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Energy Research and Development Division

FINAL PROJECT REPORT

From the Laboratory to the California Marketplace: A New Generation of LED Lighting SolutIOns

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

From the Laboratory to the California Marketplace: A New Generation of LED Lighting Solutions is the final report for Contract Number: EPC-14-011conducted by the California Lighting Technology Center at the University of California, Davis. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

Widespread adoption of light emitting diode (LED) lighting for general illumination is one of the most significant advances in building efficiency of the twenty-first century. LED manufacturers have historically focused on research and development to improve lighting efficacy and reduce costs often at the expense of product quality and feature optimization. This has led to consumer dissatisfaction for LED indoor lighting in both residential and commercial buildings.

To address this disconnect, the California Lighting Technology Center launched a four-year research program to design and develop novel, energy-efficient LED lighting with quality and performance features that better meet consumer expectations. To meet this need, product designs were based on two studies. The first was a series of consumer studies that evaluated quality, performance, and function through laboratory-based, immersive, product-characterization experiments; the second consisted of a long-term evaluation of commercially available LED sources to determine if the products delivered performance over time.

Key research outcomes include:

- Proposed changes to American National Standards Institute LED color bins that address consumer expectations for noticeable and acceptable color difference.
- Documented consumer preferences for color fidelity.
- Quantification of the impact of color fidelity on visual acuity.
- Consumer preferences for lighting-product packaging.

These primary outcomes, in addition to many others, informed product specifications and designs as part of this research. Solutions include linear LED lamps, retrofit kits, spectrally optimized luminaires, and corresponding lighting-control packages.

Keywords: LED, lighting, circadian, energy-efficiency, consumers, preference studies, buildings, lighting controls

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EXECUTIVE SUMMARY

Introduction

Widespread adoption of light emitting diode (LED) lighting for general illumination is one of the most significant advances in building efficiency of the twenty-first century. To compete in this market, LED manufacturers focused on efficacy improvements and cost reductions at the expense of product quality and feature optimization. The U.S. manufacturing sector has not sufficiently addressed consumer-optimized design as a means to improve product performance, consumer satisfaction, and sustained use of LED solutions, all of which will lead to increased environmental benefits and electricity savings for California.

Project Purpose

The purpose of this project was first to determine consumer preferences for major lighting performance features, and second to apply that knowledge to lighting-industry specifications. By increasing consumer value for LED lighting products, this research can increase LED lighting across California, which will in turn decrease both energy use and carbon emissions.

Project Process

Quality, performance, and function were rigorously evaluated through a series of laboratory-based consumer-preference and product-feature studies. These studies identified the best technically feasible LED architectures and performances and the LED lighting features that most influence consumer purchases, installations, and use. Study outcomes then determined performance specifications and the development of lighting prototypes that best matched those specifications. Experimental studies were broadly based on three test concepts: to assess absolute perception and preference differences in a laboratory setting, to assess those preferences under more realistic conditions (e.g., mock-up spaces and vignettes), and to gather market data for lighting-industry manufacturers, utilities, and other third parties. These experimental studies had approximately 200 participants.

Consumer Preference Studies – Light Sources

To address gaps in our understanding of consumer lighting preferences and to provide the foundation for consumer-preferred product development, the California Lighting Technology Center conducted a series of laboratory studies that isolated visually perceptible lighting parameters to determine consumer lighting preferences in specific applications and under specific conditions. Experimental studies focused on:

- Perception of color consistency: Designed to quantify two fundamental aspects of lighting’s impact on human observers: the average level of perceptible color variation and the average acceptable color variation of products installed in select building applications.
- Value of high-color fidelity: Designed to determine if increased color fidelity positively correlates to perceived brightness and improved color discrimination.
- Expectations regarding lighting metrics and product packaging: Designed to quantify consumer understanding of common lighting metrics and other information displayed on product packaging.

- Perception of intentional color shift during dimming: Designed to evaluate if an intentional color shift is preferable to no color shift during dimming and, from a consumer's perspective, what range of color shift is most desirable.
- Multi-spectral melanopic lighting perception: Designed to measure the impact of variable color on perception and productivity.

Study Outcomes - Color

Results from color-consistency studies show that consumers notice a significantly smaller deviation off the blackbody root locus than along it. The blackbody root locus is the path that the color of an incandescent light source would take in a particular chromaticity space as the temperature changes. Results also show that consumers are more accepting of deviations that are along the root locus than similar-sized deviations across the root locus. The chromaticity ranges in Table ES-1 are recommended for LED source binning, or the tolerances for manufacturing variation, to achieve stated levels of acceptable and detectable color differences. Chromaticity ranges are defined in terms of correlated color temperature (CCT) and delta u,v (Duv).

Table ES-1: Proposed Chromaticity Bins

	2700K		4000K	
	CCT Shift	D_{UV} Shift	CCT Shift	D_{UV} Shift
50% Undetectable	2725 ± 70 CCT	0.0 ± 1.1e-3 Duv	3985 ± 133 CCT	+ 1.0 ± 1.7e-3 Duv
95% Undetectable	± 22 CCT	± 0.2e-3 Duv	± 43 CCT	± 0.3e-3 Duv
50% Acceptable	± 164 CCT	± 3.4e-3 Duv	± 308 CCT	± 4.3e-3 Duv
95% Acceptable	± 74 CCT	± 0.3e-3 Duv	± 178 CCT	± 0.7e-3 Duv

Table 0 shows recommended chromaticity ranges for LED source binning to achieve stated levels of acceptable and detectable color differences.

Source: California Lighting Technology Center

The proposed bins are much smaller and differently shaped than those in current practice. It has not been shown that the currently used quadrangle is the appropriate shape for LED lamp binning. Further research is recommended to determine an optimal binning shape. These results also show that consumers clearly see the color variations among current, similarly rated commercial products and consider them unacceptable for home and business use.

For phosphor-converted blue-pump LEDs (the typical industry choice), the increase from 80 to 95 color rendering index (CRI) significantly affected consumers. Based on these study results, residential replacement lamps should be in the range of 95 CRI. A frequent objection to requiring 80 CRI or greater for lighting products is that the greater power required of high-color-fidelity lighting to deliver the same light output as low-color-fidelity lighting outweighs the benefit of increased color fidelity. This is based on the assumption, proven false in this study, that consumers require equal light levels independent of color fidelity.

Results show that consumers required 25 percent less light when using higher-color-fidelity lamps. This increase in color fidelity was significant because participants were better able to perform color tasks to the point that 60 percent preferred lighting with increased color fidelity (and decreased light output) for color sorting activities. This shows that the difference in color fidelity was more significant than the difference in brightness.

In the residential settings tested, participants charged with selecting a vanity's light level consistently selected a significantly lower-light output of high- compared to low-fidelity lighting. This indicates that the color fidelity degradation between the high- and low-fidelity scenes decreased the usefulness of the light to the participant, which further supports requiring a higher level of color fidelity.

Study Outcomes – Product Packaging and Lighting Information

With respect to LED product packaging and metrics, survey results suggest that the primary metrics consumers use when evaluating lamps to purchase at a retailer are light output, energy consumed, and color temperature. The efficacy of the lamp itself fell just short of being in the top half of consumer ranking; however, efficacy is the relation between energy consumed and light output, a metric composed of the top two parameters.

It is understandable that these are the most important factors since they most directly relate to consumers' conscious reactions to a space's lighting: how bright a room feels, the amount of energy used, and the color of the light.

As to lamp longevity, consumers predominantly perceived a rating given in years (such as 22.7 years) as longer than its equivalent in hours (25,000 hours in this case). Consumers also tended to assume that a lamp would noticeably dim and burn out at the end of its stated life.

Consumers appreciated the information on an LED Lighting Facts label; it was highly ranked in their decision-making process despite its widespread use, which would typically diminish its relevance. Consumers valued the full, colored Lighting Facts label, which allowed them to compare the products' attributes. General differences in package color, lamp shape, and other aesthetic considerations appeared to influence their purchase decisions slightly.

Study Outcomes – Color Shift During Dimming

Looking at the overall average, there was no clear preference for any of the intentional color-shift scenes. Based on consumer color preferences for home lighting, it appears that participants who preferred the warmer color temperatures preferred the dim-to-warm chromatic shift, where the light source becomes warmer as it is dimmed to lower light levels, and participants who preferred the cooler color temperatures preferred the dim-to-cool chromatic shift. There does appear to be a segment of the consumer market that finds value in dim-to-warm lamp functionality.

Study Outcomes – Circadian Lighting

Results show that when designing spaces for circadian lighting, using lights 2,700 Kelvin (K) or less is ideal for visual acuity, or sharpness. Participants scored lights 3,500 K or less to be in the "normal" visual acuity range. The 3,500 K and 3,000 K channels scored in the 75-percent quartiles are the legal visual acuity limit required for California drivers. This means that for lights cooler than 2,700 K to stay below the melanopic threshold, light would have to be reduced to the point where nearly 25 percent of drivers would not be legally allowed to drive.

The marked improvement in visual acuity under the non-phosphor-converted amber LED suggests that this may be an appropriate light source for areas where high visual acuity is needed at night. In general, 2,700 K appears to be the best balance between visual acuity and color appearance for circadian-based nighttime lighting designs.

Consumer Preferences – Lighting Controls

The California Lighting Technology Center developed lighting-control consumer-preference studies designed to gather information on preferences for control scenarios as they relate to control device settings including dimming level, dimming rate, and automated switching. Those study results shaped recommendations for control features and scenarios that manufacturers can use to create preconfigured, out-of-the-box lighting systems with controls that a majority of consumers want and expect. Increased acceptance and sustained use of aggressively and appropriately designed lighting control strategies ultimately translates into long-range electricity savings in commercial buildings.

Testing was conducted in two phases. The first phase focused on activities to increase understanding of end-use preferences for various control strategies and devices. The second phase explored research questions surrounding lighting control use and acceptance. Five individual tests were completed:

- Evaluation of amber lighting for nighttime use in corridors.
- End-user preferences for control-system-user interfaces.
- Identification of desired control-system functionality.
- Perception of visible flicker.
- Perception of color tuning.

Collectively, these topics address end-user preferences for control-system functionality and provide guidance for lighting-control-system design and development of spectrally optimized luminaires. Outcomes measured control-system performance from an end-user perspective, with the goal of increasing user acceptance.

Study Outcomes – Amber Lighting

Initial reactions to the amber light were negative. After receiving an explanation of the benefits of amber lighting, consumer acceptance increased by 52 percent. This indicates that successful implementation of amber lighting will require education for both current and future occupants.

Study Outcomes – Control User Interfaces

Of the six commercially available dimmer-control interfaces demonstrated for participants, simple sliders and pre-selector switches were preferred. People's preferences for advanced-control interfaces such as app-based solutions were divided. Some valued the convenience of cellphone-based control. For others, simplicity was highly desired and the app-based solution proved problematic and was not well received.

Study Outcomes - Control System Functionality

End users were most interested in energy savings from control systems and more control over lighting in their environments. These critical points should be foundational when designing and marketing new control systems.

Most participants stated that, given the opportunity, they would choose to control the amount of light from both general and task lights, and just under half of the participants preferred to turn off their lights in favor of daylight. Forty-six percent of participants would choose to change the light-color appearance of the lights in their space, though it is not known how many would actively use color tuning features; there is, however, an evident desire for it.

Nearly all (99 percent) participants had used dimmer switches. They showed a small preference for dimmer switches rather than on/off switches. Seventy-five percent stated that they liked personal control of the lights in their workspaces, provided that user control is not a hindrance.

More than 35 percent of participants thought that all dimmable LEDs are compatible with all dimmer switches. This is not true in today's marketplace since many dimmable LEDs perform poorly when paired with incompatible dimmers. Participants also indicated that the only way they were likely to assess light source/dimmer interoperability was to read the outside of the packaging. Based on these results, the project recommends that dimmer compatibility be clearly communicated to consumers on the outside of light-source packaging to avoid general dissatisfaction with the lighting system.

Study Outcomes – Visible Flicker

More than 75 percent of participants reported that they saw lights flickering; and at least 26 percent blamed the flicker on incompatibility between the light source and dimming controls.

The shape of the flicker waveform has a small effect on the perceptibility of flickering lights. Sinusoidal and pulse-width modulated waveforms have similar perceptibility, while the "inverted cycloid" waveform appears to be less noticeable at some frequencies. Specifically, this is true at the 70 Hz frequency with the same percent modulation. Results from the visible-flicker study are plotted in Figure ES-1. A colored "x" shows scenes where a significant number of participants saw the flicker, with the color indicating the flicker frequency. A light-gray "x" shows scenes that were not observed by a significant number of participants.

Percentage modulation appears to be a usable metric to estimate the visibility of flicker, where a higher-percent modulation correlates to higher visibility for each waveform shape. Overall, the results align with the IEEE's 1789 guidelines for limiting flicker to lessen viewer health risks including seizures, headaches and eyestrain. It is recommended that the IEEE 1789 guideline be used to predict whether flicker is visible to end users.

Figure ES-1: Results of Visible Flicker Study and IEEE Chart Information

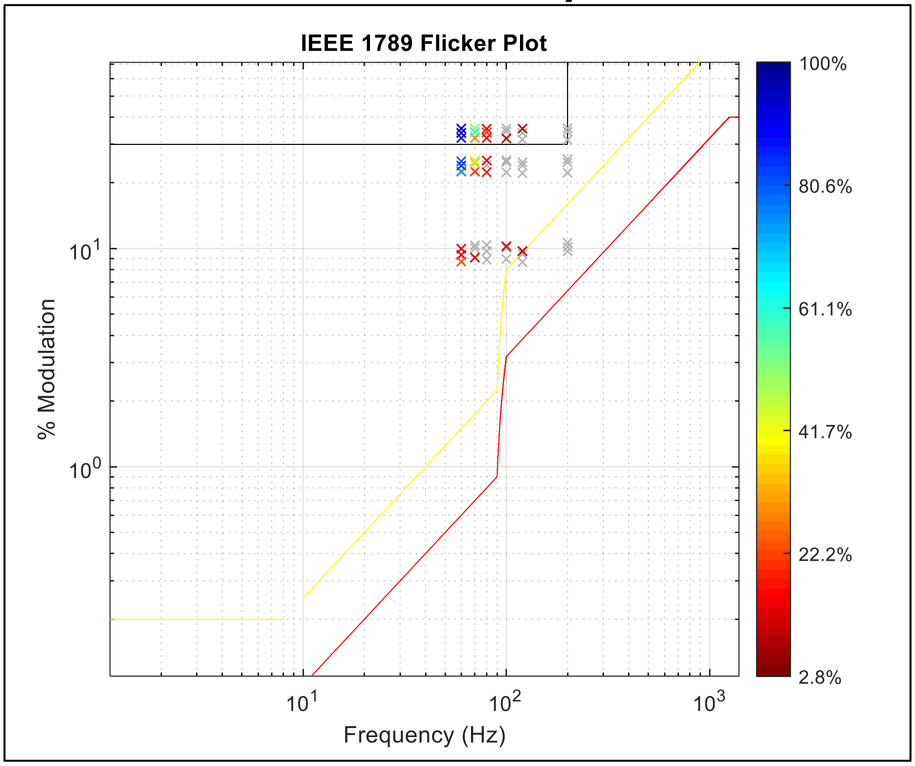

Figure ES-1 shows the results of the CLTC visible flicker study overlaid with the IEEE 1789 flicker plot information.

Source: California Lighting Technology Center

Study Outcomes – Color Tuning

Most participants valued color tuning capability and believed they would use color tuning controls as frequently as they would use dimming controls in their workspaces.

In terms of noticeable color change, location within the field of view had no impact. Scenes where all four lights changed together were noted with greater frequency than scenes where only pairs of lights changed. This was probably because the change was twice as large in intensity since twice as many fixtures were changing.

Overall, participants noticed all rates of color change. The slowest dimming rate of 10 K per second was noticed 46 percent of the time. Based on these results, it is recommended that color tuning for circadian lighting in shared spaces be changed at 1 K per second or less to minimize the noticeability of the color change.

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Product Evaluation

Of the 23 evaluated LED products, only eight fulfilled the full set of performance criteria for this research's limiting factor of a CRI of 90 or greater. Approximately 35 percent of the market met the Voluntary California LED Quality LED Lamp Specification when products were purchased.

Evaluation results showed that LED replacement lamps met most of the performance criteria claimed by their manufacturers; however, no single commercially available product met all dimming, color quality, and efficacy thresholds. The overall best-performing product still failed to reach required color-quality goals. The products that met those goals were not dimmable and did not meet light-output and efficacy goals.

Lifetime Performance

The lifetime-performance sample set consisted of six lamps each of 23 lighting products, for 138 lamps. Forty-nine individual lamps failed to turn on after 12,000 hours of testing. This is a 36-percent failure rate for the sample set.

Projected rated life (L70) calculations using IES LM-84-14 and TM-28-14 determined that nine of the 23 products were unable to meet the manufacturer-claimed rated life when operated in conditions typical of California buildings. This is a 39 percent failure rate of the products tested.

Product Safety and Reliability

No safety concerns were encountered over the course of the evaluation. No issues regarding safety markings were identified for the lamps evaluated. The evaluation confirmed that readily available lamps marketed for the four-reviewed product categories complied with industry-standard safety markings and compatibility labeling.

All samples of two filament-style omni-directional LED design medium screw-base lamps failed over the course of the 12,000-hour life testing. This indicates that while the filament-style lamp design is aesthetically pleasing, further product development is needed to improve its reliability for California consumers.

Performance Specifications

Study outcomes contributed to recommendations for the next update of the Voluntary California LED Quality LED Lamp Specification (Specification). The recommendations and justifications for the recommendations are summarized here:

- Expand the eligible light-source language in the Specification to include linear light source applications such as the medium bi-pin base (G13), commonly used for T8 and T12 lamps, and the miniature bi-pin base (G5), commonly used for T5 lamps.
- Align the minimum luminous efficacy requirements for the Specification with the 2020 efficacy projections made by the US Department of Energy (DOE). This includes the addition of multiple lamp-product categories as well as an increase in required efficacy.
- Offer the option of color fidelity index (Rf) in addition to the CRI to comply with the color-rendering requirements in the Specification.
- Include requirements for the electrical architectures of the linear LED replacement lamps.
- Revise the chromaticity and color-consistency requirements according to proposed color bins.

Benefits to California

This project will generate California ratepayer benefits by reducing electricity demand and electricity transmission requirements, which together would reduce strain on the electric grid and the likelihood of system outages. Reduced demand, estimated at more than 8,000 Gigawatt hours (GWh) annually for the products developed through this project, would therefore ultimately lower costs to ratepayers. For both residential and commercial ratepayers, the products developed will help reduce lighting electricity consumption in the morning and evening hours, hours that see the highest use. Similarly, for commercial ratepayers, the products developed under this agreement will result in peak-demand reductions and cost savings.

In addition, this work addressed key barriers to widespread market adoption of LED technologies, namely quality and performance of commercially available products. This research resulted in energy-efficient, safe, and simple LED solutions that can quickly be brought to market.

Consideration and incorporation of evidence-based consumer preferences in LED lighting product design and development will have a positive effect on LED market uptake. Currently in California, less than one percent of residential and indoor commercial lighting uses LED technology. This project provides designs and prototypes to improve LED technologies with the potential to significantly increase LED market share in both residential and commercial applications. In addition, research outcomes regarding customer preference for lighting attributes such as light color, dimming, light distribution, fixture form, and product packaging are now available to all lighting manufacturers so that they can capitalize on and incorporate product features that consumers will both want and embrace.

CHAPTER 1: Background and Project Purpose

Widespread adoption of light emitting diode (LED) lighting for general illumination is one of the most significant advances in building efficiency of the twenty-first century. However, due to this potential, a variety of market actors have introduced LED products and made associated performance claims that have set the technology up with somewhat unrealistic expectations regarding efficacy and longevity. To compete in this market given such expectations, LED manufacturers have historically focused on research and development in efficacy improvements and cost reductions at the expense of product quality and feature optimization. This has led to a lack of consumer satisfaction for LED products in residential and commercial applications.

To address these gaps, the California Lighting Technology Center (CLTC) initiated a four-year research program to design and develop novel, energy-efficient LED lighting solutions with the quality and performance features desired by consumers. Solutions included linear LED lamps, retrofit kits, luminaires with spectrally optimized options, and corresponding lighting control packages and specifications.

To achieve alignment with consumer needs, designs and other performance outcomes are based on results of two characterization studies. The first consisted of consumer studies that evaluated quality, performance, and function through a series of unique laboratory-based, immersive, product characterization experiments. The second consisted of long-term testing of commercially available LED sources to determine if their products met their stated performance over time and in accordance with industry test methods. All experiments include product specifications and designs. Consumer-preference studies increased understanding of the lamp characteristics that tend to limit market acceptance of LED technology. This then led to the identification of related product performance goals that ultimately contributed to development of the project's research plan for increasing LED market adoption and lighting energy savings in both commercial and residential buildings. These studies increased understanding of the metrics and testing used to assess LED quality and performance, ultimately increasing manufacturers' compliance with future energy codes and standards. Throughout the course of this research, CLTC worked closely with its manufacturing, education, and other partners so that the research would be both useful and available to the manufacturing community at large.

This research benefits California by delivering greater grid reliability through reduced electricity demand and transmission requirements, which together reduce strain on the electric grid and the potential for outages. Reduced demand could save more than 8,000 gigawatt-hours (GWh) annually, which could lower electricity costs. The products developed under this research program would reduce both commercial and residential lighting consumption in the high-demand morning and evening hours.

This report is organized in chapters around four themes in addition to separate introductory and technology-transfer chapters. Detailed information on technical activities may be found in:

- Chapter 2: Consumer preference studies – light sources.
- Chapter 3: Consumer preference studies – lighting controls.
- Chapter 4: Characterization of commercially available products.
- Chapter 5: Prototype development.

CHAPTER 2: Understanding Consumer Lighting Preferences

It is important to understand the colors, color temperatures, and intensities that building occupants prefer in their homes and work places, and to identify if those preferences correlate with specific end-use applications. There is ample available literature regarding consumer lighting purchase preferences developed through point-of-sale surveys and market sales data. However, limited and conflicting research results exist on customer preference and performance when considering perceived lighting effects. Research gaps exist within consumer preferences, both for lighting over a prolonged period of time and in a contextual environment. In addition, there is a large research gap about how people interpret and imagine lighting information, and even general awareness of residential LED lighting alternatives, which together translate directly to purchase decisions and broader market acceptance.

Study Background, Organization, and Goals

To address existing gaps in understanding consumer lighting preferences and provide an empirical foundation for consumer-optimized product development, CLTC conducted a series of laboratory studies to isolate the effects of visually perceptible lighting parameters, with the goal of determining consumer lighting preferences for these parameters in specific applications and under specific conditions. Experimental studies included approximately 200 participants. Experimental studies focused on the following topics:

- Perception of color consistency
- Value of high-color fidelity
- Expectations regarding lighting metrics
- Interpretation of lighting-product packaging
- Perception of intentional color shift during dimming
- Multi-spectral melanopic lighting perceptions

Color Consistency

When a consumer purchases two lamps that he or she believes will emit the same color and they turn out noticeably different once installed, the lamps have not delivered what the consumer expected. This becomes especially relevant during lamp replacement. When a consumer purchases and installs a lamp to replace another and to match existing lighting, color mismatches can be unappealing, distracting, and potentially lead to replacement with less-efficient lighting sources.

Due to the inherent but minor variability in LED manufacturing processes, it is not possible to produce two LEDs with identical color (if that color is defined in terms of wavelengths of light emitted). However, it is possible to produce two LEDs with a color difference that is undetectable to the human eye.

Chromaticity binning is a defined process where light sources are grouped, or "binned" according to the chromaticity of the light produced by the device. Chromaticity is an objective measure of color separate from brightness. It is typically shown as a set of coordinates, one representing color hue and the other color saturation. Chromaticity binning is based, in part, on the "just-noticeable color difference" defined in research published in 1942 by Dr. David Lewis MacAdam. The results of his research led to the development of chromaticity bins used in today's LED industry. The most notable binning standards are published by the American National Standards Institute (ANSI). ANSI bins are defined by ranges of chromaticity values. When two light sources are grouped within the same bin, they are considered to have the same nominal chromaticity even when their wavelength spectrum (color) may be different.

Given that two light sources with different colors could be considered equal under this paradigm, it is critical to understand what level of variability is noticeable to the average observer and, as importantly, what level of difference is acceptable. To begin to answer these questions, CLTC researchers designed and conducted two laboratory tests. The first focused on chromaticity perception and preference. The second addressed color fidelity preference. Both were designed to determine noticeable and acceptable levels of color difference among various lamps installed in the same room or field of view.

High-Color Fidelity

A light source's color fidelity is a measure of how "true" the colors illuminated by the light appear as compared to a reference standard. The reference standards for defining "trueness" are daylight for high-color temperature light sources and blackbody radiators for low-color temperature light sources. These reference standards are frequently defined as physiologically relevant as they represent the light sources present in the natural world: daylight and fire.

It is generally accepted that high-color fidelity for general-purpose illumination is an important characteristic for today's light sources. Many daily activities require accurate color assessment. Color fidelity tests completed as part of this research sought to determine if increased color fidelity positively correlates to increased perceived brightness and improved color discrimination.

High-color fidelity studies encompassed two test activities. The first assessed the trade-off between light output and color fidelity. The second assessed the impacts of differences in delivered lighting service (lumens) by both high- and low-color-fidelity light sources.

The CRI is today the metric most commonly used to communicate a light source's color fidelity. Other color fidelity metrics have been proposed as more accurate for color fidelity, most notably those included in the Illuminating Engineering Society's *Method for Evaluating Light Source Color Rendition* (IES TM-30-15). The underlying questions regarding acceptable light levels and their color-fidelity thresholds apply to all color fidelity metrics available today. CRI was adopted for this study.

Intentional Color Shift during Dimming

The color of light produced by incandescent lamps becomes warmer as the lamp is dimmed. This is due to how incandescent lamps and other Planckian radiators[1] produce light. When the Planckian radiator is dimmed, less power is used to heat the filament, which correlates to a warmer color temperature (CCT). This change in CCT is commonly referred to as 'color shift.'

