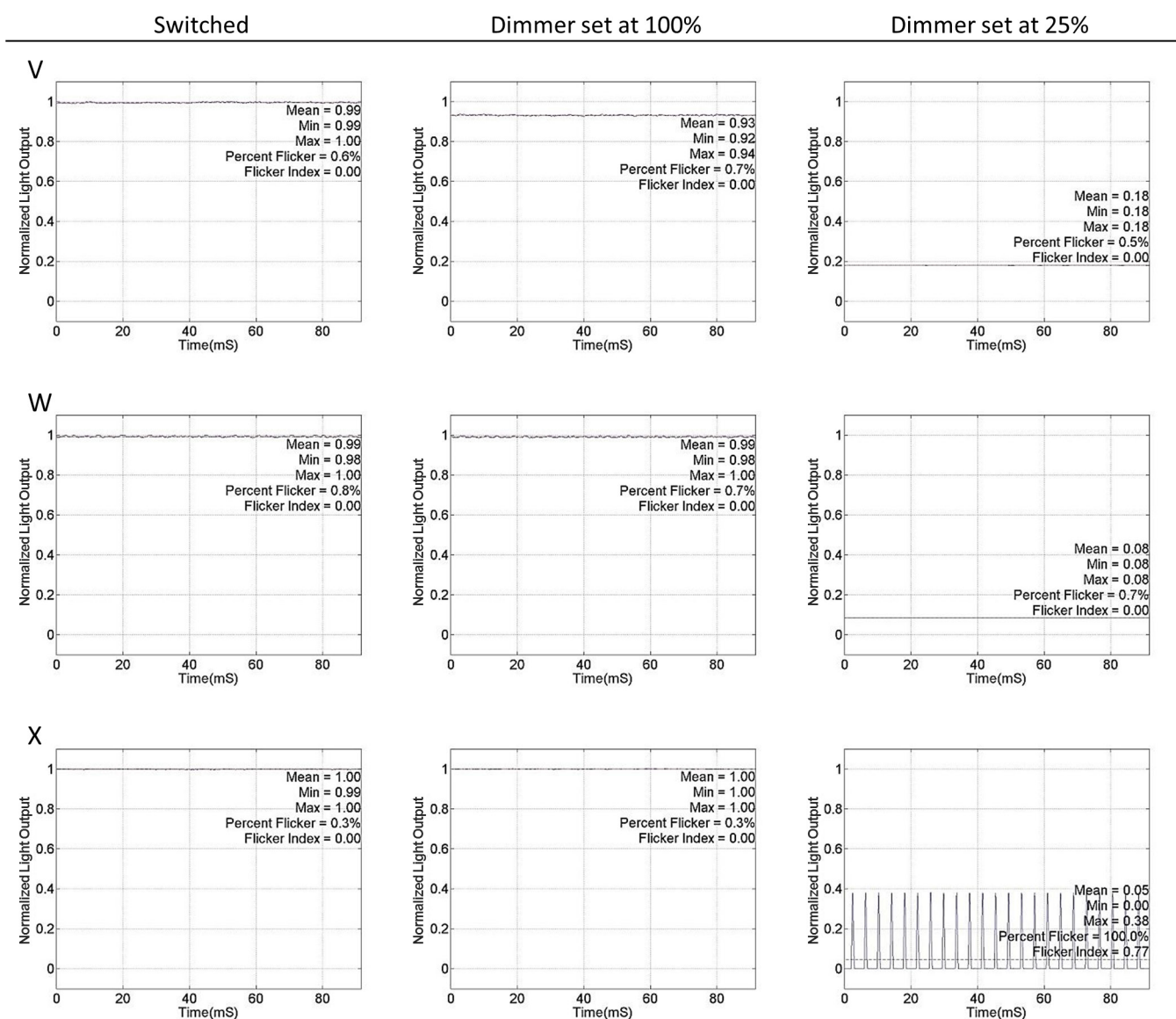


Figure F6. Dimming and flicker characteristics for product types V through X.