LEDs do not exhibit this change in CCT as they dim. However, it is possible to create an LED that mimics the variable color characteristics associated with incandescent lamp dimming. This requires LED emitters in at least two CCTs and more complex control circuitry.

The study on intentional color shift during dimming explores whether this added feature and its complexity are necessary to increase consumer acceptance of LED sources by anticipating consumer expectations surrounding lamp dimming. To date there has been no direct attempt to determine consumer expectations regarding color shift while dimming.

Melanopic Stimulus and Visual Performance

The daily variation of daylight's intensity and spectral composition is critical to human health. It affects the biological clock and related functions including alertness, hormone levels, and body temperature. Figure 1 shows an example of circadian rhythms in the human body.

Figure 1: Circadian Rhythms Showing the Variation of Cortisol, Melatonin, Alertness, and Body Temperature over Two 24-Hour Periods

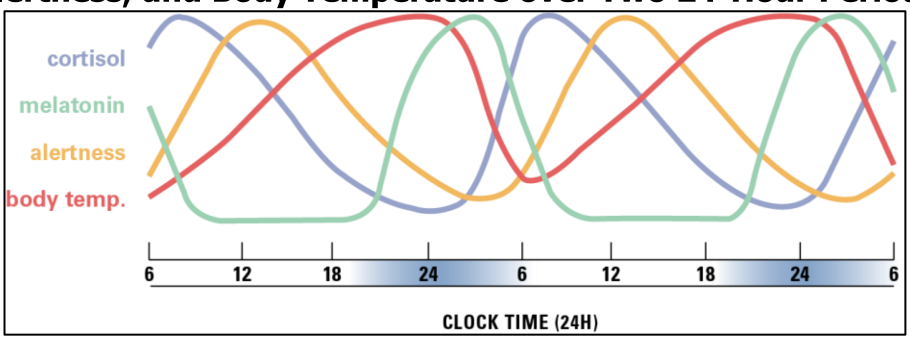

Figure 1 shows circadian rhythms including how cortisol, melatonin, alertness, and body temperature vary over two 24-hour periods.

Source: California Lighting Technology Center

Circadian rhythms are predominantly driven by light intercepted by the intrinsically photosensitive retinal ganglion cells (ipRGCs). ipRGCs respond to light based on the absorption of light by the photopigment called melanopsin. This is distinctly different from the light absorption and function of other photoreactors in the eye: the rods and cones. The common photopic sensitivity curve is used for quantifying many common lighting metrics, including the lumen. The action spectrum of melanopsin when compared with the photopic sensitivity curve is shown in Figure 2.

[1] Objects heated to the point of incandescence.

Figure 2: Melanopic vs. Photopic Action Spectrum

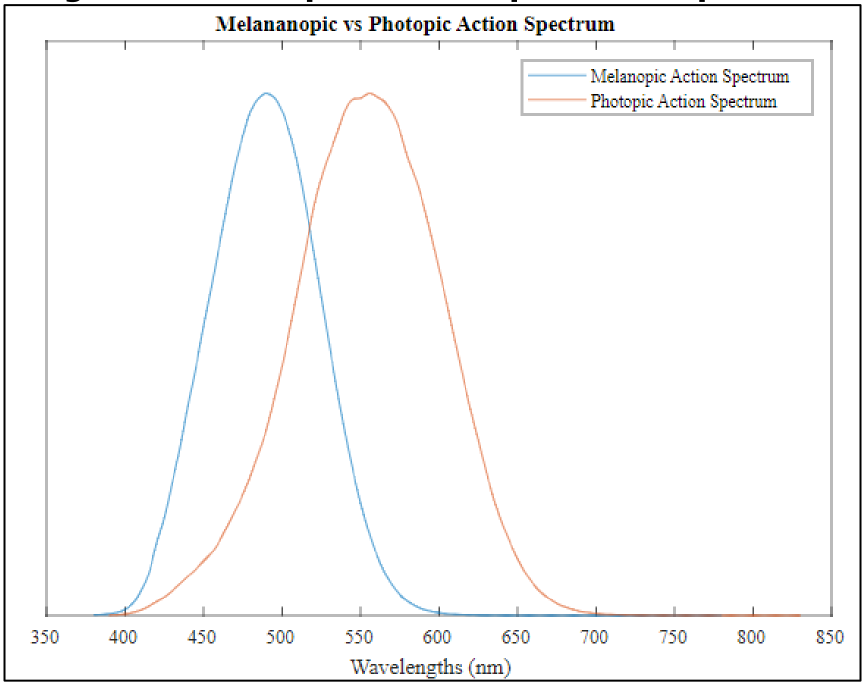

Figure 2 shows the melanopic and photopic action spectrums.

Source: California Lighting Technology Center

This relationship shows that light with significantly more long-wavelength spectral content (as opposed to short-wavelength content) can provide more photopic light. Producing light with significantly more short-wavelength content is key to manufacturing a light fixture that will have a greater impact on circadian rhythms without requiring more power. Understanding the impact of light on both visual performance and circadian rhythms is a critical design component for lighting products used at night.

Common Lighting Metrics and Packaging Information

Understanding consumer expectations for lighting product performance is essential for designing to consumer-centric lighting specifications. To supplement current knowledge on consumer lighting preferences, CLTC conducted an online survey focused on issues related to lighting metrics, packaging, and product warranties.

In addition to general information regarding the relative importance of common lighting metrics to consumers, the survey addressed consumer interpretation of "rated life" for light sources, specifically for medium screw-base LED lamps. Emphasis on product life addressed a potential issue with the current metrics used to define "rated life," which may not clearly communicate the concept of lamp life to consumers or meet their expectations for product longevity. Additionally, the survey addressed consumer expectations when confronted with various lamp warranty terms and other product-packaging information.

Responses to those survey questions provided insights on the type and style of lighting information that is clearest and most beneficial to consumers. The goal was to use this information to improve product literature and packaging so that energy-efficient, environment-friendly LED lighting acceptance increases and persists in California's lighting marketplace.

Test Methodology

Experimental studies were generally built around three test concepts: to assess absolute perception and preference differences using a strictly artificial, laboratory setting; to assess these preferences under more realistic conditions (mock-up spaces and vignettes); and to gather market data useful for lighting-industry manufacturers, utilities, and other third-parties.

Laboratory test stations were generally made up of an enclosed viewing booth with a viewing window where test participants could view light sources and evaluate various performance characteristics. Mock-up spaces were also created to assess consumer preference differences under more realistic conditions. These test stations staged full-sized vignettes that immersed study participants in a realistic residential or commercial building environment to evaluate light-source performance. Evaluations were conducted in two rounds. The first round gathered preliminary answers to study questions from the study participants, while round two further evaluated user preference and new, secondary research questions.

Test Areas and Equipment

All consumer-preference tests were conducted in custom-built test environments located at CLTC's research facilities. Overall, the test area consisted of three distinct test stations. Figure 3 shows the layout of the test area and each station.

Figure 3: Layout of the Consumer Preference Testing Stations

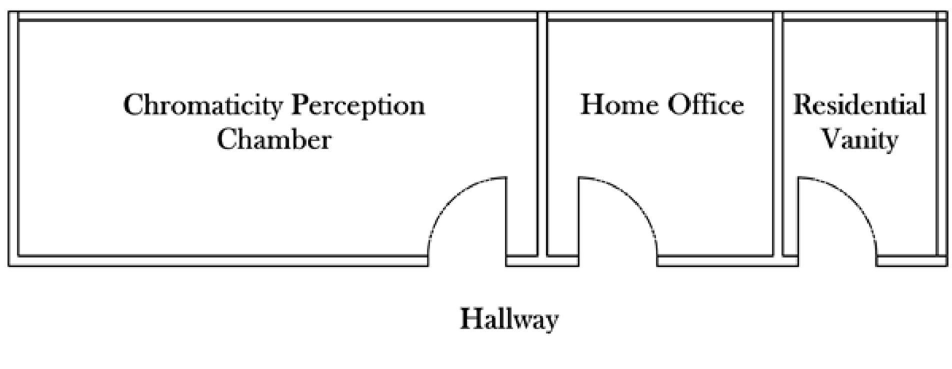

Figure 3 shows the layout for the consumer preference testing stations at the California Lighting Technology Center.

Source: California Lighting Technology Center

Chromaticity Perception Chamber

The Chromaticity Perception Chamber was configured with light booths illuminated by custom light engines built to resemble a typical table lamp. These light engines were designed around a variable spectrum source, which allowed very fine control of chromaticity. Test table lamps are shown in Figure 4.

Figure 4: Table Lamps Used in Chromaticity Perception Study

Figure 4 shows the custom light booths illuminated by custom light engines built to resemble a typical table lamp.

Source: California Lighting Technology Center

During calibration, each table lamp was installed and tested to verify specific chromaticity points. Due to the light engine's high-control granularity, lamps were calibrated to within 0.5 percent of the lumen output of the reference standard lamp. The chromaticity coordinates of the test lamps are illustrated in Figure 5. Also shown are the ANSI 7-Step, 4-Step, 2-Step, and 1-Step bins as green, blue, red, and black quadrangles, respectively. As ANSI only defines 7-Step and 4-Step bins, the 2-Step and 1-Step are extrapolated based on 7- and 4-Step configurations. When two sources fall within the same bin, they are considered equal in color; however, they will have different chromaticity coordinates and thus potentially different appearances. Larger-numbered bins allow a larger tolerance for chromaticity differences between two sources considered equal.

Figure 5: Test Points for Chromaticity Samples in the CIE 1964 u'v' Chromaticity Diagram

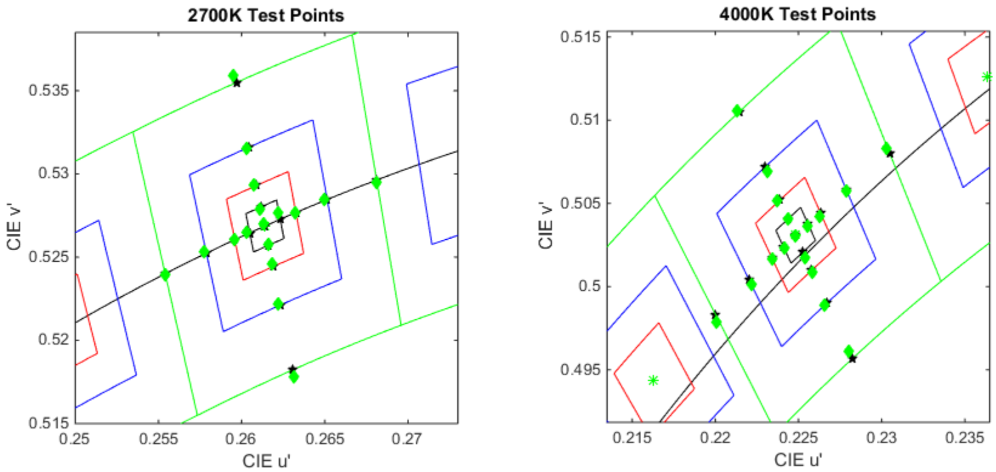

Figure 5 shows the chromaticity points in the CIE 1964 u'v' coordinate system verified for custom table lamps shown in Figure 4.

Source: California Lighting Technology Center

Due to limitations in the calibration setup, the CIE 1931 2-degree standard observer was used for calibration. However, the CIE 2006 10-degree standard observer was identified as the most relevant to test activities and was therefore used in the analysis. The change in standard observer has two main effects: a general shift of chromaticity coordinates and a "stretching" of points along the equal CCT line (the black line sweeping lower left to upper right in Figure 6). The chromaticity points in this color space are shown in Figure 6.

Figure 6: Chromaticity Test Points Using the CIE 2006 10 Deg. Observer

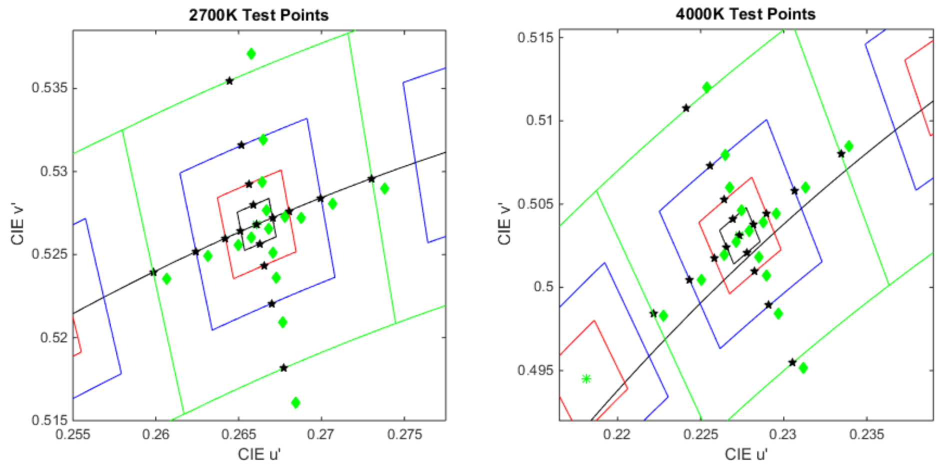

Figure 6 shows the chromaticity points in the CIE 2006 10-degree observer coordinate system used for analysis of study participants responses.

Source: California Lighting Technology Center

The test chamber was also equipped with overhead programmable LED lighting that focused on color shift during dimming. Each ceiling-recessed downlight was programmed with the same dimming profiles as previously described for the table lamps. A photo of the complete lighting layout used in the chromaticity perception chamber is shown in Figure 7.

Figure 7: Intentional Color Shift during Dimming

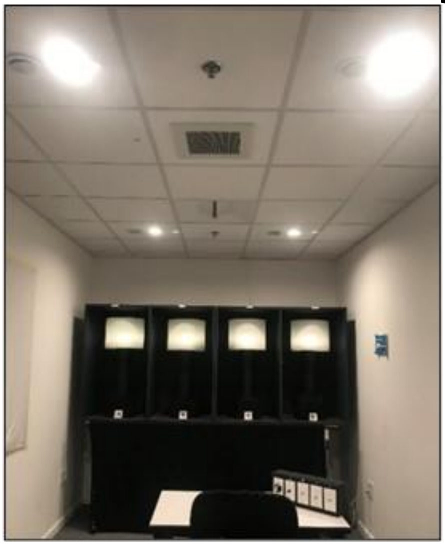

Figure 7 shows light sources used in the laboratory set up for studying intentional color shift during dimming.

Source: California Lighting Technology Center

Home Office

A sub-area of the test space replicated a home office and was used for color fidelity tests. Pairs of table lamps, one with high-color fidelity, the other with low-color fidelity, were designed around a major manufacturer's commercially available LED chips. These table lamps were installed on turntables so that the light distribution in the room was the same among all lighting scenes shown to study participants. The home-office test area is shown in Table 1. Figure 8 shows the color fidelity trade-off study testing area at the California Lighting Technology Center. Figure 9 shows a secondary table lamp placed on the opposite side of the home office that delivered lower-level ambient lighting. This table lamp used a 60-watt incandescent lamp.

The table lamps used for high- and low-color fidelity scenes were powered by DC power supplies installed under the desk. The lamps were designed to have the same input power and CCT, but the light output was allowed to vary based on the industry-standard difference in efficacy between typical low- and high-fidelity LEDs. The low-fidelity lamp delivered approximately 25 percent more light than the high-fidelity lamp at the same input power. Photometric and electrical data for each scene are provided in Table 1.

Table 1: Color Fidelity Trade-Off Study – Lamp Characteristics

	Color Fidelity (CRI)	Light Output (lumens)	CCT (Kelvin)	D_{UV}	Electrical Power (Watts)	Drive Current (Amps)
High Color Fidelity	96	2,050	2,652	–0.0010	25.9	0.34
Low Color Fidelity	81	2,635	2,658	0.0003	25.8	0.35
% Difference	—	25.0%	—	—	0.4%	2.0%

Table 1 shows the photometric and electrical characteristics for the high color fidelity and low color fidelity scenes used in the color fidelity trade-off study.

Source: California Lighting Technology Center

Figure 8: Color Fidelity Trade-Off Study Testing Area

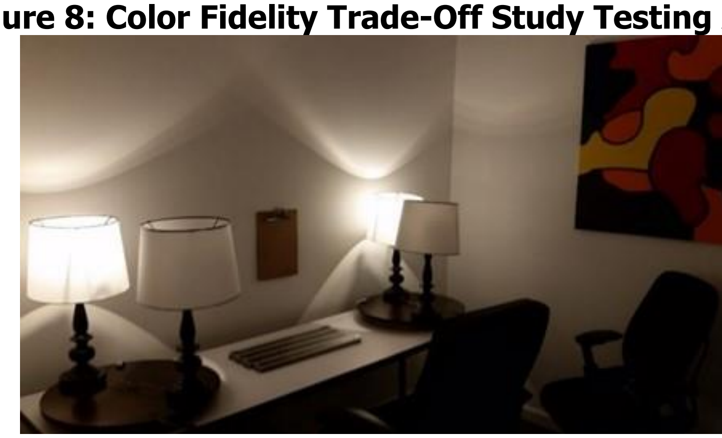

Figure 8 shows the color fidelity trade-off study testing area at the California Lighting Technology Center.

Source: California Lighting Technology Center

Figure 9: Color Fidelity Room Incandescent Light

Figure 9 shows an incandescent light used in the color fidelity room at the California Lighting Technology Center.

Source: California Lighting Technology Center

Residential Vanity

A second vignette designed to resemble a residential vanity was used for the *Lighting Service Delivered* test. The test setup is shown in Figure 10. Arrays of high- and low-color fidelity LEDs were installed behind each side of the vanity mirror. The LEDs were powered by dimming drivers and manually controlled, which enabled dimming down to one percent of full power. The optical distribution of the vanity lighting was designed so the high- and low-color fidelity scenes delivered near-identical distributions.

Because test participants were allowed to adjust light levels as part of this test and the light level could not easily be measured directly, researchers used power as a proxy to evaluate test results. An identical lighting system consisting of LED arrays, drivers, and a controller was used to determine the dimming-versus-power curve of the vanity lighting system in the test. Test results showed that the power drawn by the drivers was linearly related to the system's luminous flux (light output), allowing calculation of the amount of light produced based on the power consumed.

Figure 10: Residential Vanity Mock-Up

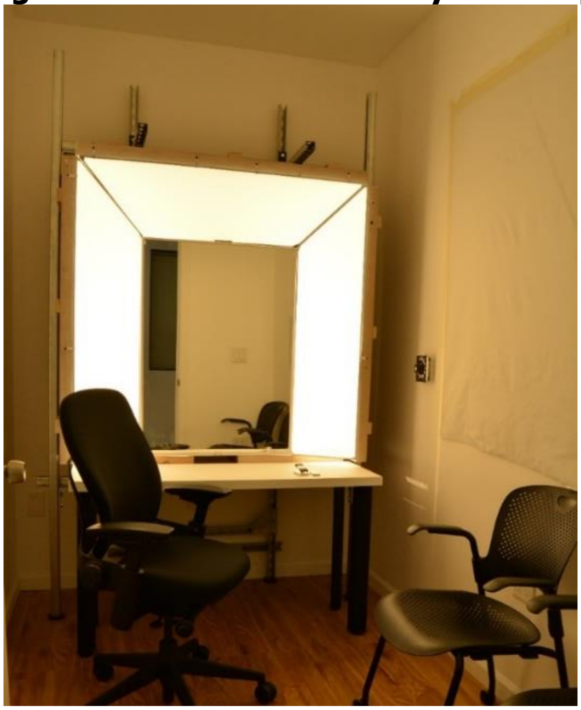

Figure 10 shows residential vanity mock-up used for the 'Lighting Service Delivered' study at the California Lighting Technology Center.

Source: California Lighting Technology Center

During the actual tests, the power draw of the system was recorded by a Xitron 2802 Power Analyzer installed behind the test chamber. Key photometric and electrical characteristics of the vanity lighting system are provided in Table 2. Recorded power measurements were translated to light levels using the power-versus-dimming curve.

Table 2: Vanity Mock-Up Light Source Performance

	Color Fidelity (CRI – R_a)	R_9	Light Output (lm)	CCT (K)	D_{UV}
High Color Fidelity	95	76	11,721	2679	0.0004
Low Color Fidelity	82	9	14,746	2666	0.0005

Table 2 shows the key photometric and electrical characteristics for the high and low color fidelity scenes used in the vanity mock-up.

Source: California Lighting Technology Center

Multi-Spectral Melanopic Lighting

The *Multi-Spectral Melanopic Lighting* test consisted of two phases conducted in different test rooms. Both test rooms consisted of converted, private offices within the CLTC facility. Each room contained custom-built, multi-spectral luminaires equipped with eleven LED channels. Eight channels controlled high-color fidelity and phosphor-converted white LEDs. The remaining three channels controlled colored LEDs selected for their low emission in the blue portion of the visible spectrum. The spectral-power distribution and corresponding CCT of each channel is provided in Figure 11. Figure 12 shows the overall layout of the test space during Phase A (left) and Phase B (right).

Figure 11: Spectral Power Distribution of the 11 LED Channels

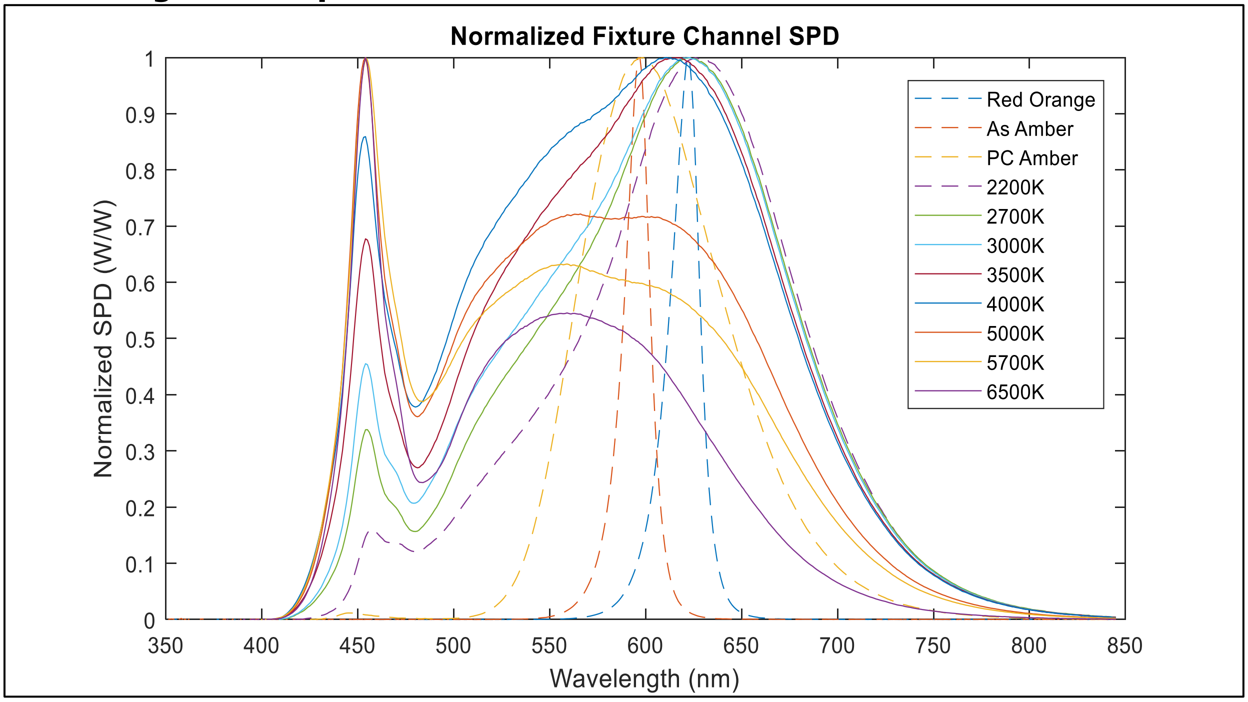

Figure 11 shows the normalized spectral power distribution for each of the 11 LED channels used in the multi-spectral melanopic lighting study at the California Lighting Technology Center.

Source: California Lighting Technology Center

Figure 12: Multi-Spectral Melanopic Study During Phase A (Left) and Phase B (Right)

Figure 12 shows two settings used in the multi-spectral melanopic study during Phase A (left) and Phase B (right).

Source: California Lighting Technology Center

Test Descriptions

Color Consistency

The *Chromaticity Perception and Preference Test* is designed to quantify two fundamental aspects of lighting's impact on human observers: the average level of perceptible color variation and the average acceptable color variation of products in common building applications. Tests were designed to determine the just-noticeable-difference in color temperature for common LED sources to understand if current CCT tolerances were acceptable to consumers or required revisions to increase product acceptance.

For this test, researchers asked test participants to observe four identical table lamps under 40 different configurations, one for each direction of chromatic variance within each bin, and each with all the lamps displaying the center of a specific chromaticity bin. In each lighting scene, either all four of the table lamps were the same chromaticity, or one randomly selected table lamp was set with a different chromaticity than the other three.

For each test, lamp brightness was constant and CCT was varied. CCT values were varied across the Planckian locus, along a constant color temperature line, and along the root locus, along a changing color temperature, which assessed the impact of "directionality" on perception. The Plankian locus and root locus are shown in Figure 13 as blue and red arrows, respectively. Points within the "7-step," "4-step," "2-step," and "1-step" chromaticity bins were included in each round of testing. Participants were first shown chromatic variations for 2,700 K light sources and 4,000 K light sources.

Figure 13: Evaluated 2,700 Kelvin ANSI Bins

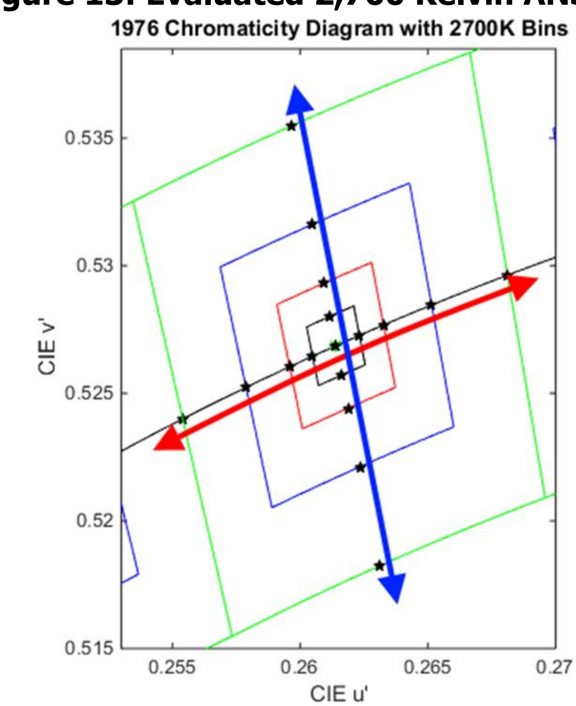

Figure 13 shows the chromaticity points that study participants were shown for the 2,700 K scene of the study.

Source: California Lighting Technology Center

Researchers asked each test participant to identify which, if any, of the table lamps looked different from the others. If a participant observed a difference, researchers then asked if the difference in color was acceptable (assuming all four lamps were to be used in the same fixture or space). This was repeated multiple times to evaluate the perception of "7-step," "4-step," "2-step," and "1-step" chromaticity bins.

High-Color Fidelity

The *High Color Fidelity (HCF)* test sought to determine if increased color fidelity is positively correlated to increased perceived brightness and improved color discrimination. The HCF test was composed of two test activities. The first assessed the trade-off between light output and color fidelity. The second assessed impacts from differences in delivered lighting service (lumens) by both high- and low-color fidelity light sources.

The "home-office" area was used for this mock-up evaluation. During this test, participants were asked to evaluate a room illuminated by 95 CRI LED lighting and 82 CRI LED lighting, each with the same CCT. Both lighting schemes were configured to consume identical amounts of power. During each test, the participant entered the test space, which was illuminated with an incandescent lamp at a low-light level, then asked to wait for one minute so their eyes could adapt to the lighting. Then, the room was illuminated by an LED source. Participants were instructed to look around the room and evaluate the "naturalness" and "brightness" of the space.

Following this observation period, participants were asked to perform a color-sorting task using the blue-red and red-green trays of the Farnsworth-Munsell 100 Chroma test chips shown in Figure 14. "Tray 1" is red-green, and "Tray 2" is blue-red.

The goal of the test is to organize the chips ranging from most red to most green, and from most blue to most red, respectively. The participants sorted the color chips twice, once under high-color fidelity lighting and once under low-color fidelity lighting. Equal numbers of participants sorted first under high-color-fidelity lighting or first under low-color-fidelity lighting. Following both rounds of testing, each participant was asked to rate how similar the two scenes appeared and which scene seemed brighter.

Figure 14: Farnsworth-Munsell 100 Chroma Test

Figure 14 shows blue-red and red-green Farnsworth-Munsell 100 Chroma test chips used to evaluate how well study participants could discern color under high and low color fidelity scenes.

Source: California Lighting Technology Center

Delivered Lighting Service

The *Delivered Lighting Service* study, also conducted in the residential-vanity test area, allowed researchers to assess the impact of color fidelity on perceived brightness (and thus energy use) in a common residential environment.

For this test, participants were seated at the bathroom vanity within a space illuminated by diffuse, ambient lighting. Researchers then varied the initial light level and color fidelity provided by ambient lighting and asked participants to adjust the vanity light level to reach a level suitable for normal grooming tasks such as styling hair, shaving, or applying makeup. Participants were not allowed to adjust color fidelity, only brightness.

Each participant performed the activity 10 times, once for each of 10 different, preconfigured initial lighting scenes. After each test, researchers dimmed the lighting and switched the ambient system to the next lighting scene. The set of 10 initial scenes included an equal number of high- and low-color fidelity scenes; for each participant the order of the scenes was also randomly varied to reduce ordering effects in his or her selections.

For each scene, after participants indicated that they had reached their final, desired light level, researchers recorded the vanity's power draw. The final, selected light level for each scene was determined by correlating the vanity's power draw to its dimming level, using the linear dimming curve described in the previous section.

Color Shift

The *Consumer Perception of Intentional Color Shift (CPIC)* study was designed to evaluate if an intentional color shift, while dimming, is preferable to no color shift during dimming, and to determine, from the consumer's perspective, what range of color shift is most desirable.

The Chromaticity Perception Chamber was used for this laboratory evaluation. The test was conducted in two phases. During Phase A, the lighting system consisted of three LED table lamps, one incandescent table lamp, and four overhead LED downlights. Each table lamp was contained in a "cell" to limit its light contribution from the others. All table lamps were set for the start of the test at full brightness, with the same CCT and D_{UV}. Each table lamp was programmed with a unique color shift/dimming profile:

- A standard incandescent lamp with dim-to-warm performance
- An LED source commissioned to dim with the same CCT profile (CCT shift per unit brightness) as an incandescent lamp (dim-to-warm)
- An LED source commissioned to dim without changing CCT (dim-to-same)
- An LED source commissioned to dim with the same CCT shift per unit brightness as an incandescent, but to shift cooler rather than warmer (dim-to-cool).

Figure 15: Dimming Profiles for Sources Used to Determine Color Shift Preferences

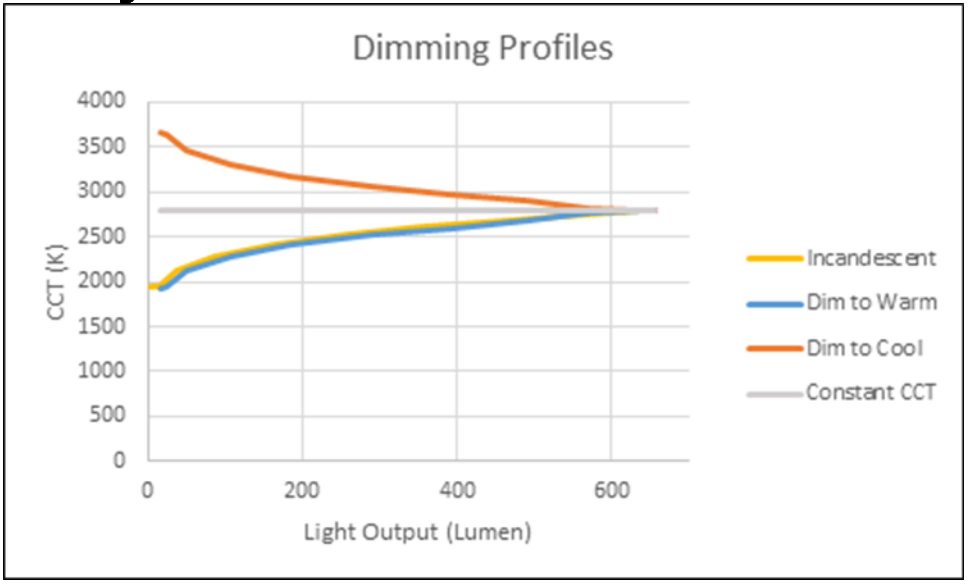

Figure 15 shows the dimming profiles for light sources used to gather feedback from study participants on color shift preferences.

Source: California Lighting Technology Center

Before starting the test, participants were asked a series of questions about their experiences with dimmable lamps. Then test participants were asked to press a button to dim the lamps to pre-set levels. All lamps dimmed simultaneously over five seconds and then participants were asked additional questions and to rate their preferences for the lamp-dimming profiles.

Once complete, table lamps were turned off and participants evaluated the general overhead lighting and its color shift. For each of the three dimming scenes, participants were allowed to dim up to full output or dim down to minimum output (0.5 percent of full) as often as they wished; however, users had no way to set the lighting to a mid-range dimming level. Once each participant was done comparing the high- and low-level lighting, they were asked a series of questions regarding the lighting scene and its associated dimming profile. This procedure was repeated for each of the three scenes: dim-to-warm, dim-to-same, and dim-to-cool.

For Phase B, the incandescent table lamp was replaced with an LED source (Figure 17). Each of the four LED table lamps was programmed with a specific CCT based on a review of commercially available residential LED products. Programmed CCTs were 2,200 K, 2,700 K, 4,000 K and 5,000 K. Users had no control over the table lamps during this phase. The overhead lighting remained the same as Phase A, with three user-selectable dimming profiles.

Figure 16: Lamps Used For Intentional Color Shift Study – Phase B

Figure 16 shows lamps used for the intentional color shift study during Phase B.

Source: California Lighting Technology Center

Before starting the test, and identical to Phase A, participants were asked a series of questions regarding their experiences with lamp dimming. Participants then identified their CCT preferences from among the four table lamps and answered a series of related questions. They then evaluated the color shift of the general overhead lighting and, again, selected their preferred dimming profile and interests in color-tunable lighting that were controlled by the dimmers in Figure 17.

Figure 17: Controls Used in the Intentional Color Shift Study

Figure 17 shows the controls used in the intentional color shift study.

Source: California Lighting Technology Center

Multi-Spectral Melanopic Lighting

The Multi-Spectral Melanopic Lighting test consisted of two phases. Participants completed two tasks during each phase:

1. A visual acuity assessment using a Landolt-C chart.
2. Sorting Farnsworth-Munsell D-15 color chips.

The visual acuity assessment was performed using a Landolt-C chart with lines of text (Phase A) and C-shape characters (Phase B). For Phase A, participants were asked to identify the smallest line of text where they were able to recognize individual letters and characters. For Phase B, participants were asked to indicate the direction of the opening of the C-shapes for successively smaller lines of text until they reached a line they were unable to read. If a participant made a mistake on one character, he or she was instructed to read previous larger lines until able to read a complete line correctly. The smallest readable line was recorded. For each of the 10 CCT scenes, a different configuration of the Landolt-C chart was used. Both types of charts are shown in Figure 18.

During Phase A of the study, participants entered the test space illuminated with 6,500 K light (Channel 1). They were asked to select a line of text from a sheet of paper and rate their difficulty in recognizing the text under these conditions. Participants were then asked to remember the difficulty level during subsequent study rounds. Lastly, participants completed a color-sorting task using the Farnsworth-Munsell D-15 chip set.

After completing the sorting task, the lighting was dimmed and transitioned to the next CCT setting. Participants were asked to increase the light level until they felt that they were able to recognize their previously selected text line as easily as they were able to do so under the 6,500 K light. Participants were again asked to sort the color chips and the lighting was transitioned to the next CCT setting. This process continued for all 10 remaining channels. During each round, researchers recorded the chip-sort order and the selected power level of the LED lighting.

Figure 18: Example Landolt-C charts Used to Test Participants' Vision in the 'Multi-Spectral Melanopic Lighting Study' Round 2

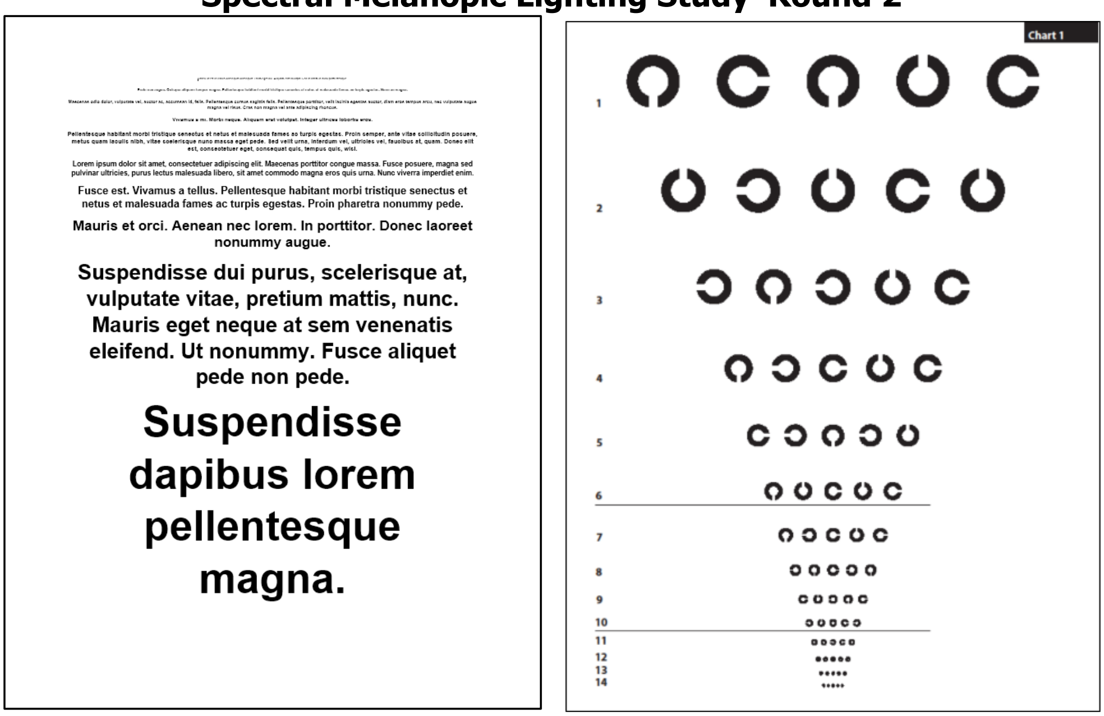

Figure 18 shows examples of the Landolt-C charts used to test participants' vision in the multi-spectral melanopic lighting study.

Source: California Lighting Technology Center

During Phase B, participants could not control light levels. Instead, lighting was automatically set to a threshold with lower melanopic stimulus. To move through each available scene, lighting was dimmed automatically, switched to the next channel, and then raised to the next test level. For each scene, participants performed the same visual-acuity assessment and a sorting task. During each round, researchers recorded the chip-sort order and line-legible C-shapes from the Landolt-C chart.

Lighting Metrics and Packaging Survey

CLTC administered a basic survey designed to quantify consumer understanding of common lighting metrics and information found on product packaging. The survey consisted of a two-part online questionnaire composed of seven multiple-choice questions. Part One of the survey used the full-color LED Lighting Facts label, which provides a basic level of information on lighting characteristics including metrics such as life and lumen output. The second part of the survey focused on the overall appearance of the lighting-product packaging and the information it contained. CLTC asked laboratory-study participants to take the survey prior to participating in the other tests previously described. A complete list of survey questions is provided in APPENDIX B:
Lighting Survey Details.

Results

Chromaticity Perception

For each of the 40 lighting scenes presented as part of the Chromaticity Perception study, researchers recorded the table lamp that participants identified as different from the other three.

Table 3 summarizes, for each chromaticity difference and CCT bin, the percent of participants who correctly identified the lamp with the different CCT.

Researchers then analyzed the collected perception data for both CCT bins using curve-fitting techniques. The detection thresholds for both positive and negative color temperature shifts were averaged to estimate the level of detectable color temperature variation for each bin. Likewise, the detection thresholds for the positive and negative shift along the lines of constant CCT were averaged to provide an estimate of the level of detectable variation along the root locus. Results are shown in Figure 19.

The positive and negative shifts along and across the Plankian locus were similar in magnitude, which confirms, from a visual perceptibility standpoint, that they are related. The positive and negative detectable perception threshold for each participant was averaged to determine the size of the chromaticity shift at which five and 50 percent of people are able to see a color change. At 2,700 K, 95 percent of people are unable to see a variance of 22 CCT or less (0.0002 D_{UV}). Fifty percent of people are able to see a variance of 70 CCT or more (0.0011 D_{UV}). Similarly, for 4,000 K, 95 percent of people are unable to see a variance of 43 CCT or less (0.0003 D_{UV}) and 50 percent of people would be able to see a variance of 133 CCT or more (0.0017 D_{UV}).

Table 3: Percent of Participants Able to Detect Each Difference

2700 K Bins		
Size	*Edge*	*% Perceived*
1 Step	+CCT	4%
	-CCT	13%
	+duv	31%
	-duv	53%
2 Step	+CCT	17%
	-CCT	9%
	+duv	93%
	-duv	84%
4 Step	+CCT	65%
	-CCT	72%
	+duv	98%
	-duv	100%
7 Step	+CCT	98%
	-CCT	98%
	+duv	100%
	-duv	98%

4000 K Bins		
Size	*Edge*	*% Perceived*
1 Step	+CCT	22%
	-CCT	2%
	+duv	22%
	-duv	28%
2 Step	+CCT	9%
	-CCT	4%
	+duv	72%
	-duv	63%
4 Step	+CCT	63%
	-CCT	70%
	+duv	91%
	-duv	93%
7 Step	+CCT	91%
	-CCT	93%
	+duv	98%
	-duv	98%

Table 3 summarizes, for each chromaticity difference and CCT bin, the percent of participants who correctly identified the lamp with the different CCT.

Source: California Lighting Technology Center

Figure 19: Curve Fitting for Chromaticity Study

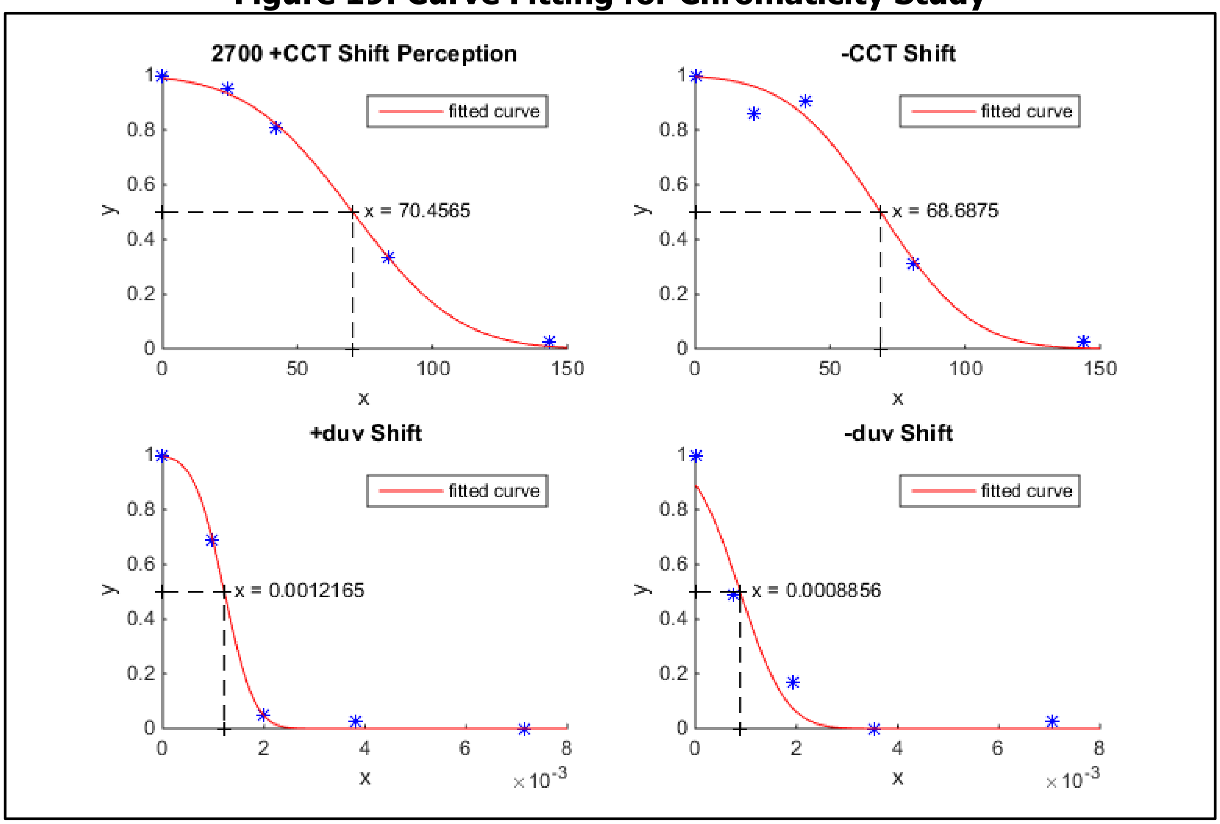

Figure 19 shows curve fitting used for the chromaticity study.

Source: California Lighting Technology Center

Chromaticity Acceptance

In addition to determining if participants saw a difference among the table lamps displayed, researchers sought to identify the level of difference that was "acceptable" to consumers should the color difference occur between two products that were in close proximity to each other. Table 4 summarizes, for each chromaticity difference, the percent of participants who stated that the lighting difference was acceptable. Acceptance thresholds were determined in the same manner as the perception thresholds described in the previous section.

At 2,700 K, 95 percent of people accepted a variance of 74 CCT or less (0.0003 D_{UV}) and 50 percent of people accepted a variance of 164 CCT or less (0.0034 D_{UV}). Similarly, for 4,000 K, 95 percent of people accepted a variance of 178 CCT (0.0007 D_{UV}) and 50 percent of people accepted a variance of 308 CCT or less (0.0043 D_{UV}).

Table 4: Percent of Participants Accepting Each Sample

2700 K Bins		
Size	*Edge*	*% Acceptable*
1 Step	+CCT	100%
	-CCT	100%
	+duv	100%
	-duv	96%
2 Step	+CCT	98%
	-CCT	100%
	+duv	63%
	-duv	78%
4 Step	+CCT	96%
	-CCT	91%
	+duv	17%
	-duv	52%
7 Step	+CCT	67%
	-CCT	59%
	+duv	4%
	-duv	22%

4000 K Bins		
Size	*Edge*	*% Acceptable*
1 Step	+CCT	100%
	-CCT	100%
	+duv	98%
	-duv	100%
2 Step	+CCT	98%
	-CCT	100%
	+duv	80%
	-duv	91%
4 Step	+CCT	98%
	-CCT	96%
	+duv	41%
	-duv	61%
7 Step	+CCT	74%
	-CCT	52%
	+duv	17%
	-duv	33%

Table 4 shows summarizes, for each chromaticity difference and CCT bin, the percent of participants who accepted the lamp with the different CCT.

Source: California Lighting Technology Center

Color Fidelity Trade-Offs

For the *Color Fidelity Trade-Off* test*,* participants completed two tasks: the Farnsworth-Munsell 100 Hue Color test and a questionnaire about their perceptions of the lighting scenes under which they worked.

Farnsworth-Munsell 100 Hue Color Test

Under this test, the colored chips have a correct order and each chip is sequentially numbered so that following a sort, the chips' numbers can be used to grade the accuracy of the sort and the visual acuity of the test-taker completing the test under each lighting scene. To grade the test, each sorted chip is assigned an error value that is calculated as the difference between a chip's numbered value and the numbered value of its neighboring chips. For each test (sort), error values determined the overall grade for each participant under each lighting scene. A perfectly ordered chip set has a score of zero.

The hypothesis is that participants show an increased ability to perform a color-based task illuminated by a commercially available, high-color-fidelity LED source as compared with their ability to perform that same task under a commercially available, lower-color-fidelity source, when those sources are powered to the same level (watts). For this study, the Farnsworth-Munsell 100 Hue Color Test represents the color-based task called out in the hypothesis. The statistical significance level for this test is set at a P-value of $p = 0.05$, meaning the test result is deemed significant when it is more than 95 percent likely to have been the result of the experiment (change in color fidelity), as opposed to inter-observer variability (i.e. the amount of variation between the results obtained by two or more observers examining the same material).

The difference in scoring between high- and low-color-fidelity tests, on average, was 4.1 points for the tray of red-to-green chips and 1.3 points for the tray of blue-to-red chips. Half the test participants were asked to perform the test, first under high-color-fidelity lighting, then under low-color fidelity. The other half were asked to perform the test under low-fidelity lighting, then high. Those performing first under low-color-fidelity lighting are grouped under "Scene 1." Those taking the test first under high-color-fidelity lighting are grouped under "Scene 2." Due to the nature of the test, participants were able to perform better on tests completed under the second CRI within each scene because they were more familiar with the test process. Results are shown in Figure 20.

Figure 20: Average Error Scores for Each Scene (95 CRI or 82 CRI)

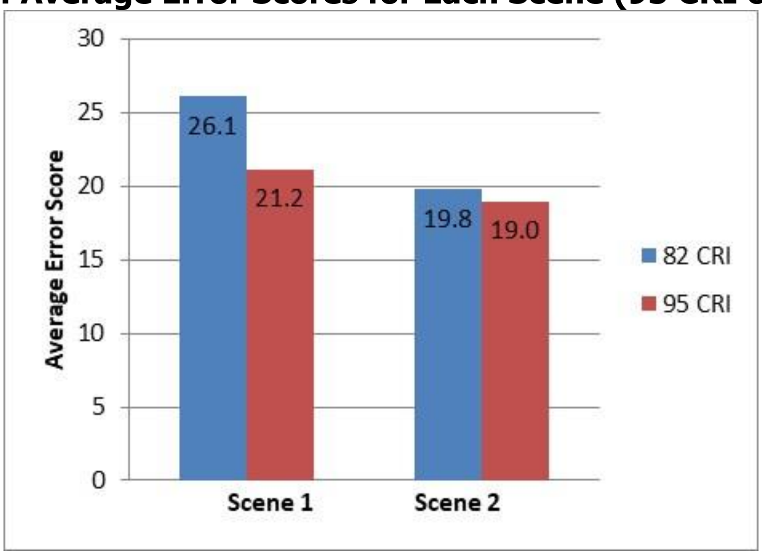

Figure 20 shows the average error scores for high color fidelity and low color fidelity.

Source: California Lighting Technology Center

Looking at the error scores for the first lighting scene shown to participants (Figure 21 – left), the difference in average score between the high- and low-color fidelity for the tray of red-to-green chips is 8.0 with a P-value of $p = 0.06$, which is nearly statistically significant at the 95-percent confidence level. The blue-to-red chips showed less difference between high- and low-color-fidelity scenes. The participant's scores for the first scene represent untrained error scores. For the second sort (second CRI), overall test scores improved as test-takers became more familiar with the process.

Figure 21: Average Error Scores for First and Second Lighting Scenes

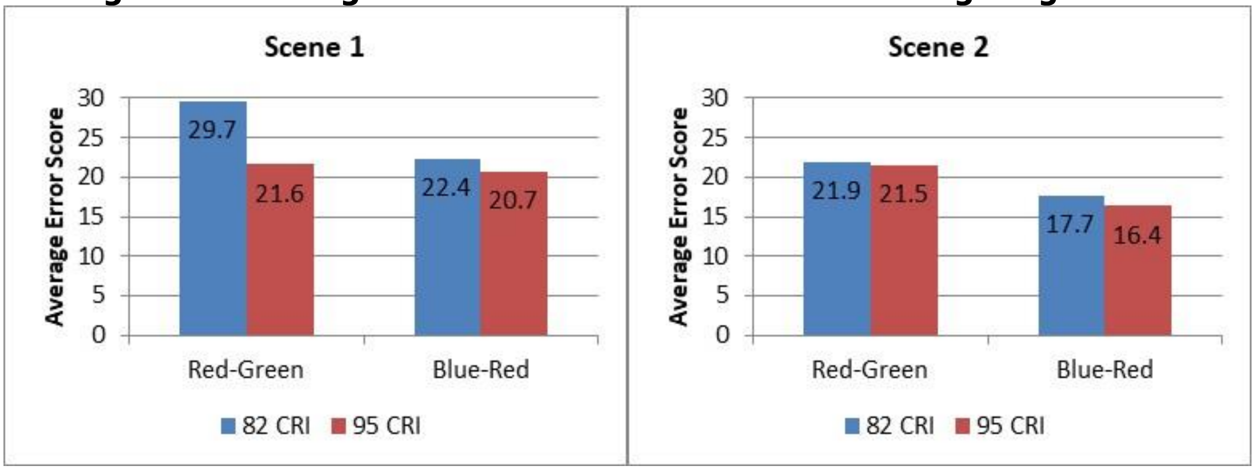

Figure 21 shows the average error scores for Scene 1 and Scene 2. The overall test scores improved as test-takers became more familiar with the process between Scene 1 and 2.

Source: California Lighting Technology Center

Questionnaire Results

Participants completed a questionnaire to rate the high- and low-color-fidelity lighting used during their test experience. They were asked which appeared brighter, in general, in addition to which they preferred for the color-sorting task. Participants were asked to rate how natural the lighting in the room seemed and how well lit the room felt under each light, using a five-point Likert scale. As shown in Figure 22, the peak rating for naturalness decreased (increased naturalness perception) as color fidelity increased. Also, under both high- and low-CRI lighting, the room was rated as "well lit," which was at the middle of the scale.

Figure 22: Ratings of Room Brightness and Naturalness

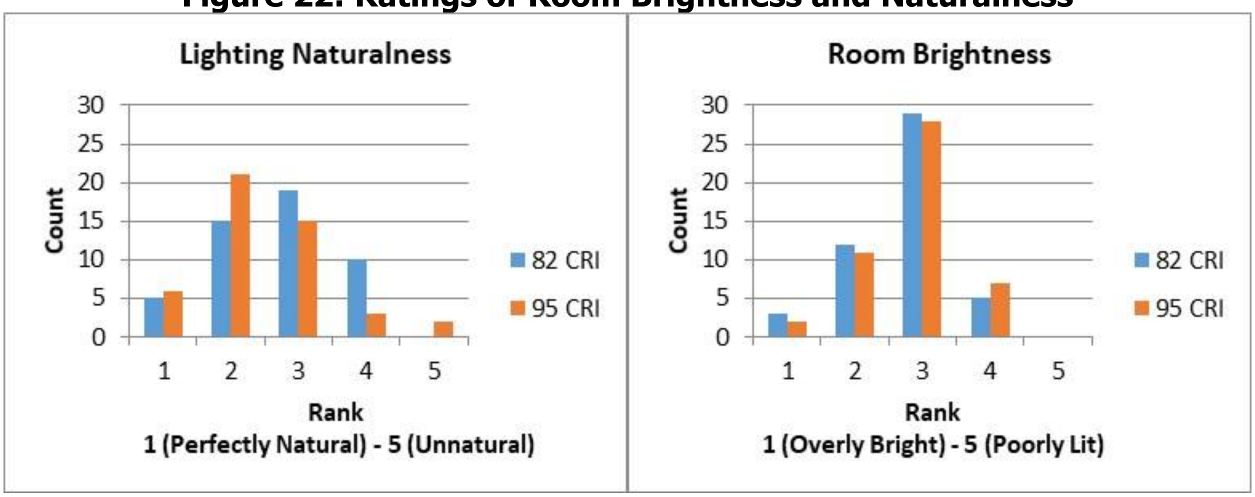

Figure 22 shows ratings from the study participants for lighting naturalness and room brightness.

Source: California Lighting Technology Center

Participants were then asked to rate how different the room seemed using the same scale, first in general and then with respect to brightness. The two lighting environments were most frequently rated as "somewhat similar" in general (score of 3) and between "somewhat similar" and "very different" in brightness (score of 3) as shown in Figure 23. One person felt that the scenes looked identical, and two people felt that the brightness of the scenes was identical (scores of 1).

Figure 23: Ratings of How Similar Scenes and Brightness Look

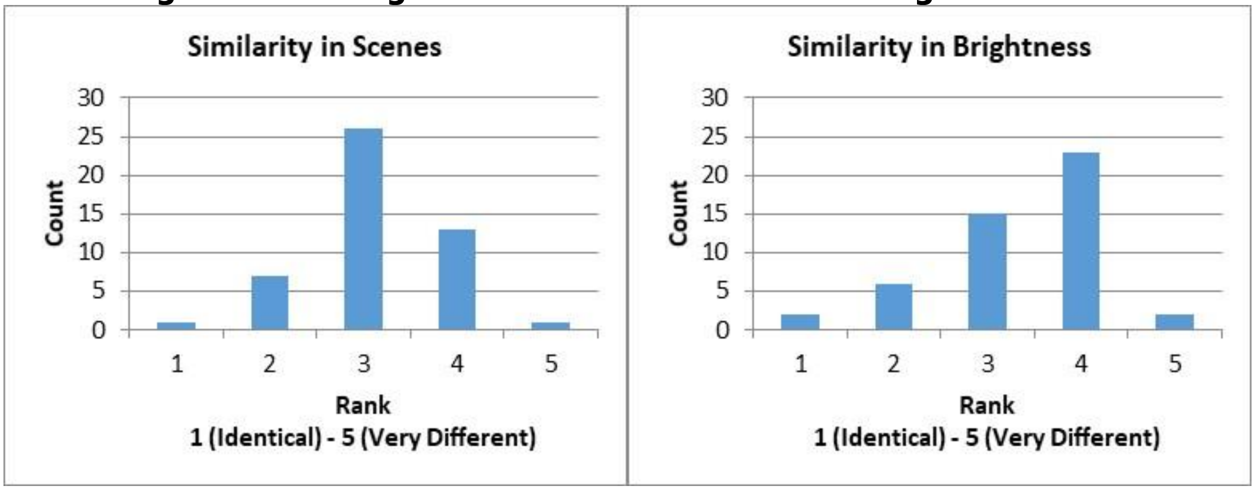

Figure 23 shows the results from asking study participants to rate how different the room seemed in terms of similarity in scenes and in brightness.

Source: California Lighting Technology Center

Participants were then asked which lighting environment seemed brighter. Twenty-six participants found that the low-color-fidelity environment was brighter, and 22 found the high-color-fidelity environment brighter, as shown in Figure 24. Two people did not see a difference in brightness between the environments.

Figure 24: Scene Brightness Selection by Gender

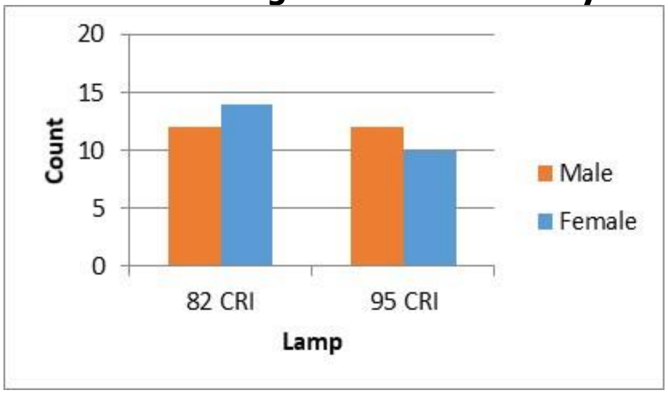

Figure 24 shows the scene brightness data analyzed based on gender.

Source: California Lighting Technology Center

Finally, the participants were asked which room/lighting environment they preferred for the sorting of the Farnsworth-Munsell 100 Hue test. Twenty-nine people preferred the high-color-fidelity environment for sorting the color tiles and 19 people preferred the low-color-fidelity environment. Preference for two individuals was not recorded. Figure 25 shows the preferred color fidelity of the study participants sorted by gender.

Figure 25: Selection for Preferred Color Fidelity Lighting by Gender

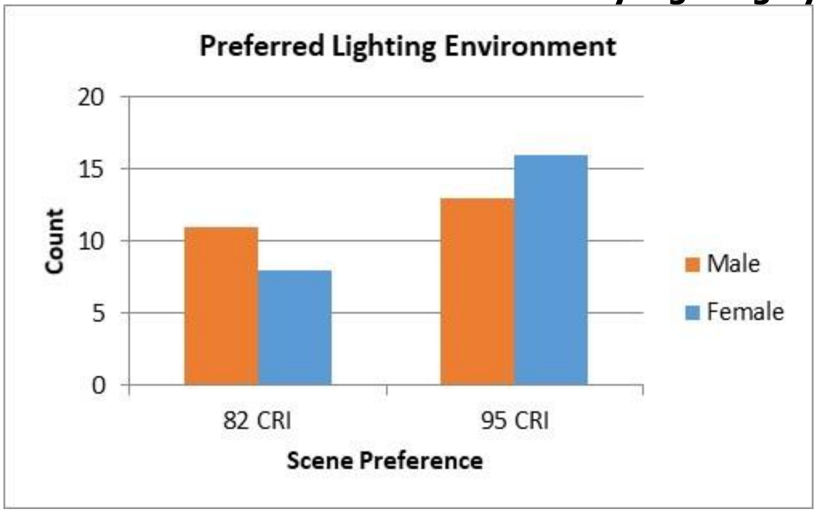

Figure 25 shows the preferred color fidelity analyzed by gender.

Source: California Lighting Technology Center

Lighting Service Delivered

For this study, researchers recorded the power level to which the participants raised the lights when asked to adjust the lighting for personal grooming activities. Based on selected light levels, researchers calculated the average preferred light level (over 10 test runs). Using this value, researchers calculated the average increase in electrical power, radiant power, and light level requested from the low- (80 CRI) and high- (95 CRI) fidelity light. The average percent change in light level was a decrease of almost 10 percent from low- to high-color fidelity, as shown in Table 5.

Table 5: Change in Average Vanity Levels Selected

From 80 CRI to 95 CRI	Average	Min	Max	Std.
% Change in Power	11.3%	–15%	37%	10%
% Change in Radiant Power	8.8%	–30%	54%	15%
% Change in Light	–9.8%	–47%	36%	15%

Table 5 shows the average percent change for power, radiant power and light of the vanity between the high and low color fidelity scenes.

Source: California Lighting Technology Center

To aid in understanding the range of the individual percent differences between selected low- and high-fidelity sources, Figure 26 shows the data presented in a boxplot, as well as the average and standard deviation of the percent differences. The boxplot is a graphic representation of the individual results: the red line in the middle (at -12 percent) of the blue box is the median-percent change; the blue box shows the second- and third-quartile (the middle 50 percent) of the results. The whiskers and red pluses (+) above and below the blue box show the first and fourth quartiles, indicating that more than 75 percent of individuals requested less light with high-color fidelity. The red pluses (+) are data that are greater than 1.5 times the width of the blue box away from the median, which is a standard method of determining outliers. The average and standard deviation plot graphically represents the data in the last row of Table 5.

Figure 26: Percent Change of Light Selected from 82 CRI to 95 CRI

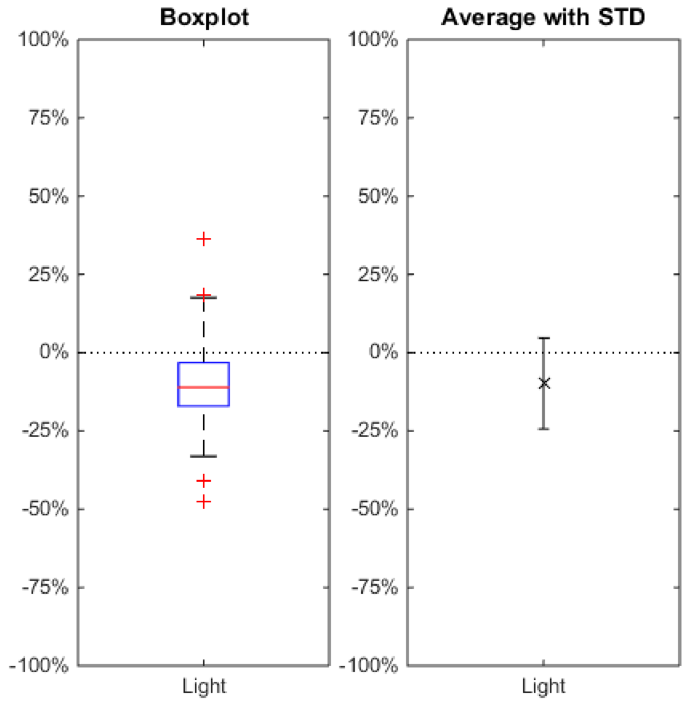

Figure 26 shows the percent change of light selected from 82 CRI to 95 CRI.

Source: California Lighting Technology Center

In addition to the analysis of all 10 interactions, researchers isolated the first four data sets for evaluation. This was done to consider the tiring effect that a protracted repetition of the test may have had on test participants. Table 6 shows the average increase in electrical power, radiant power, and light level requested from the low-fidelity to the high-fidelity lighting for the first four repetitions. Looking at just the first four runs for each participant, the median reduction in light was almost 25 percent, and the mean (average) reduction was 18 percent. Additionally, more than 75 percent of individuals requested less light with high-color fidelity, as shown in Figure 27.

Table 6: Change in Average Vanity Levels Selected for First Four Runs

From 80 CRI to 95 CRI	Average	Min	Max	Std.
% Change in Power	4.9%	–33%	57%	20%
% Change in Radiant Power	0.6%	–52%	81%	29%
% Change in Light	–17.6%	–69%	65%	29%

Table 6 shows the average percent change for power, radiant power and light of the vanity between the high and low color fidelity scenes for four iterations of study.

Source: California Lighting Technology Center

Figure 27: Percent Change of Light Selected From 82 CRI to 95 CRI for First Four Runs

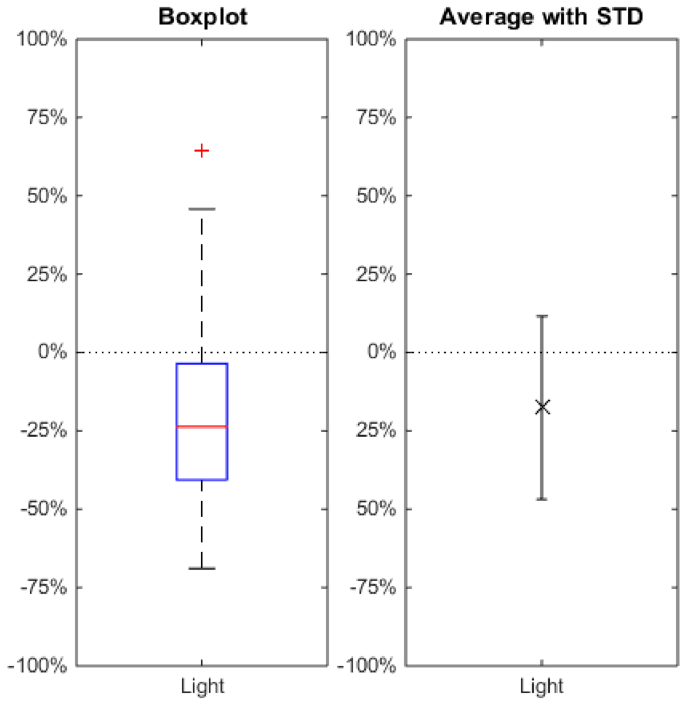

Figure 27 shows the percent change of light selected from 82 CRI to 95 CRI for first four runs.

Source: California Lighting Technology Center

Lighting Information Survey

Participants completed a survey to document their understanding of lighting metrics and their use of lighting-product packaging. During the first part of the survey, participants were presented with an LED Lighting Facts label and asked their opinions regarding several metrics listed on the label. Questions and question options were randomized for all participants.

As LED "life" is often presented as a long-term benefit of using LED sources, the survey asked two questions specifically about consumer understanding of this metric. Life ratings may be presented in terms of hours, years, or warranty periods; however, the study showed that making accurate comparisons and selections among these choices did not result in selection of the longest time. Information presented in terms of years, for example, relies on an assumed number of operating hours per year. When presented with three different statements regarding life of the same LED product, presented in different units of hours, years and warranties, and asked to select the one with the longest life, 74 percent of people believed that a lamp rated in terms of years would last longer than the same lamp rated in hours. Individual results are shown in Figure 28.

Figure 28: Percent of Survey Respondents Indicating Metric for LED Life with the Longest Period

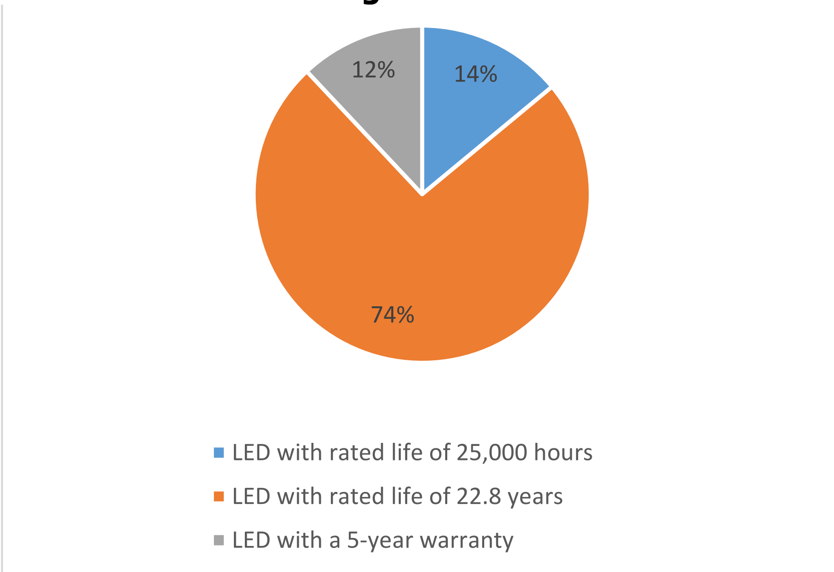

Figure 28 shows the percent of survey respondents indicating which metric for LED life had the longest period. The majority selected 22.8 years.

Source: California Lighting Technology Center

When survey participants were asked how the LED lamp might behave at the end of its life, 50 percent of respondents believed that the LED would fail completely or "die." Similarly, 46 percent thought the lamp would be less useful in terms of lighting provided and would be dimmer, faded, or less bright. Other responses included comments that the LED lamp would flicker, be less efficient, or change color (yellow). In contrast, a significant number of respondents thought the LED lamp would be unchanged at the end of its rated life.

Given that consumers may often link a product's life to the length of its warranty, warranty terms and information can indirectly affect product purchase decisions when product longevity is a decision-making factor. Survey respondents were presented with several different common LED product warranty terms and asked to select those that were unacceptable and likely to affect their purchase decisions negatively. Only four percent of respondents felt that all of the warranty terms were acceptable. Participants could select more than one term as unacceptable. All options and selection rates are provided below.

In addition to questions regarding product life, the survey included one question focused on better understanding consumer expectations regarding other product benefits. People were asked to rank the relative importance of nine individual product characteristics on a scale of 1 to 5, where one indicates "most important" and five, "least important." Scores were summed and lower scores indicated characteristics most important to consumers. Cost and light output ranked as the top two characteristics. Brand name was ranked as the least important. All characteristics and rankings are shown in Figure 29.

Table 7: Warranty Terms Included in Lighting Product Survey Question

Warranty Language or Clause	Unacceptability Rate
Cost of returning the lamp to be paid by the customer.	72%
This warranty only applies to lamps operating on a burn cycle of 12 hours or more per start and no more than 4400 hours per year.	58%
Lamp must be returned with proof of purchase or cashiers receipt to receive a refund or replacement.	38%
To obtain coverage under this warranty, customer must complete and deliver to the manufacturer a "warranty form" within 30 days of product installation.	38%
Manufacturer may issue a partial refund (cost of original purchase reduced by duration of use) or send you a replacement lamp.	26%
Lamp must be properly installed, wired and operated or the warranty is void.	22%
All the terms listed are appropriate.	4%

Table 7 shows warranty terms included in the lighting product survey and the survey respondents unacceptability rate.

Source: California Lighting Technology Center

Figure 29: LED Lamp Characteristics Ranked From Lowest to Highest Importance by Survey Respondents

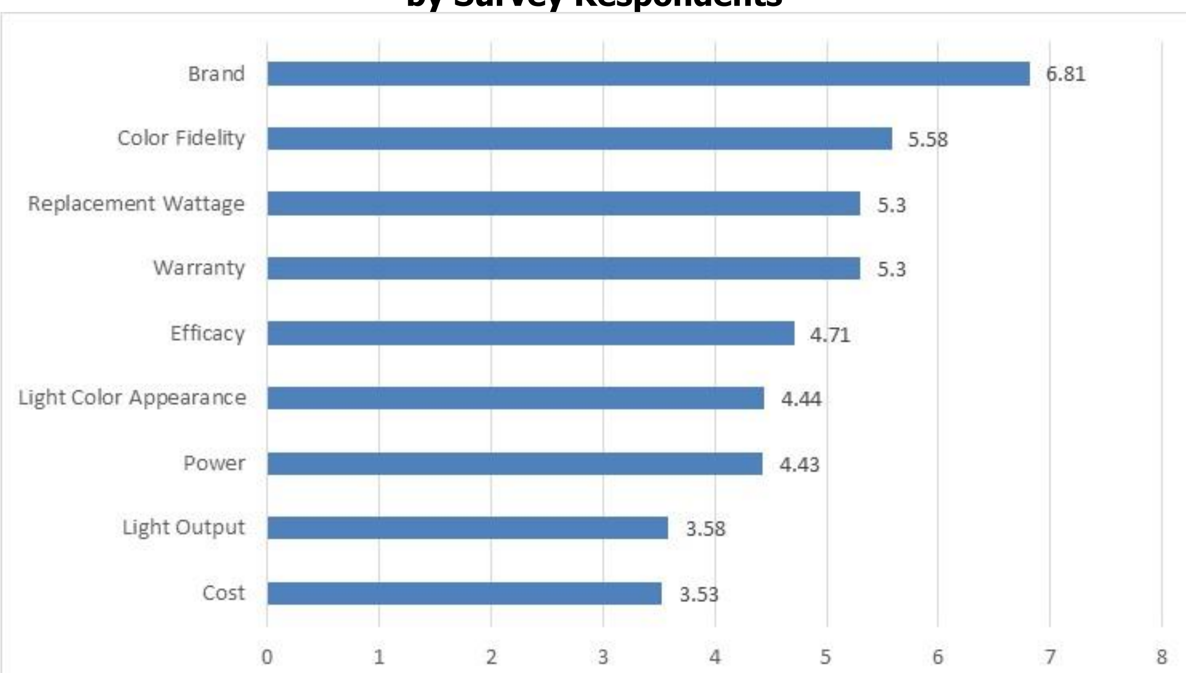

Figure 29 shows responses from survey respondents ranking LED lamp characteristics from lowest to highest importance.

Source: California Lighting Technology Center

The second part of the survey consisted of three questions focused on consumer perception of LED product packaging. Questions addressed general preference for packaging features as well as relative preference. The products used for these questions are shown in Figure 30.

Lamp C ranked highest overall due to its inclusion of the Lighting Facts label and overall aesthetic. Overall, packaging that included the Lighting Facts label, Energy Star label, and other common information ranked higher than purely aesthetic considerations such as lamp shape, package color, or brand name. However, when respondents were asked to rank their overall relative preference for their top pick as compared to the other two, respondents indicated only a "slight" preference for their top pick.

Figure 30: Lighting Packaging Shown in Survey

Figure 30 shows images of lighting packaging used in the survey to assess consumer perception of LED product packaging.

Source: California Lighting Technology Center

Intentional Color Shift during Dimming

A majority of participants had experience with incandescent and LED dimming prior to their participation in this study: 75 percent and 68 percent, respectively. Most participants also expressed initial interest in light sources capable of providing variable color. Results indicate that a significant number of people are not familiar with color-tunable light sources and do not know if they would be interested in the technology. Individual results for each background question during each phase (Phase A – left, Phase B – right) are provided in Figure 31.

Figure 31: Results to Background Questions Asked as Part of the Intentional Color Shift during Dimming Study

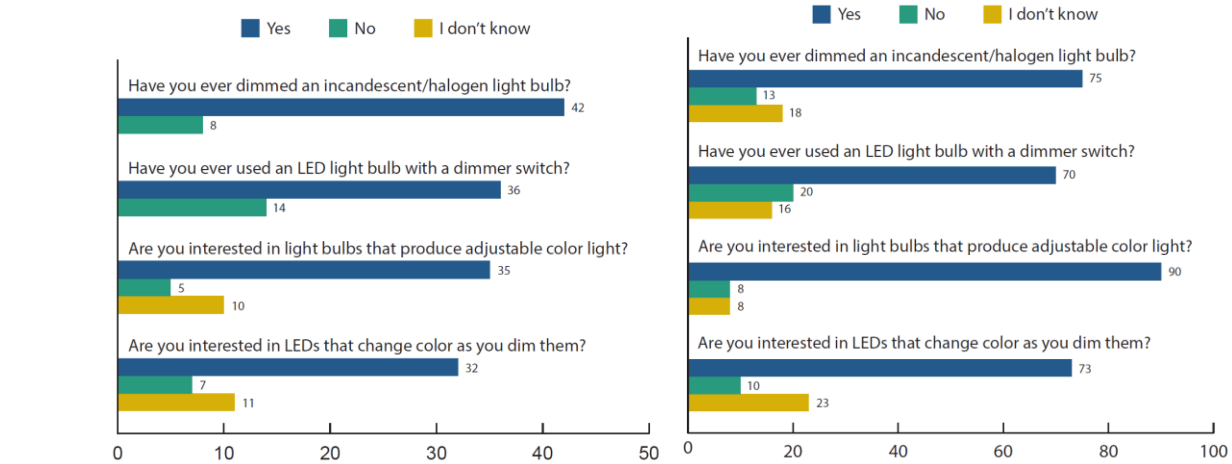

Figure 31 shows the results to the survey respondents' background questions asked as part of the intentional color shift during dimming study.

Source: California Lighting Technology Center

During Phase A, participants shared their expectations regarding color shift while dimming and ranked the appearance and acceptability of various dimming profiles, including a standard incandescent, dim-to-warm profile. Results varied significantly across profiles with respect to expectations and preferences. Nearly equal numbers of people ranked dim-to-cool profiles (not currently available on the market) as most expected and least expected. Similarly, results varied significantly regarding color appeal. Summary rankings for appeal and expected use in the home are shown in Figure 32.

Figure 32: Phase A – Rankings Regarding Appeal and Expected Use for Certain Color-Shift Profiles during Dimming

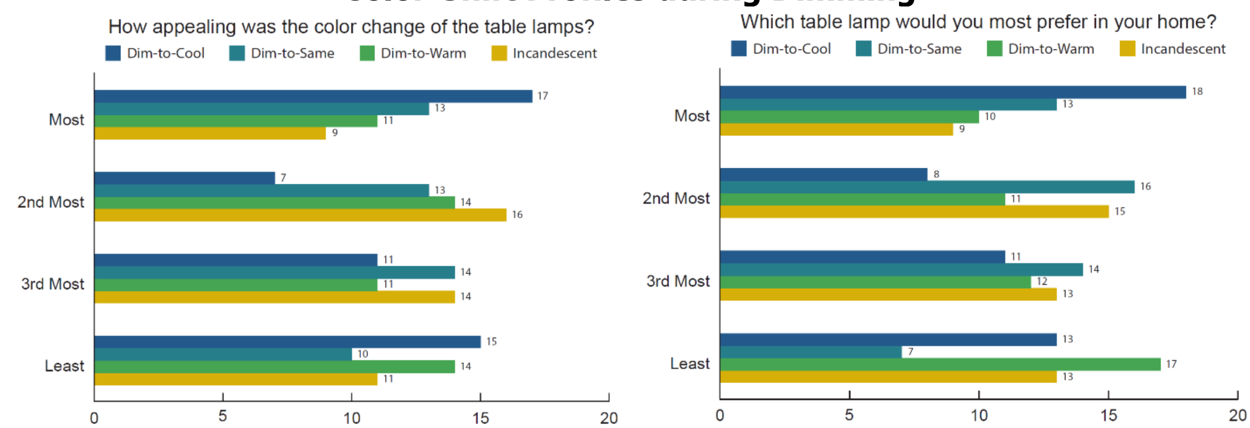

Figure 32 shows the survey respondents' rankings on appeal and expected use of color-shift profiles during dimming.

Source: California Lighting Technology Center

When it came to overhead lighting, participants generally agreed on dim-to-same functionality. A majority of participants rated this dimming profile as "pleasant" and expected. Those who did not rate dim-to-same in this way were generally split in their preference and appeal for dim-to-warm and dim-to-cool profiles. However, the majority of respondents rated dim-to-warm as expected, while very few thought that a dim-to-cool profile behaved the way they expected. Figure 33 shows expectations regarding color shift for all three profiles evaluated. In addition, no one thought the dim-to-cool setting was unpleasant, even though it was rated as the least likely to be installed for home use.

Figure 33 shows the survey respondents' expectations regarding three color-shift dimming profiles used for overhead lighting. Figure 34 shows the relative "for home use" preference rankings of all three color-shift dimming profiles.

Figure 33: Expectations Regarding Three Color-Shift Dimming Profiles Used With Overhead Lighting

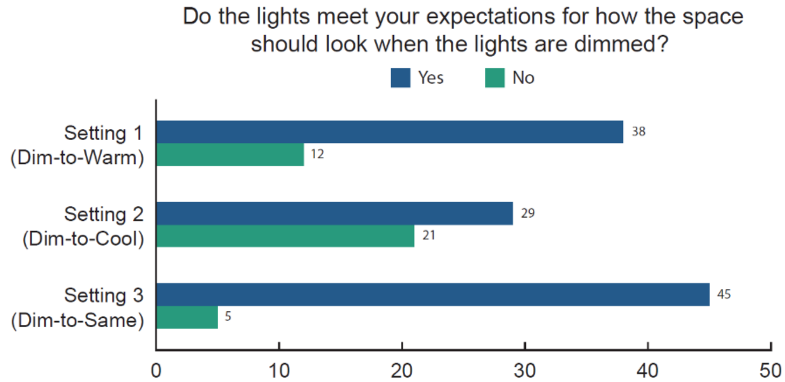

Figure 33 shows the survey respondents' expectations regarding three color-shift dimming profiles used for overhead lighting.

Source: California Lighting Technology Center

Figure 34: Relative Preference Ranking of Three Color-Shift Dimming Profiles for Use in the Home

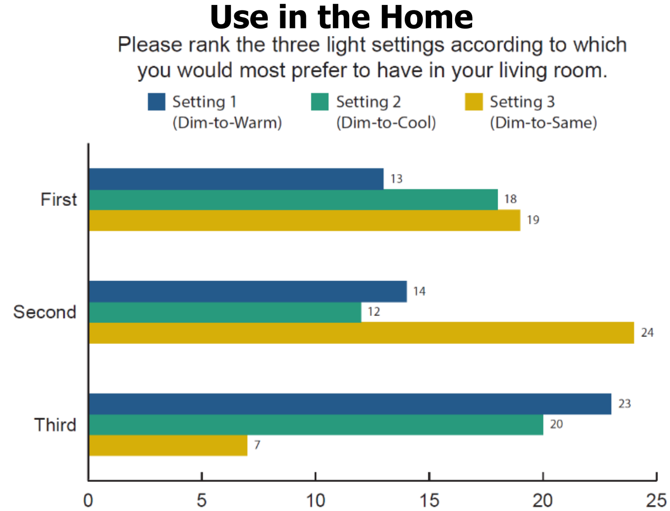

Figure 34 shows the survey respondents' relative preference rankings for three color-shift dimming profiles for use in the home.

Source: California Lighting Technology Center

For Phase B, where CCT was fixed and participants were asked to select their preferred setting, most people preferred lamps with mid-range CCT (2,700 or 4,000 K). A majority of participants selected the low-color-temperature lamp (2,200 K) as their least preferred.

Respondents were generally split on their preference for the high-color temperature lamp (5,000 K). Overall rankings for appeal and home use are shown in Figure 35.

Figure 35: Rankings for Appeal and Preferred Home Use of Lamps by CCT

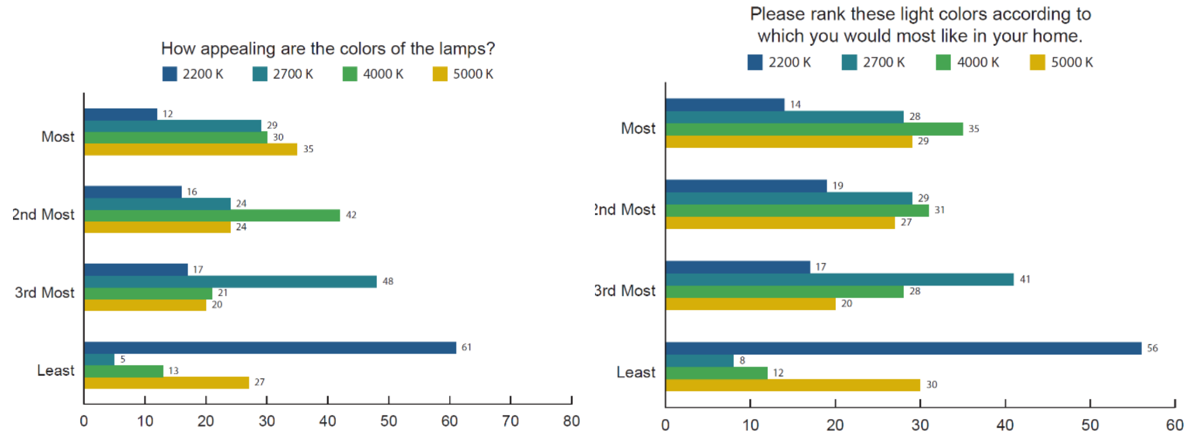

Figure 35 shows survey respondents' rankings of lamps by CCT with respect to appeal and likelihood to use in the home.

Source: California Lighting Technology Center

Phase B included the same tests of overhead lighting and color shift during dimming as Phase A. Again, most respondents stated that all three scenes dimmed the way they expected.

Multi-Spectral Melanopic Lighting Study

During Phase A, participants were asked to raise the light level until they could just read equally well as compared to a fixed light output under the 6,500 K light. The light levels that participants selected are provided in Figure 36.

Next, participants sorted the Farnsworth-Munsell D-15 chips under each light scene. The average and standard deviation of the participant's scores are provided in Figure 37. The Total Error Score (TES), as used in this study, is a relative value for how well a participant was able to sort the color chips. The chips are numbered from 0–16, with a sequential order being the correct sorting of the color chips. The total error score is calculated based on the following equation:

$$TES = (|Num_1 - 0| + |Num_2 - Num_1| - 2) + \sum_{i=2}^{15}(|Num_i - Num_{i-1}| + |Num_{i+1} - Num_i| - 2) + (|Num_{16} - Num_{15}| + |17 - Num_{16}| - 2)$$

Where:

$$TES = Total\ Error\ Score$$

$$Num_i = Chip\ number\ at\ location\ \text{"i"}\ from\ the\ reference\ chip$$

Note that a value of two is subtracted from the error for each chip to make the TES of a perfectly ordered tray equal to zero. Higher scores indicate lower ability to sort the colors, and lower scores indicate higher ability to sort the colors. A score of 25 was calculated as the highest TES at which a participant with normal color vision[2] could perform under the 6,500 K light.

Figure 36: Phase A: Light Levels Selected in Multi-Spectral Melanopic Room

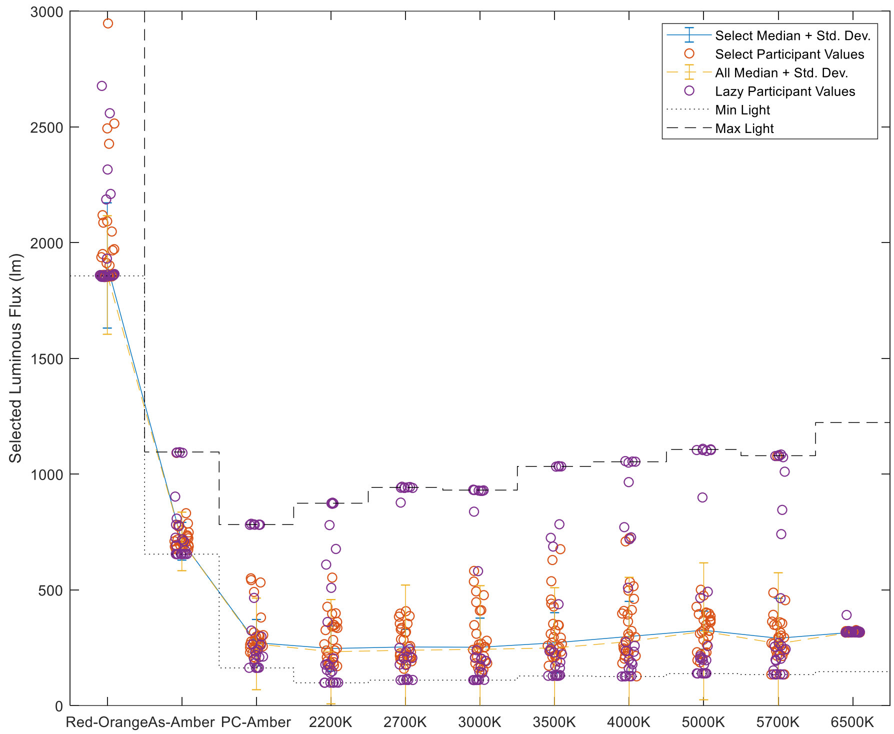

Figure 36 shows the light levels used in the multi-spectral melanopic room.

Source: California Lighting Technology Center

During Phase B, the output of the 10 channels was fixed at the maximum light level that would minimally suppress melatonin production. Under each channel, participants 1) performed a visual acuity assessment using the Landolt-C chart, and 2) sorted the Farnsworth-Munsell D-15 color chips.

Results from five participants were excluded due to apparent color-blindness as determined from the Farnsworth-Munsell D-15 test, under the 6,500 K setting (see Appendix C). The data from two additional participants were excluded due to incomplete collection of color chip datasets.

[2]https://www.good-lite.com/cw3/Assets/documents/730022_FarnsworthD-15English.pdf

Figure 37: Average and Standard Deviation of Farnsworth-Munsell D-15 Total Error Score for Phase A Participants

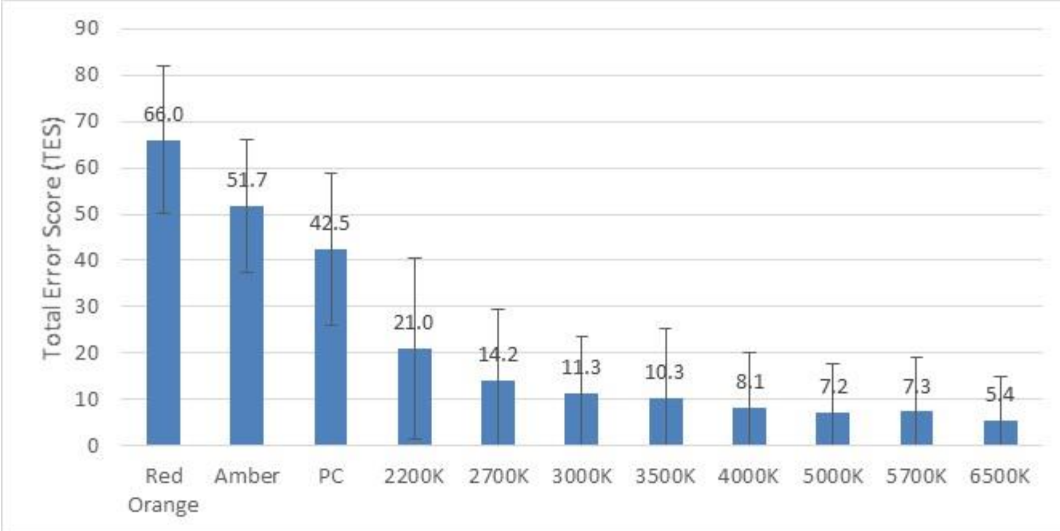

Figure 37 shows the average and standard deviation of Farnworth Munsell D-15 total error score for study participants (Phase A).

Source: California Lighting Technology Center

Visual Acuity

The average visual acuity is computed by converting the Snellen visual acuity (also known as the 20/20 standard)[3] data into a linear scale (known as logMAR), calculating the average, and then converting back to the Snellen acuity scale. This is done, as the Snellen data is not linearly scaled.[4] On the bottom of Figure 38, colored bands indicate under which CCT channel the average visual acuity is statistically similar:

- 2,200 K and 2,700 K
- 3,000 K, 3,500 K, and 4,000 K
- 3,000 K, 3,500 K, 5,700 K, and 6,500 K
- 5,000 K, 5,700 K, and 6,500 K

Participants' visual acuity scores were recorded under each channel. A boxplot is provided in Figure 38 to analyze the results of the visual-acuity test. The boxplot includes the following metrics:

- Maximum (upper whiskers).
- 25-percent quartile (upper edges of blue boxes).
- Median (red line in middle of blue boxes).

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[3] The Snellen visual acuity metric is the standard "20/20" metric of visual acuity. It is the ratio of normal distance that the test is made (20 feet) to the distance that a standard observer would see the resultant line. For example, a Snellen visual acuity of 20/40 indicates that what the observer was able to discern at 20 feet, a standard observer would be able to see at 40 feet.

[4] Holladay, Jack T. "Proper Method for Calculating Average Visual Acuity." Journal of Refractive Surgery Volume 13, 1997, pdfs.semanticscholar.org/9645/6b86671320880d6e5e7e9e1745d250a35224.pdf.

- Mean (black line in middle of blue boxes).
- 75-percent quartile (lower edges of blue boxes).
- Minimum (lower whiskers).

Additionally, the lower limit of the range of visual acuity that is considered "normal" (20/25) is shown as a blue-dashed line across the plot.[5] The vision-screening standard for visual acuity required to receive or renew a driver's license in California (20/40)[6] is shown as a red dashed-line across the plot. The vertical photopic illuminance (fc) measured at the eye chart located in the test area for each lighting setting is provided in Figure 39.

Figure 38: Visual Acuity Test Results under the 10 CCT Channels for Phase B

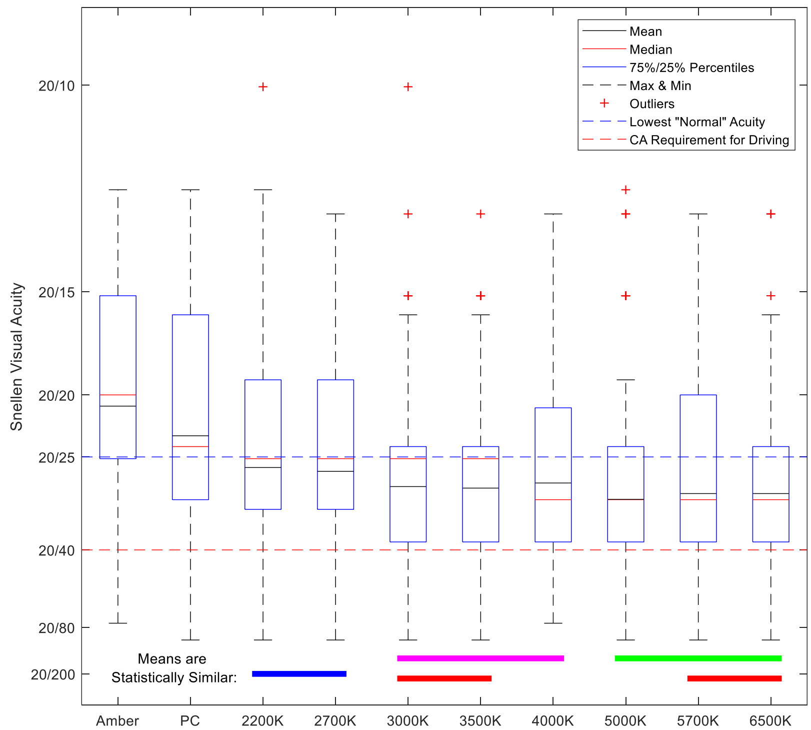


Figure 38 shows the visual acuity test results. Blue boxes indicate 25 percent and 75 percent quartiles, red lines in blue boxes indicate median visual acuity, and black lines in blue boxes indicate average visual acuity.

Source: California Lighting Technology Center

[5] Colenbrander, August. Visual Standards: Aspects and Ranges of Vision Loss with Emphasis on Population Surveys. Apr. 2002, www.icoph.org/downloads/visualstandardsreport.pdf.

[6] https://www.dmv.ca.gov/portal/dmv/detail/pubs/brochures/fast_facts/ffdl14.

Figure 39: Vertical Photopic Illuminance (fc) Measured at the Eye Chart for Each Lighting Setting

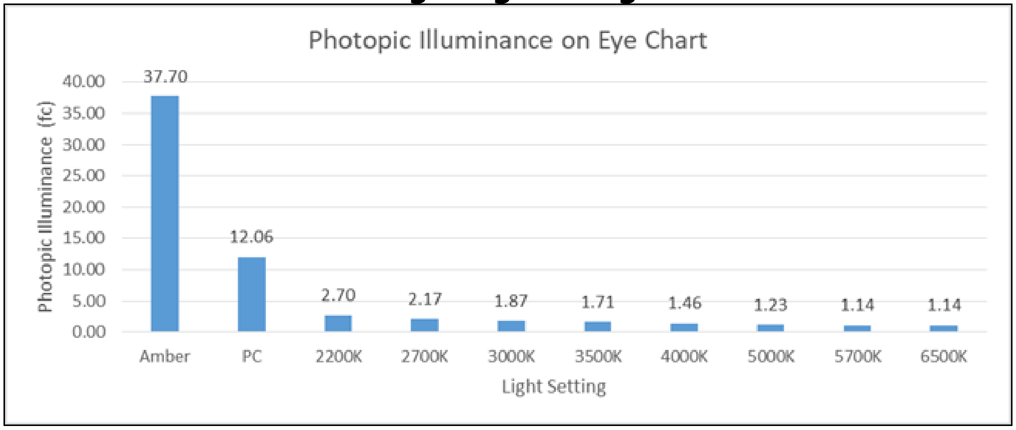


Figure 39 shows the vertical photopic illuminance in foot-candles (fc) measured at the eye chart for each lighting setting.

Source: California Lighting Technology Center

Color Sorting

Participants sorted Farnsworth-Munsell D-15 color chips under each CCT lighting channel. The average and standard deviation of the participants' scores are provided in Figure 40. Table 8 provides the total error score (TES) for sorting the Farnsworth-Munsell D-15 color chips.

Figure 40: Phase B: Average and Standard Deviation of D-15 Total Error Score

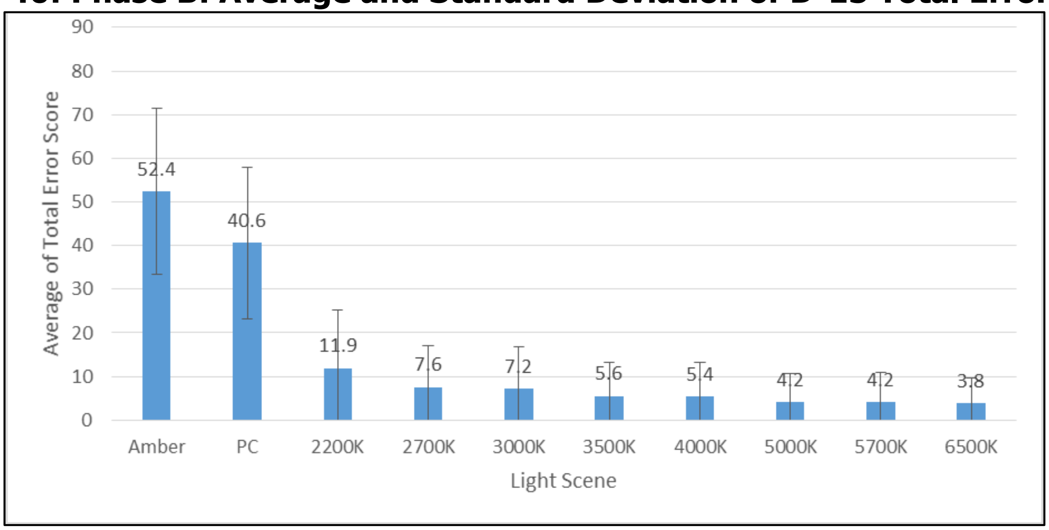


Figure 40 shows the average and standard deviation of the Farnsworth-Munsell D-15 total error score for study participants (Phase B).

Source: California Lighting Technology Center

Table 8: Total Error Score for Sorting the D-15 Color Chips for Phase B Data

	Total Error Score						
CCT	Average	STD	Max	Q3	Median	Q1	Min
Amber	52.4343	18.9625	109	64	50	38.5	12
PC	40.5657	17.3412	78	53.5	41	30	0
2200K	11.9192	13.2509	60	19.5	8	0	0
2700K	7.56566	9.4125	43	10	4	0	0
3000K	7.19192	9.72864	50	11	4	0	0
3500K	5.56566	7.76985	38	8	3	0	0
4000K	5.37374	7.76516	52	7.5	4	0	0
5000K	4.23232	6.53379	36	7	0	0	0
5700K	4.15152	6.7919	43	6.5	0	0	0
6500K	3.80808	5.91035	28	4	0	0	0

Table 8 shows the total error score for the Farnsworth-Munsell D-15 color chips for Phase B data.

Source: California Lighting Technology Center

Study Conclusions

The research team used the study results to identify appropriate thresholds for metrics critical to a consumer-oriented lighting product specification. Study results regarding metrics, consumer interpretation of product packaging, warranty, light source binning, and color fidelity were all considered and integrated into product specifications and prototypes, which are described in Chapter 5.

Light-Source Binning

The results of the Chromaticity Perception Study show that consumers notice a significantly smaller deviation off the root locus than along it. Similarly, the results of the Chromaticity Acceptance Study show that they are also much more accepting of deviations that are along the root locus than similar-sized deviations across the root locus. The chromaticity ranges in Table 9 are recommended for LED source binning to achieve the stated levels of acceptable and detectable color difference.

Table 9: Proposed Chromaticity Bins

	2700K		4000K	
	CCT Shift	D_{UV} Shift	CCT Shift	D_{UV} Shift
50% Undetectable	2725 ± 70 CCT	0.0 ± 1.1e-3 D_{UV}	3985 ± 133 CCT	+ 1.0 ± 1.7e-3 D_{UV}
95% Undetectable	± 22 CCT	± 0.2e-3 D_{UV}	± 43 CCT	± 0.3e-3 D_{UV}
50% Acceptable	± 164 CCT	± 3.4e-3 D_{UV}	± 308 CCT	± 4.3e-3 D_{UV}
95% Acceptable	± 74 CCT	± 0.3e-3 D_{UV}	± 178 CCT	± 0.7e-3 D_{UV}

Table 9 shows the proposed chromaticity bins results for the light-source binning study in terms of CCT and D_{uv}.

Source: California Lighting Technology Center

The proposed perception-based chromaticity bins are shown when compared with the ANSI 7-Step and ANSI 4-Step ranges in Figure 41. The proposed acceptance-based chromaticity bins are shown compared with the ANSI 7-Step and ANSI 4-Step ranges in Figure 41 shows the proposed perception-based chromaticity bins when compared with the ANSI 7-Step and ANSI 4-Step ranges in Figure 42.

The proposed bins are much smaller and differently shaped as compared with those used in current practice. It has not been shown that the quadrangle, which is used currently, is the appropriate shape for LED lamp binning. Further research is recommended to determine an optimal binning shape. In addition, these results demonstrate that consumers can clearly see the color variation among current, commercial products that are rated as the same, and they view those variations as unacceptable when it comes to using those products in their homes and businesses.

Figure 41: Undetectable Chromaticity Ranges

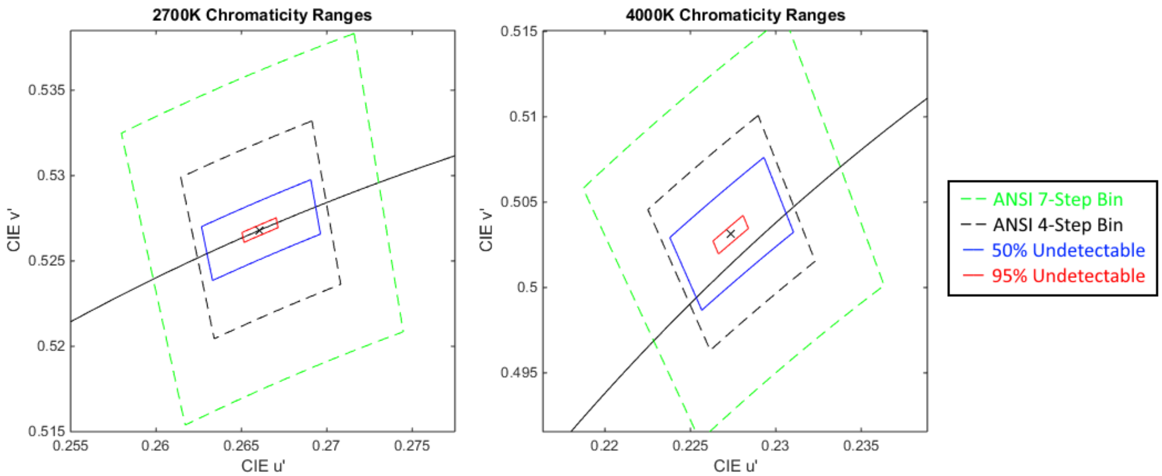


Figure 41 shows the proposed perception-based chromaticity bins when compared with the ANSI 7-Step and ANSI 4-Step ranges.

Source: California Lighting Technology Center

Figure 42: Acceptable Chromaticity Ranges

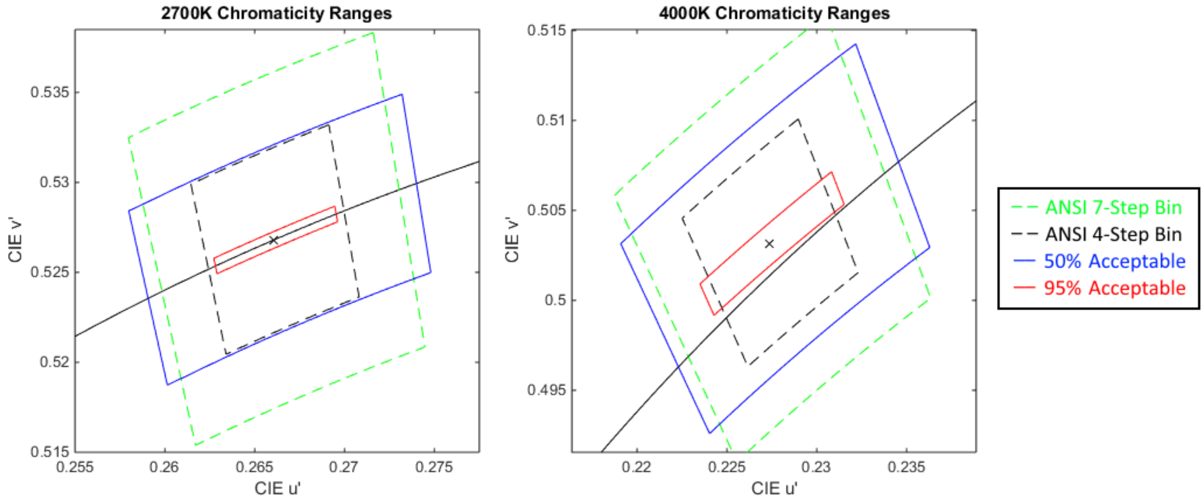


Figure 42 shows the acceptable chromaticity ranges when compared with the ANSI 7-Step and ANSI 4-Step ranges.

Source: California Lighting Technology Center

Color Fidelity

For phosphor-converted blue-pump LEDs (the typical technology used in industry), the increase from 80 to 95 CRI had a significant impact on consumers. Based on study results, residential replacement lamps should target 95 CRI. The frequent objection to putting a requirement of 80 CRI or greater on commercial products is that the increase in power required of high-color-fidelity lighting to deliver the same light output as low-color-fidelity lighting outweighs the benefit of increased color fidelity. Inherent to this assumption is that consumers require equal light levels independent of color fidelity. This assumption is incorrect based on study results.

In the *Color Fidelity Trade-Off* study*,* the power supplied to lamps of different color fidelity and chromaticity within three MacAdam steps was held constant, and there was a 25 percent decrease in light output required by consumers when using the higher-color-fidelity lamps. In addition, the increase in color fidelity was significant enough that there was an observable increase in the ability of test participants to perform color tasks, to the point that 60 percent of the participants preferred the lighting with increased color fidelity (and decreased light output) for the sorting activities. This indicates that the difference in color fidelity was more significant than the difference in brightness.

Additionally, in the *Lighting Service Delivered Test,* participants tasked with selecting a light level for vanity use consistently selected a significantly lower-light output of the high- than the low-fidelity lighting. This indicates that the color-fidelity degradation between the high- and low-fidelity scenes resulted in a noticeable penalty to the usefulness of the light to the participant, which further supports the requirement of higher levels of color fidelity.

Lighting Metrics and Product Packaging

Survey results suggest that the primary metrics consumers use when evaluating lamps to purchase at a retailer are light output, energy consumed, and color temperature. The efficacy of the lamp fell just short of being in the top half of the consumer's ranking; however, efficacy is the relation between energy consumed and light output, a metric composed of the top two parameters selected.

It is understandable that these are the most important factors to consumers, as they most directly relate to their conscious reactions to the lighting in a space: how bright a room feels, the amount of energy being used, and the color of the light. The other metrics are factors of their decisions (note the low number of "N/A" answers, compared with other rankings in the survey), but are less directly relatable and so less important to consumers. For example, color fidelity is an important factor related to how natural lighting can make a room feel and look; however, it is difficult to get two lighting professionals to agree exactly what the metric means. This does not mean that color fidelity is not an important factor, just that consumers are unable to easily conceptualize it or quantify the value of increased color fidelity.

With respect to lamp longevity, consumers predominantly interpret a rating given in years (e.g., 22.7 years) as longer than the equivalent rating in hours (25,000 hours in this case). Additionally, consumers tend to envision lamp failure as the lamp growing noticeably dim and burning out at the end of its stated life.

Consumers appreciate the information available to them on an LED Lighting Facts label; it is highly ranked on their decision-making process despite its widespread use, which would tend to negate its relevance as a deciding factor. Consumers valued the full, colored Lighting Facts label, as it allows them to compare all the attributes of the products under consideration. General differences in package color, lamp shape, and other aesthetic considerations appeared to influence consumer purchase decisions only slightly.

Warranty

Residential light-source-warranty descriptions should not be the same as the warranty description used with a commercial luminaire or lighting system. When presenting the warranty in commercial terms, it results in nonsensical language for a residential system, such as: "This warranty only applies to lamps operating on a burn cycle of 12 hours or more per start and operated a maximum of 4,400 hours per year." Such a description may make sense on a commercial system and at scale, but not for an inexpensive screw-base LED lamp used a few hours each day in a home office.

A majority of the participants stated that being required to pay the cost of returning a lamp is unacceptable. Consumers do not like to pay to receive a replacement lamp for a product that fails under warranty; if possible, this disclaimer should be avoided, as it may negatively influence consumers against both the particular product and LED lighting in general.

Intentional Color Shift During Dimming

Survey results indicate approximately 75 percent of consumers have dimmed incandescent lamps and LED lamps prior to working with dimmable sources as part of this study. Additionally, the majority of the study participants were initially "interested" in lamps that changed color as they dimmed.

The average ranking of all the intentional color shifts (dim-to-warm, dim-to-cool, dim-to-same) were similar; however, the dim-to-cool color shift was the most polarizing. During Phase B, dim-to-cool was most frequently rated both most preferred (50 participants, or 47 percent) and least preferred (45 participants, or 42 percent).

During Phase B, consumers were first asked what light-source color they prefer in their home, and then asked to rate the three full-room settings: "dim-to-warm," "dim-to-cool," and "dim-to-same." This allowed the participant's ranking to be sorted based on which color temperature the participant preferred. The sorted ranking of the lights are provided in Figure 43.

Looking at the overall average, there is no clear preference for any of the intentional color-shift scenes shown to the participants. By evaluating the final ranking based on what color temperature people preferred in their homes, it appears that the participants who preferred the warmer color temperatures preferred the dim-to-warm chromatic shift and participants who preferred the cooler color temperatures preferred the dim-to-cool chromatic shift. There does appear to be a segment of the consumer market that finds value in dim-to-warm lamp functionality.

Figure 43: Preference for Chromatic Shift Based on a Side-By-Side Analysis

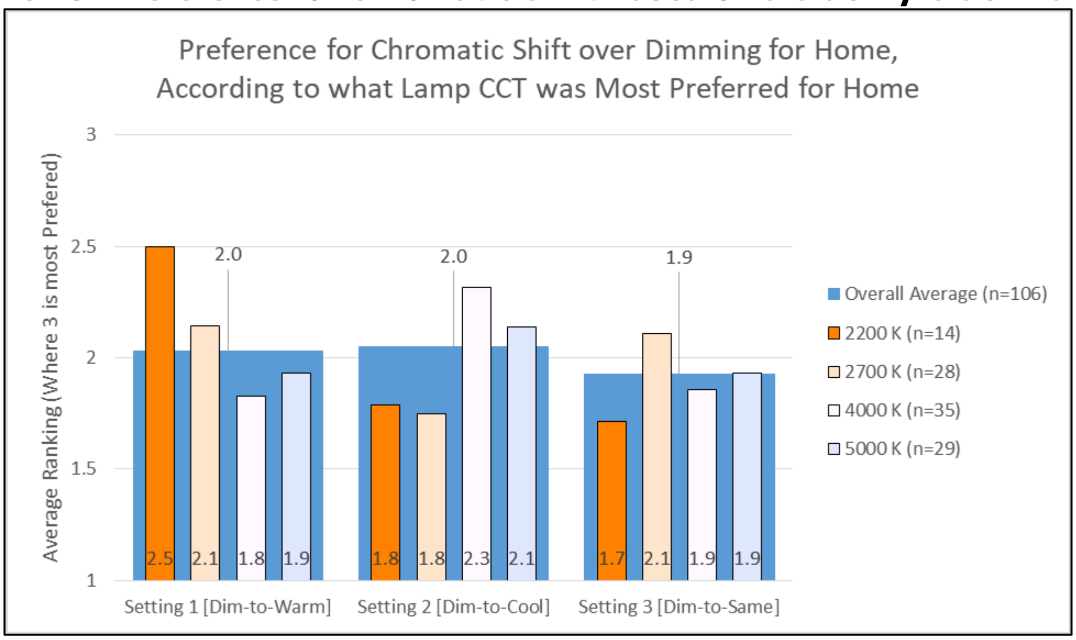


Figure 43 shows the study participants' preference for chromatic shift based on a side-by-side analysis.

Source: California Lighting Technology Center

Appropriate Circadian Lighting at Night

Phase A results of the *Multi-spectral Melanopic Lighting Perception* study indicate that the CCT of white light (and even phosphor-converted amber light) does not affect occupants' visual acuity. This is important, as changing the CCT affects the amount of light used by the eye to control pupil size. For the range of light sources used in this study, changing the CCT had no noticeable effect on the amount of light needed to read the lines of text by the 50 participants.

Both phases of the study showed that the ability of the participants to sort the color chips was moderately affected by CCT, despite almost no variation in color fidelity between most of the lights. Participants performed best under the 6,500 K-light source despite its lowest color fidelity of the white-light sources. Analysis of the color of the chips used in the sorting task provides one possible explanation for this result. Figure 44 provides the chromaticity coordinates of the color of the chips in CIE CAM02UCS, under the lights used in this study.

Figure 44: Chromaticity Coordinates of Farnsworth-Munsell D-15 Chips under Multi-Spectral Melanopic Lights

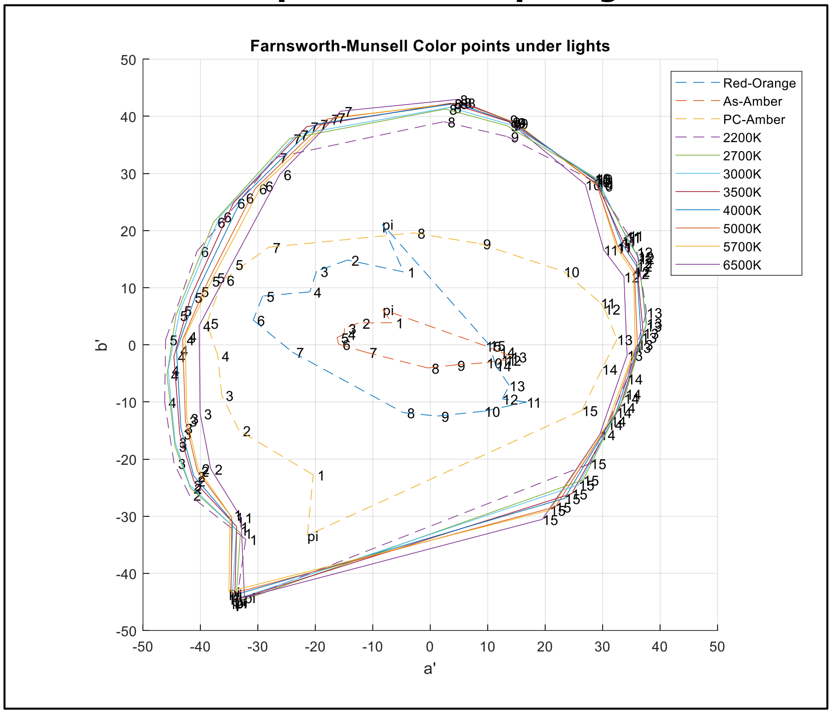


Figure 44 shows the chromaticity coordinates of the color of the chips in CIE CAM02UCS, under the lights used in the appropriate circadian lighting study.

Source: California Lighting Technology Center

The coordinates of some color chips, especially chip numbers 11 and 12 in the upper-right side of Figure 44, become closer together under the warmer CCT lights. The Farnsworth-Munsell D-15 chips are designed for sorting under a D65 daylight simulator, and the dyes used in the construction of these chips appear to have been selected to produce approximately equally spaced colors around the color space. When other CCTs are used in this study, it appears that the color chips are more difficult to properly order since some of the colors are closer together. These are artificial colors, so it is likely that were the D-15 chips designed to be sorted under a 2,700 K Planckian radiator (e.g., an incandescent lamp), the error score would have been lowest for that light, and increased for the other channels.

Despite this inherent issue with the Farnsworth-Munsell D-15 color chips, the results of the color-sorting task of this study suggest that if color tasks are to be performed in a space, choosing a white-LED light is important. The increase in performance from 2,200 K to 2,700 K is significant and suggests that 2,700 K may be the most appropriate white-LED light for color-sorting tasks.

Furthermore, Phase B results show that when designing spaces for circadian lighting, using lights 2,700 K or less is ideal for visual-acuity purposes. All lights 3,500 K or less had at least 50 percent of the participants score in the range of "normal" visual acuity. The 3,500 K and 3,000 K channels had 75 percent quartiles at the legal limit for visual acuity imposed on California drivers. This means for lights cooler than 2,700 K to stay below the melanopic threshold, the light needs to be reduced to the point where nearly 25 percent of drivers would not be legally allowed to drive. Additionally, the marked improvement in visual acuity under the non-phosphor-converted amber LED suggests that it may be an appropriate light source for areas where high visual acuity is needed at night. In general, 2,700 K appears to be the best balance between visual acuity and color appearance for circadian-based nighttime lighting design.

CHAPTER 3: Lighting Control Preferences

Existing California commercial buildings consume approximately 31,000 Gigawatt hours (GWh) annually for lighting. Many existing programs address energy-efficient-lighting retrofits including lighting controls as a means to reduce this use; however, studies show that the actual energy savings of lighting-controls projects, as compared with predicted savings, is often less than claimed.

Reasons for this shortfall are varied, but all studies cite improper calibration, poorly designed commissioning, or inappropriate luminaire response or functionality as key contributors to the problem. This leads to consumer dissatisfaction with the control devices themselves, and often to disconnection of the controls entirely. These effects indirectly compound lost energy savings well beyond any one particular project and hinder market adoption of advanced-lighting control systems.

As part of this research, CLTC developed lighting-control consumer-preference studies designed to gather information on preference for control scenarios as they relate to control-device settings including dimming level, dimming rate, and automated switching. Outcomes were used to recommend control features and scenarios that manufacturers can use to provide preconfigured, out-of-the-box lighting systems with controls that will function the way a majority of consumers wants and expects.

Study Background, Organization, and Goals

This study's goal was to identify how consumers and occupants expect advanced-lighting controls to operate under ideal conditions and what their preferences are for control-device settings. To accomplish this goal, the research team selected two objectives that form a picture of consumer and occupant expectations and requirements:

- **Objective 1: Understand the user experience that results in successful market transformation for lighting controls.** Industry needs to understand how a user expects lighting to be controlled to provide the best lighting-control solution to their customers.
- **Objective 2: Understand occupant preference for lighting-control-device settings.** The goal of typical commercial lighting-control systems is to reduce energy consumption as much as possible while still providing adequate light to occupants. If the user is not satisfied with the light levels or system performance, there is a risk that the system could be disabled and potential energy savings lost.

Testing was conducted in two phases. The first phase focused on activities that increase understanding of end-use preferences for various control strategies and devices. The second phase explored research questions surrounding lighting-control use and acceptance. In total, five individual tests were completed:

1. Evaluation of amber lighting for nighttime use in corridors
2. End-user preferences for control-system user interfaces

3. Identification of desired control-system functionality
4. Perception of visible flicker
5. Perception of color tuning

Collectively, these topics address end-user preferences for control-system functionality; provide guidance for lighting control-system design; and provide guidance for development of spectrally optimized luminaires. Outcomes begin to quantify control system performance from the end-user perspective with the goal of increasing user acceptance of the control solutions. Increased acceptance and sustained use of more aggressive and appropriately designed lighting-control strategies translate to persistent electricity savings in commercial buildings.

Amber Lighting at Night for Corridors

One of the primary ways in which light affects human circadian rhythms is through the suppression of melatonin. Melatonin is a hormone that regulates the body's sleep-wake cycle by lowering temperature and causing drowsiness. Light at night can suppress the body's production of melatonin and disrupt natural circadian rhythm.

Recent research indicates that melatonin suppression is driven by two of the eye's photoreceptors: the short-wavelength (cyanopic) cones and iPRGCs (melanopic). Additionally, the minimum amount of light required to suppress melatonin production is significantly greater than the light level required for mesopic vision (vision in which both rods and cones are active). This means that longer-wavelength light and/or low-light levels can support vision at night without affecting melatonin production. A common light selected for "circadian-friendly" night lighting is amber-LED lighting. Figure 45 shows the difference between 4,000 K white-LED light, amber-LED light, and spectral sensitivities of the human eye. Note that the light that affects the melatonin production is essentially bounded by the cyanopic and melanopic sensitivities, while photopic vision is mediated by the photopic sensitivity curve.

This suggests two potential benefits of amber lighting:

- The peak wavelength of amber lighting is very close to the peak of the photopic-sensitivity curve and has very little overlap with the melanopic- and cyanopic-sensitivity curves. This means that amber lighting has reduced impact on the melatonin production compared with white lighting.
- As opposed to current LED general-purpose illumination that uses a broad spectrum light to produce high-color-fidelity light, amber light can have a narrow spectrum. This means that amber lights are naturally more efficacious.

Figure 45: Normalized Spectral Power Distribution of Amber and White LEDs with Cyanopic (S-Cone), Melanopic (iPRGC), & Photopic Sensitivities

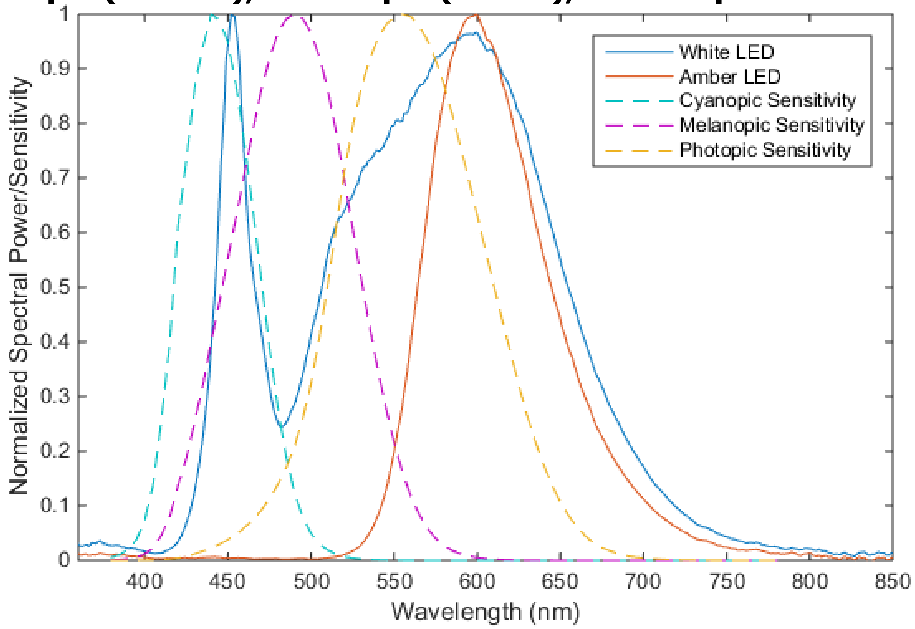


Figure 45 shows the difference between a 4,000 K white-LED light, amber-LED light, and spectral sensitivities of the human eye.

Source: California Lighting Technology Center

The Control-System User Interface

User interfaces provide the primary connection between a lighting-control system and the occupant or end user. The user interface enables selection of specific control functions. If a control system allows for significant changes in lighting service, but the end user does not use the system, then there is no advantage to advanced-control capabilities. In fact, there may be significant disadvantages due to the greater risk of poor end-user experiences, leading to override or removal of the control system.

Personal dimming controls are one such example. Studies show that personal-tuning controls can save up to 31 percent of connected lighting energy usage.[7] To achieve energy savings, the tuning controls must be intuitive and comfortable to use. To understand basic preferences for common dimming controls, researchers created an immersive vignette where study participants ranked their preferred dimming controls for use in a common control scenario.

Control-System Functionality

Understanding the desired control-system functionality is essential to the design of consumer-centric control specifications. The research team deployed an online survey to supplement current knowledge of consumer preferences for control systems. This survey compiles consumers' opinions about the value of control systems, preference for specific control functionality, and preferences regarding occupancy sensor performance.

[7] Williams, Alison. (2012). A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings. Leukos. Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory. LBNL Paper LBNL-5095E

Perception of Visible Flicker

The successful interoperability of light sources with control systems is paramount for user acceptance. Interoperability factors include:

1. Perception of visible flicker.
2. Performance issues common to use of LED sources with incompatible controls.
3. End-user awareness of source or control interoperability issues.

To understand these topics, researchers developed a study to determine people's perception thresholds for visible flicker in a controlled environment coupled with an online survey to understand their experience with flicker and other interoperability issues. Questions were included to understand how the typical end user is being reached with product interoperability information, which can directly affect visible flicker.

Percent modulation was used as a quantifying metric during the flicker study. Percent modulation, or percent flicker, is a measure of the amount of flicker present in a waveform. It is calculated as the ratio of the maximum, minus the minimum value, divided by the maximum plus the minimum. This results in a value between zero and 100 percent.

Figure 46: Flicker Modulation

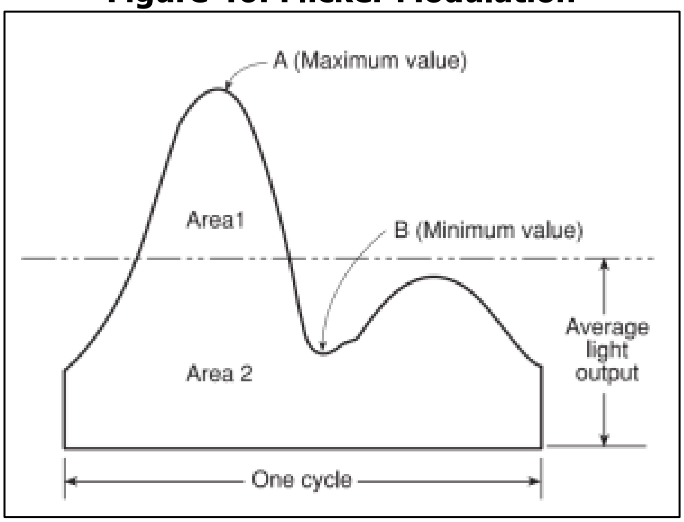


Figure 46 shows how flicker modulation, or percent flicker, is a measurement of the amount of flicker present in a waveform. It is calculated as the ratio of the maximum, minus the minimum value, divided by the maximum plus the minimum. This results in a value between zero and 100 hundred percent.

Source: California Lighting Technology Center

Color tuning Perception

Assuming people will deploy color tuning lighting technology in their homes and workplaces, the just-noticeable rate of color tuning becomes important. The color-change rate affects implementation in spaces where designers seek to minimize awareness of the change in color. To support future deployment of tunable color lighting designs, researchers developed an immersive study to identify perception thresholds for color change.

Test Methodology

A test methodology was designed to assess occupant preference for control scenarios as it relates to control-device settings, including dimming level, dimming rate, color-change rates, flicker, and automated switching. Test methods included three experimental concepts: one to assess absolute perception and preference differences using a strictly artificial setting (laboratory); a second to assess these preferences under more realistic conditions (mock-up); and a survey to gather market data for lighting-industry manufacturers, utilities, and other third parties. Tests were conducted in two sessions.

The first phase testing focused on activities to increase understanding of end-use preferences for various control strategies and devices. Fifty individuals from the greater Sacramento area participated. The studies included the following three topics:

- Perception of amber lighting for nighttime illumination of corridors.
- End user preferences for control-system user interfaces.
- Desired functionality of control systems.

The second phase focused on perception of visible flicker and color tuning. Collectively, these topics address end-user preference for control system functionality, provide guidance for design of lighting-control systems, and provide guidance for the development of spectrally optimized luminaires.

Test Areas and Equipment

Testing took place at multiple stations within the CLTC test area. Figure 47 shows the layout of the primary test spaces. Relative humidity in the testing spaces was recorded and all the rooms were wired with temperature probes to enable the recording of environmental data, which was used to verify that the test spaces remained comfortable to the occupants.

Figure 47: Layout of the Consumer Preference Testing Stations for Controls – Phase 1

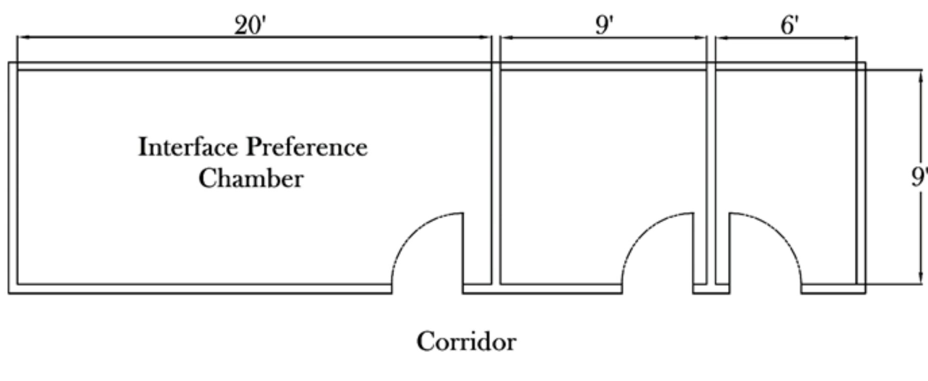


Figure 47 shows the layout of the primary test spaces at the California Lighting Technology Center.

Source: California Lighting Technology Center

Amber Lighting at Night for Corridors

The "Amber Corridor Lighting" study was conducted in the space marked 'corridor' in Figure 47. One end of the corridor was equipped with a lighting fixture with both white and amber LED arrays, separately controlled. The other end of the corridor was illuminated by color tuning fixtures, which were used only for general illumination during this study. Table 10 shows four dimming-lighting levels that were selected for the amber fixture (100 percent, 75 percent, 25 percent, and 10 percent of full output). The corresponding illuminance values are provided. Figure 48 shows the corridor illuminated by the amber LED fixture.

At maximum output, the amber light has a horizontal illumination of 13.4 foot-candles (fc) at grade directly beneath the fixture and a vertical illumination of 10.0 fc oriented towards the fixture at a height of five feet above grade where the test participant stood during the study. Four dimming-lighting levels were selected for the amber fixture: 100 percent, 75 percent, 25 percent, and 10 percent of full output. The corresponding illuminance values are provided in Table 10.

Table 10: Horizontal and Vertical Illuminance Values of Amber Lighting

	Horizontal Illuminance (fc)	Vertical Illuminance (fc)
100%	13.4	10.0
75%	11.5	8.8
25%	5.2	4.2
10%	1.3	1.0

Table 10 shows four dimming-lighting levels that were selected for the amber fixture (100 percent, 75 percent, 25 percent, and 10 percent of full output). The corresponding illuminance values are provided.

Source: California Lighting Technology Center

Figure 48: Test corridor with amber light

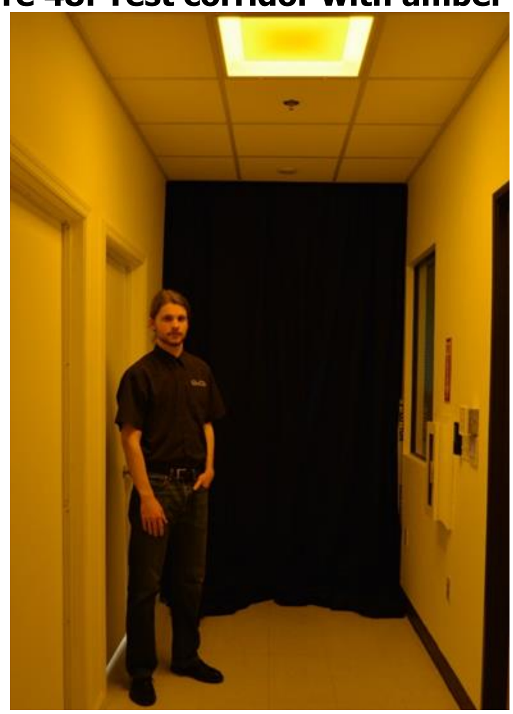


Figure 48 shows the corridor illuminated by an LED fixture with both white and amber LED arrays, separately controlled.

Source: California Lighting Technology Center

The User-Control Interface

The User Interface study was conducted in a small private-office space. A control panel with a selector switch to enable control of the overhead lighting was installed in the room. The control panel included six different control devices that spanned a wide range of commercial-dimmer styles. Figure 53 shows the control panel with all six control devices:

1. Pre-selector switch
2. Rotary-style dimmer
3. Press-and-hold paddle dimmer
4. Slider
5. Push-button desktop remote
6. Smartphone web app

Visible Flicker

For the visible flicker study, one room of the test area was equipped to produce controlled flicker scenes. Two 82 CRI LEDs were powered using a DC power supply set to provide a voltage differential of 36.42 Volts (V) to the LEDs. This voltage was determined in the laboratory as the stabilized voltage of the LEDs being run at 350 mA. A current limiting NTE 2968 N-Channel metal-oxide-semiconductor field-effect transistor (MOS-FET) was installed on the positive lead to the LEDs for control. An SFG-210 arbitrary function generator (AFG) was installed to send a control signal to the MOS-FET. The AFG generates custom waveforms and percent modulation at any frequency up to 10 MHz This was monitored by a photodiode connected to an amplifier.

Figure 49: Arbitrary Function Generator

Figure 49 shows the SFG-210 arbitrary function generator.

Source: Global Specialties

CLTC determined that a uniformly illuminated field of view is ideal to observe a light source for visible flicker. To create this, half of an integrating sphere was mounted on a table in the room. The inside of the integrating sphere was illuminated by LEDs installed at the top and bottom of the sphere. A chin rest was positioned so that the observer’s eyes would be level with the middle of the integrating sphere.

Figure 50: Layout of Test Stations for Color Tuning and Visible Flicker Perception Studies

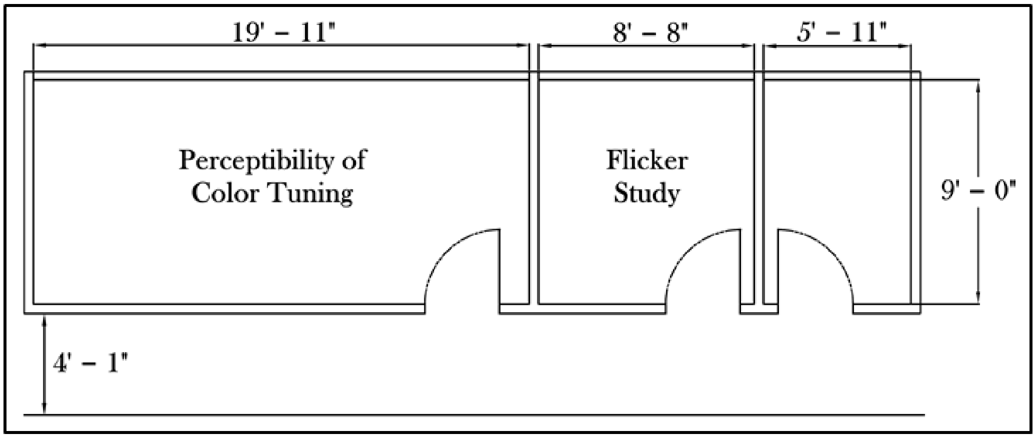


Figure 50 shows the layout of the test stations at the California Lighting Technology Center used for the color tuning and visible flicker perception studies.

Source: California Lighting Technology Center

Figure 51: View of the Inside of the Sphere and the Chinrest Used for Visible-Flicker Study

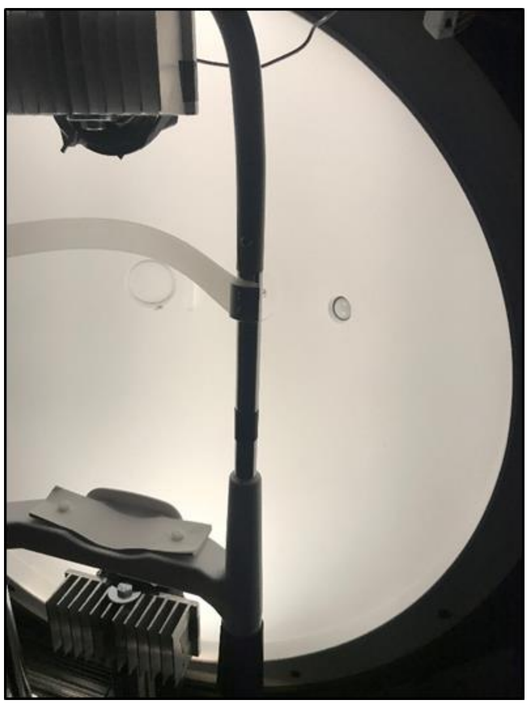


Figure 51 shows the test apparatus for flicker study.

Source: California Lighting Technology Center

Three categories of flicker waveform shapes were selected as representative of the main waveform types found in commercially available light sources: sinusoidal, pulse-width modulation (PWM), and inverted cycloid (Figure 52).

Due to technical difficulties during the commissioning of the test setup, there were only 36 participants in the flicker study. Twenty-two participants saw 45 scenes: three waveform types, for three nominal percent modulations, at five fundamental frequencies (60 Hz, 70 Hz, 80 Hz, 100 Hz and 120 Hz). During the study, researchers added the 200 Hz fundamental frequency, increasing the number of scenes to 54 for the remaining 14 participants.

Figure 52: Flicker Waveforms

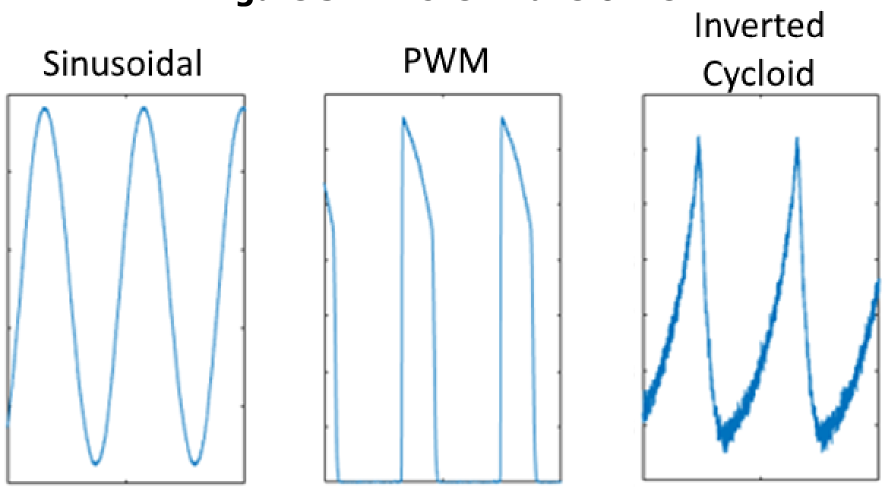


Figure 52 shows the three categories of flicker waveform shapes selected as representative of the main waveform types found in commercially available light sources: sinusoidal, pulse-width modulation (PWM), and inverted cycloid.

Source: California Lighting Technology Center

Perception of Color Tuning

Four tunable downlights were installed in the ceiling of one enclosed test area. A table was positioned in the middle of the room to create a task plane equally illuminated by each downlight. The downlights utilized LED light engines, which provide the ability to smoothly transition CCT from 8,000 K to 1,750 K in approximately 25 K steps. Based on the results presented in Chapter 2, this transition step is below the just-noticeable-difference threshold for CCTs of 2,200 K and greater. The downlights were controlled via a DMX512 module that accepted commands from a computer in the room.

Test Descriptions

Amber Light at Night for Corridors

The purpose of this study was to determine occupant preference for amber lighting at night in communal areas such as corridors. For this study, participants entered the corridor lit with white light. They were instructed to stand on a mark on the floor and face one end of the hallway. The lighting was then changed to amber light at full brightness. Participants were told to imagine the amber lights illuminating a hotel corridor late at night. They were asked if they would feel safe under the light at the current illumination level. The light was dimmed until the participant stated they would feel unsafe under the lighting.

The amber lights were then returned to full brightness, and the participants were asked to read a hotel card printed with black text. They were then asked to give their opinion about the amber lighting in the corridor. Finally, researchers explained the purpose and benefits of amber lighting at night. Researchers then asked participants if the explanation changed their opinion of the lighting.

Control User Interface

Participants were given brief instructions on how to select which user interface was controlling the overhead lights. They were instructed to use each dimmer to raise and lower the lights, and then find a light level that they liked. After the participant had used all the devices, they ranked the controls on a five-point scale.

The following questions were provided for context on what was meant by each scale:

- "Easiest to control" to "Most difficult to control"
- "Most intuitive" to "Least intuitive"
- "Most comfortable" to "Least comfortable"
- "Most preferred" to "Least preferred"

Figure 53: Control Devices Installed in the User Interface Preference Chamber

Figure 53 shows the control devices installed in the user-interface preference chamber. Study participants used each dimmer to raise and lower the lights, and then find a light level that they liked.

Source: California Lighting Technology Center

Control System Functionality

Participants completed a multi-part survey designed to identify preferences for control system functionality and control system benefits. Questions focused on dimmers, dimming LEDs, preferences for other types of control such as occupancy and vacancy sensors, and use of such controls in the residential setting. Surveys were conducted in multiple phases. The sample size for each phase varied, and some people did not respond to all questions. The sample size for each individual question is provided in the results section of this report.

Perception of Visible Flicker

During the *Perception of Visible Flicker* study, a test participant entered the room with the integrating sphere on. Participants answered the following questions using an iPad:

1. Have you ever worked in the lighting industry or have you contracted with lighting industry professionals?
2. Have you ever noticed or experienced flickering lights?

3. If you answered yes to Q2, did the flickering occur when the lights were being dimmed with a dimmer switch?

After completing the survey, the participant was instructed to place his or her chin on the chin rest within the sphere, and then shown three scenes of flickering lights:

1. 70 Hz and 100 percent modulation
2. 75 Hz and 100 percent modulation
3. 70 Hz and 50 percent modulation

Participants were then informed that they would be shown several lights which may or may not visibly flicker. The first waveform illuminated the interior of the sphere. They were asked if the light was flickering and their answers were recorded. The light then transitioned to a non-flickering scene for five seconds to let the participant's eyes adjust. The next light scene was shown to them and they were asked if they observed flicker. This was repeated for multiple light scenes.

Perceptibility of Color Tuning

Participants were given a simple task to perform - either a word search or a paper maze. They were instructed to begin this task and then push a button if they noticed the light changing. They were informed that the light would change multiple times and be reset to a cooler color temperature with each change. Thirty scenes, in random order, were shown to each participant.

The lights were initially set to 5,000 K. The CCT was slowly decreased for 30 seconds. After 30 seconds, the scene was reset to 5,000 K and started dimming again if the participant had not noticed the lights changing color. The lights were set to change color all together, or in pairs of neighboring lights. Given the room's lighting layout, five lighting configurations were possible:

- All four together
- Two lights in front of the participant
- Two lights behind the participant
- Two lights to the participant's right
- Two lights to the participants left

Additionally, six rates of change were selected lamps included in the scene:

- 100 K per second
- 80 K per second
- 60 K per second
- 40 K per second
- 20 K per second
- 10 K per second[8]

[8] The "just-noticeable" amount of change in CCT varies as a function of CCT, with changes being more noticeable at lower CCTs. The JND for 5,000 K is approximately 160 K, and for 2,700 K is approximately 60 K.

Results

Amber Lighting at Night in Corridors

This study focused on using amber lights for general-purpose nighttime illumination of corridors. Each participant was asked if they would feel safe in a corridor illuminated by the amber light under varied light levels. Figure 54 shows the last light level that the test participant said that they would feel safe under for the hotel scenario. Twenty-five individuals, 50 percent, stated that they would not feel safe under the light at any level used.

Figure 54: Number of Participants Identifying Light Level as "Safe" Limit

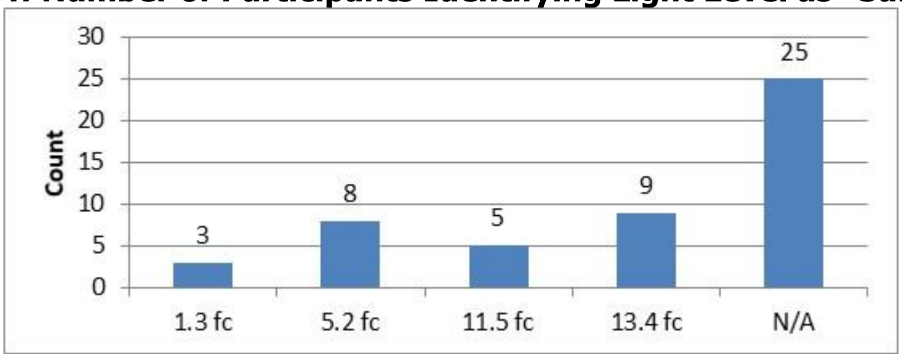


Figure 54 shows the number of participants that identified a light level as safe under the amber lighting installed in a hotel scenario.

Source: California Lighting Technology Center

Next, participants were shown a hotel card and a sample written text and asked how readable the text was under the light compared with normal. Half of the participants felt that they could read the text as well under amber light as they could under white light. Figure 55 shows the participant's rating of the readability of the texts. Due to operator error, six participants were not asked this question.

Lastly, participants were asked whether their general impression of the amber-lit corridor was positive or negative. Then, the purpose of the amber lights was explained and participants were asked if the explanation changed their opinion. Participants reporting a positive impression of the amber-lit corridor increased from 10 percent to 62 percent after the explanation.

The Control User Interface

During the *User Interface Study*, participants were asked to use and rank the controls for "ease of use," "intuitiveness," "comfortableness," and "preference." The average rankings from 1 – best to 5 – worst, for each parameter, are provided in Figure 56.

Of the six commercially available dimmer-control interfaces shown to participants, the slider- and pre-selector switches were most preferred. The response to the cellphone application was divided. Many of the participants wanted to control their personal lighting using their cellphones, while others explicitly stated that they wanted nothing to do with app-based control strategies. In general, there was demand for the capability, but the evaluated implementation (cellphone + app) had technical issues that may have limited interest.

Figure 55: Rating of Amber Light Level for Reading Purposes

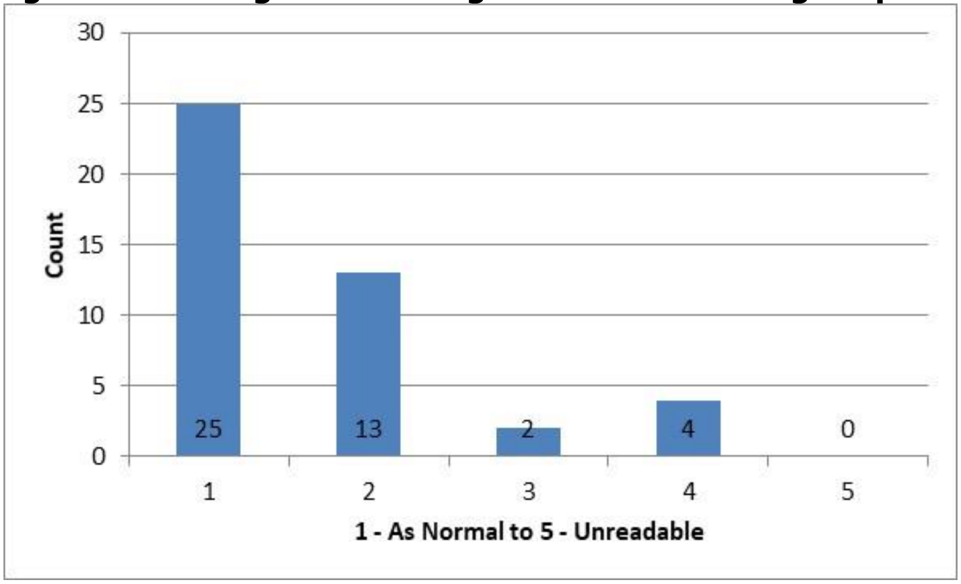


Figure 55 shows results from participants being shown a hotel card and a sample written text and being asked how readable the text was under the light compared with normal lighting.

Source: California Lighting Technology Center

The browser-based control on the cellphone sometimes moved to the wrong page for controlling the lights. This occurred when the user attempted to move the web page around for a better view of the controls, which caused the page to change. When this happened, the test proctor returned the cellphone to the correct web page, and then returned the cellphone to the participant.

The desktop remote was reasonably well received, but often participants voiced concern that they would lose the remote due to its size. The rotary knob dimmer was determined to be unusual by the participants in two regards: 1) it had a separate ON/OFF button from the knob, and 2) it had a rather large dead-band at the top causing it to not dim for the first half of the rotation.

Control System Functionality

The first part of the lighting controls survey focused on understanding people's perceptions of dimming functionality and hardware. Incompatibility between sources and dimming controls is a major cause of flicker and reduced system performance. Survey questions were designed to understand people's experience with dimming controls, their expectations regarding performance, and other issues surrounding dimming and LED sources. Results show that most people feel that dimmers are an effective control strategy and many report having a positive experience with the control type.

The first set of questions was structured as true/false responses to a series of statements regarding dimming use. Results show that all participants (except one) used dimmer switches at some point in their lives; 97 percent would like to have dimmers in the home, and 87 percent currently use one or more dimmers in their home.

The second set of questions related to dimming LEDs. Most people knew that LEDs could be dimmed, but that not all LED lamps are dimmable. However, fewer people understood that even dimmable LED lamps are not compatible with all dimmers. Forty-two percent of people stated that any dimmer switch could dim a dimmable LED source without any problem.

Figure 56: Average Rating of Each User Interface Sorted by Preference

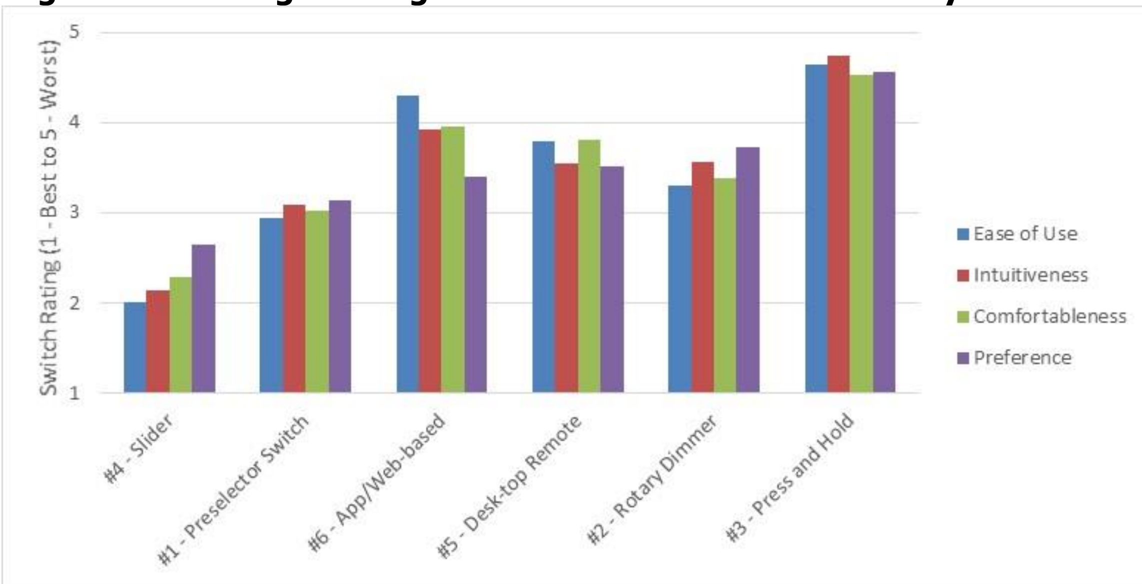


Figure 56 shows the average rating of each user interface with the slider (#4) being rated the best for ease of use, intuitiveness, comfortableness and preference.

Source: California Lighting Technology Center

Figure 57: Survey Results Pertaining to LEDs and Dimming Controls

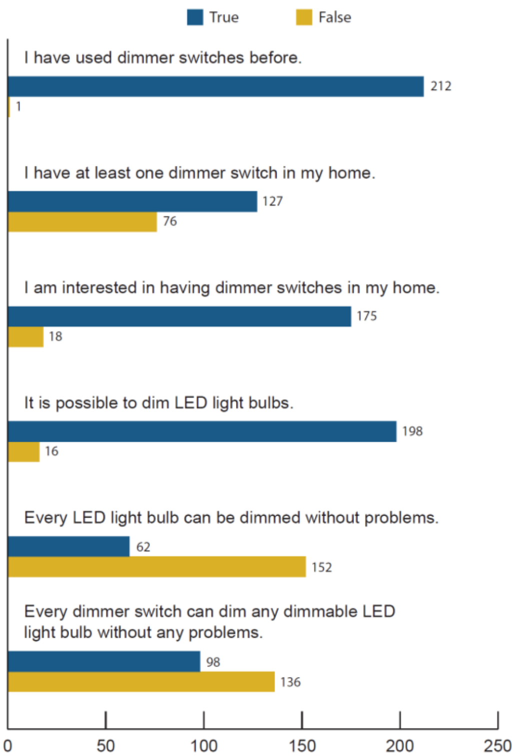


Figure 57 shows survey results pertaining to LEDs and lighting controls. The number of responses is listed to the right of each bar.

Source: California Lighting Technology Center

Additionally, a majority of people was unaware that LED manufacturers provide lists of compatible controls to use with their products. Only 25 percent of people said they knew these lists existed, and just six percent of people had used one.

Lastly, people were asked about their purchase-related actions pertaining to selection of dimmable LED lamps. Most people stated that they would read the labeling on the box and check to ensure the product was dimmable. However, fewer people indicated that they would check installation instructions or other documentation provided with the lamp (e.g., in the box).

Figure 58: Survey Responses Pertaining to Purchasing Actions and Dimmable LED Lamps

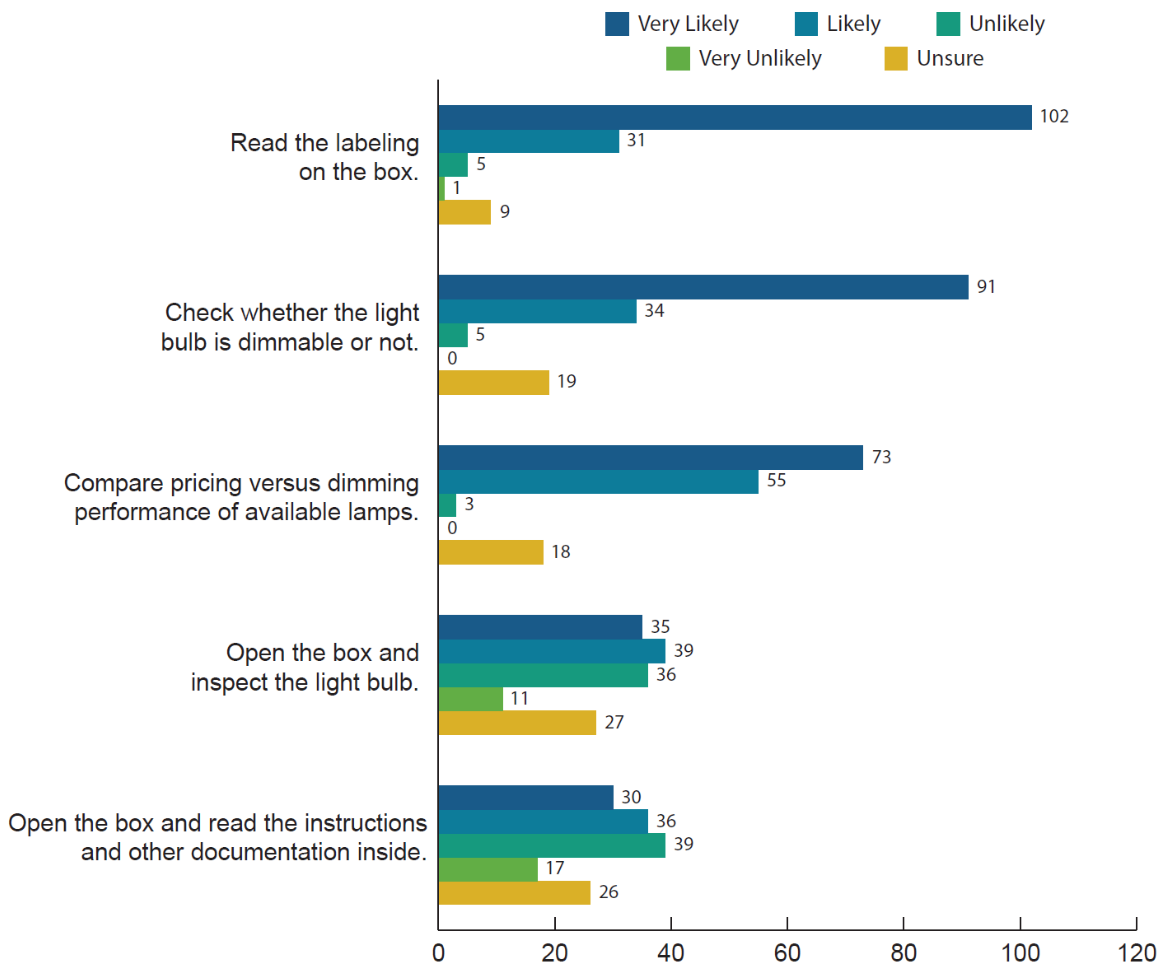


Figure 58 shows survey responses pertaining to purchasing actions and dimmable LED lamps. Number of responses are shown to the right of each bar.

Source: California Lighting Technology Center

Overall, most people felt that all major types of lighting controls were effective. People reported their most neutral opinions of daylighting controls. Very few people reported negative feelings for any control type. Complete survey results regarding people's experiences and opinions of major lighting control types are shown in Figure 59.

Figure 59: Survey Responses Regarding Experience and Opinion of Various Lighting Control Strategies

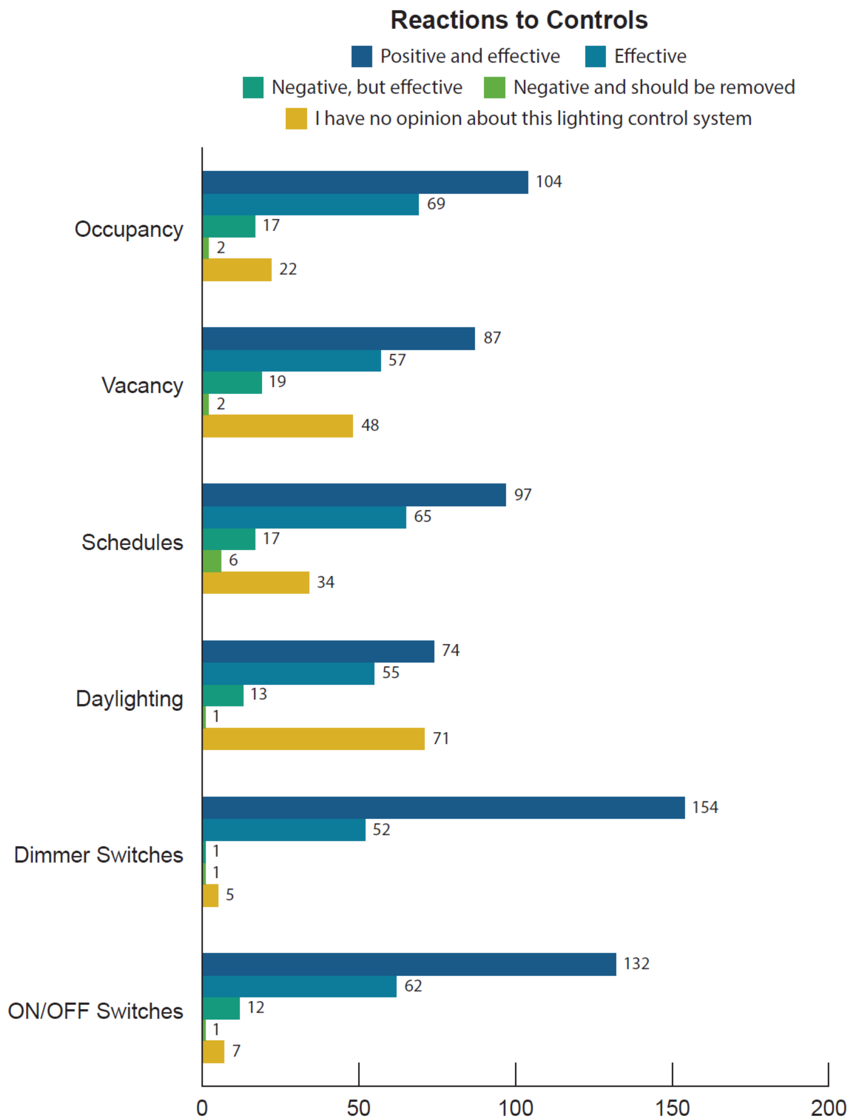


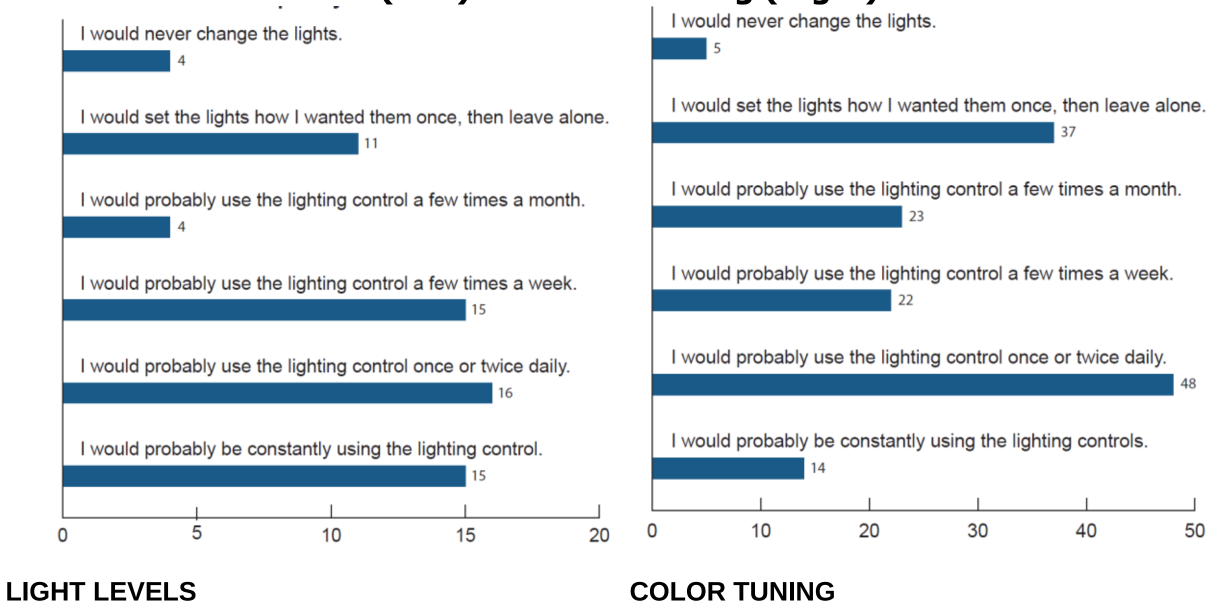
Figure 59 shows study participants' experience and opinion of various lighting control strategies. Number of responses are shown to the right of each bar.

Source: California Lighting Technology Center

The next series of questions related to personal controls such as those in a shared office environment. A majority of people would like to have personal control of the lighting in their workspaces (72 percent). However, people were generally divided on how frequently they would change the lighting in their workspaces if given the ability to do so. Seventy-one percent of people felt they would change their light levels a few times or more a week, while 21 percent felt they would either never change the light levels or set it once and leave it.

In contrast, when control included the ability to change the color of the light, many more people reported that they would set the color one time and leave it. The same number of people who reported that they would be constantly changing the light levels if given the ability to do so also reported they would constantly change the color in their workspace. Detailed results for both dimming and color tuning are shown in Figure 60.

Figure 60: Survey Responses Pertaining to Personal Lighting Controls for Dimming (Left) and Color Tuning (Right)



Source: California Lighting Technology Center

Visual Flicker

Prior to the start of the lighting tests, participants answered two questions designed to determine their experience with flicker and its possible causes. Participants were asked if they had ever experienced flicker and if so, did they believe the flicker was due to lighting controls. Seventy-eight percent of participants reported experiencing visible flicker (39 of 50). Of this group, roughly 25 percent (10 of 39) reported that the flicker happened during dimming.

Participants were then exposed to 54 different lighting scenes to assess their perceptions of visible flicker and their responses recorded. Twenty-two participants were exposed to all of the scenes except the 200 Hz scene; 14 additional participants were exposed to all of the scenes including the 200 Hz scene. The number of participants who saw each scene is provided in Figure 61.

Figure 61: Frequency of Observed Flicker Scenes: "*" Indicates Significant Number of Participants Noticed This Waveform

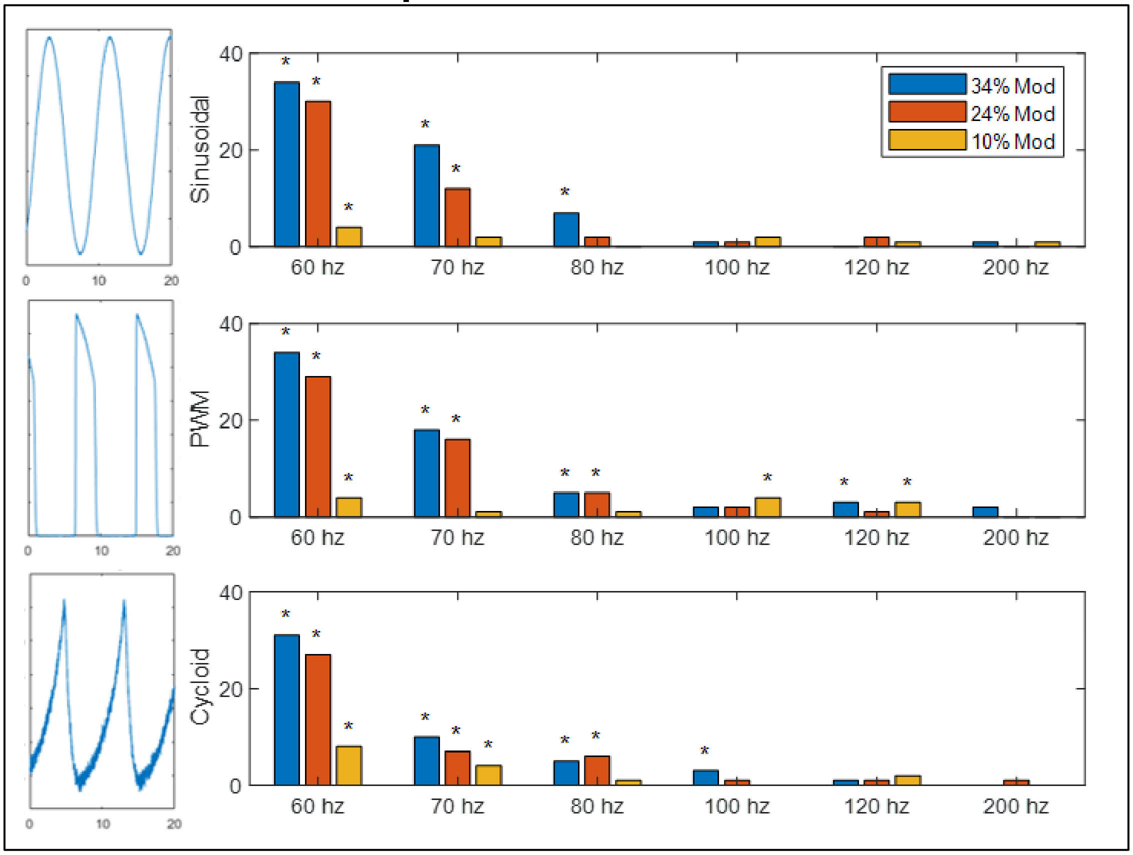


Figure 61 shows the frequency of observed flicker scenes by study participants. Scenes with an asterisk indicate that a significant number of participants notices this waveform.

Source: California Lighting Technology Center

Perception of Color Tuning

Prior to the start of the color tuning test, participants were asked, "Are you interested in light bulbs that produce adjustable color light?"

- 35 participants (70 percent) answered "Yes."
- 5 participants (10 percent) answered "No."
- 10 participants (20 percent) answered "I don't know."

Participants were then shown the 30 color tuning scenes previously described. Each participant was shown each ramp rate five times, once under each set of lights changing (e.g., both lights behind the participant). This means that each rate of color tuning was shown to the participants 220 times. Due to technical issues during the testing, the results of the first six participants were invalid. The number of times that the participants saw each ramp rate is provided in Figure 62.

Figure 62: Number of Times Color Tuning Rates Were Observed

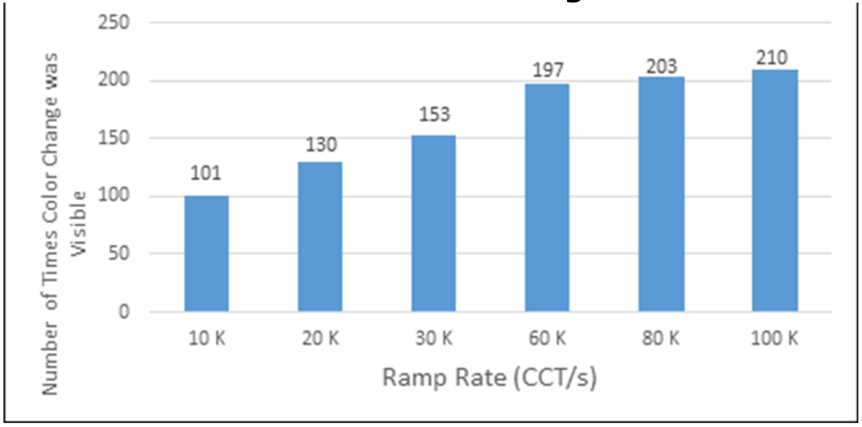


Figure 62 shows the number of times color tuning rates were observed by study participants.

Source: California Lighting Technology Center

Additionally, each participant was exposed to each set of lights (all four of them, or each pair of neighboring lights) six times, once at each ramp rate. In total, participants were exposed to 264 different lighting scenes. Orientation of lights undergoing color shift for each scene were:

1. SW/SE – The two overhead lights in front of the participant.
2. SW/NW – The two overhead lights to the participant's right.
3. NE/SE – The two overhead lights to the participant's left.
4. NW/NE – The two overhead lights behind the participant.
5. All – All four lights changing together.

The number of times that the participants saw each set of lights changing is provided in Figure 63.

Figure 63: Number of Observed Color Changes

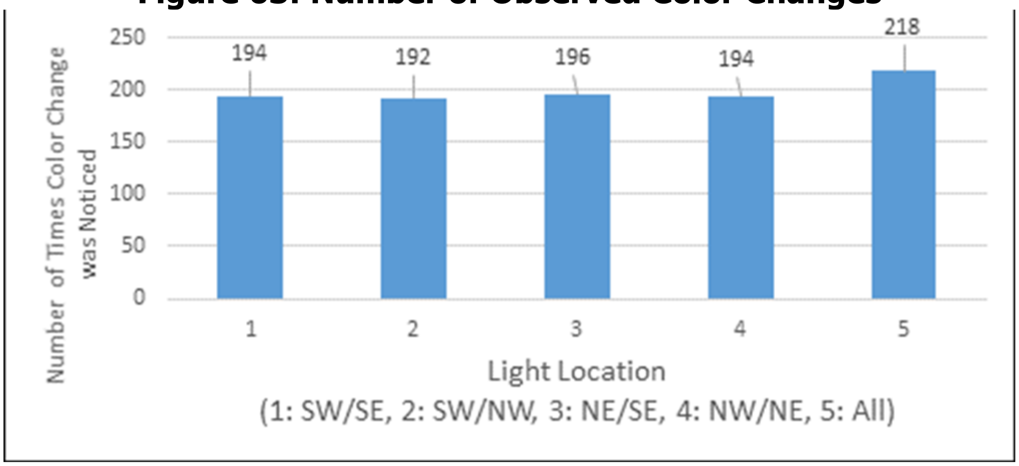


Figure 63 shows the number of times that participants saw each set of lighting changing.

Source: California Lighting Technology Center

Study Conclusions

Amber Light at Night for Corridors

Initial reactions to the amber light were negative, but after receiving an explanation of the benefits of amber lighting, acceptance of the light increased by 52 percent. This indicates that successful implementation of amber lighting will require education for occupants and continued education as new occupants arrive.

In addition, only one amber source was evaluated during this study: a yellow-amber-colored LED with a peak wavelength of 600 nm. There is a wide range of technologies capable of producing amber light, including a wide variety of colored LEDs and phosphor-converted amber LEDs. It is likely that other peak wavelengths and bandwidths of amber night lighting would result in a more natural appearance. Future studies on this topic should evaluate different amber light sources to determine occupant preference for peak wavelength and bandwidth.

Preferences for Control Interfaces

Of the six commercially available dimmer control interfaces shown to the participants, the slider- and pre-selector switches were most preferred. The response to the cellphone application was divided; many of the participants wanted to have control of the light in their spaces using their cellphones, while others explicitly wanted nothing to do with controlling the lights using their cellphones. In general, there was a demand for the capability; however, the evaluated implementation had technical issues that may have lessened interest. This may also have resulted in the cellphone being highly preferred, but much lower rated in all other evaluated categories. The desktop remote was reasonably well received, but often participants voiced concern that they would lose the remote due to its size.

Desired Functionality of Control Systems

End users are most interested in energy savings from control systems that provide more control over the lighting in their environments. These critical points should be kept in mind when designing new control systems.

Most participants in the study stated that, given the opportunity, they would choose to control the amount of light from both the general and task lights. Additionally, just under half of the participants stated that they would prefer to turn off their lights and use daylight. The question directed participants to consider their current workspace; it is likely that these participants had sufficient daylight in their workspaces at least some of the time to use daylight only.

Forty-six percent of participants stated that they would choose to change the light-color appearance of the lights in their space. It is unknown how many people would actively use color tuning features in lighting; however, there is an evident desire for it.

Nearly all (99 percent) of the participants indicated that they had used dimmer switches. Based on participant responses, there is a small preference for dimmer switches to ON/OFF switches. A significant majority (75 percent) of the participants stated that they would like personal control of the lights in their workspaces. These results suggest that personal controls of the lights in workspaces is desired by most end users assuming the user interface for the controls is not a hindrance.

More than 35 percent of the participants indicated that they thought that all dimmable LEDs are compatible with all dimmer switches. This is not true in today's market, as many dimmable LEDs perform poorly when paired with incompatible dimmers. Participants indicated that the only activity they were likely to do to assess light source/dimmer interoperability was to read the outside of the packaging. Based on these results, it is recommended that dimmer compatibility be clearly communicated to consumers on the outside of light-source packaging to avoid dissatisfaction with the lighting system being installed.

Additional questions explored the typical end user's understanding of daylighting. Results from the study showed that daylighting remains poorly understood by most end users. Approximately one-third of the participants had no opinion about the daylighting-control strategy. It is recommended that educational programs aimed at end users be developed to ensure energy savings from daylight-harvesting strategies are achieved.

Finally, the majority of participants stated that they prefer vacancy sensors to occupancy sensors. This is potentially due to people feeling like they would like to have more control over the lighting in their space, and having to actively turn on the light satisfies that desire.

Perception of Visible Flicker

Flicker, both visible and stroboscopic, causes eyestrain and headaches as well as photosensitive seizures.[9] In general, 78 percent of the participants of the *Perception of Visible Flicker* study said that they have seen lights flickering. Of this 78 percent, at least 26 percent attributed the flicker to incompatibility issues between the light source and the dimming controls.

There is a minor effect of the shape of the flicker waveform on the perceptibility of flickering lights. The "Sinusoidal" and "PWM" (Pulse-Width Modulated) waveforms have similar perceptibility, while the "Inverted Cycloid" appears to be less noticeable at some frequencies. Specifically, this is true at the 70 Hz frequency with the same percent modulation.

This can be attributed to the "Inverted Cycloid" having a lower flicker index than the other waveforms evaluated for any given percent modulation. However, percent modulation appears to be a metric that can be used to estimate the visibility of flicker, where a higher percent modulation correlates to higher visibility for each waveform shape. Results from the visible flicker study are plotted in Figure 64.

[9] IEEE 1789-2015 - IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers: https://standards.ieee.org/standard/1789-2015.html

Figure 64: Results of Visible Flicker Study, and IEEE Chart Information

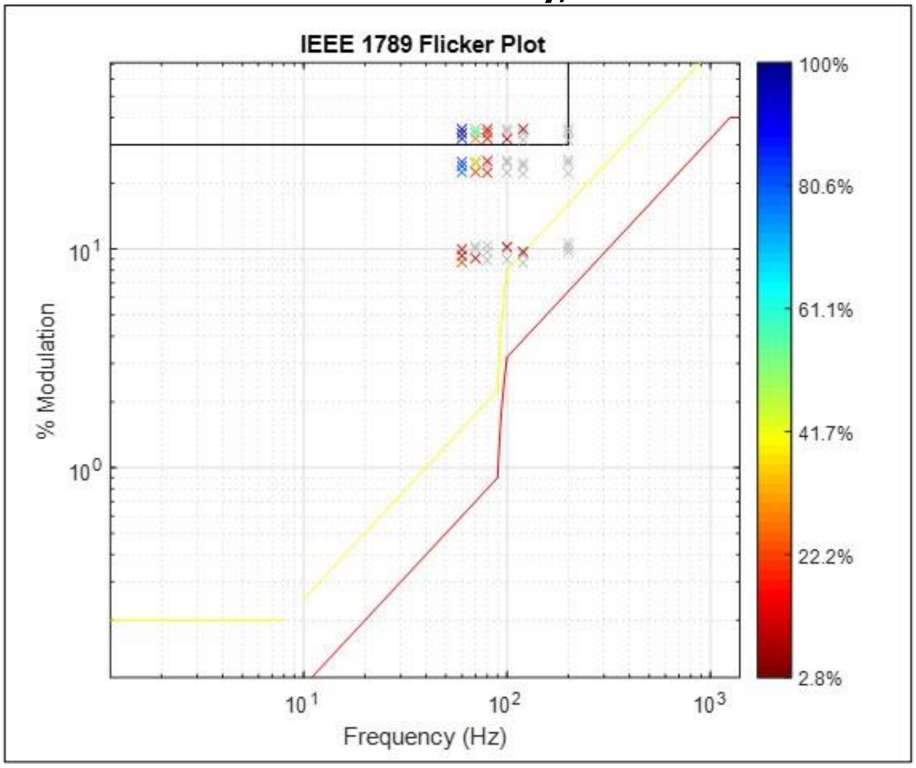


Figure 64 shows the results of the visible flicker study overlaid with the IEEE 1789 information.

Source: California Lighting Technology Center

A colored "x" indicates the scenes where a significant number of the participants saw the flicker with the color, indicating the frequency that participants saw the flicker. A light grey "x" shows scenes that were not observed by a significant number of the participants.

Percent modulation appears to be a metric that can be used to estimate the visibility of flicker, where a higher percent modulation correlates to higher visibility for each waveform shape. Overall, the results align with the IEEE 1789 guidelines for limiting flicker for mitigating health risks to viewers. It is recommended that the IEEE 1789 guideline be used to predict whether flicker will be visible to end users.

Perception of Color Tuning

Seventy percent of the study participants expressed interest in color-tunable lighting. Most participants believed they would use color tuning controls as frequently as they would use dimming controls in their workspaces.

In terms of noticeable color change, changes that included the lighting pair confirmations were noticed with approximately equal frequency (73.4% +/- 0.8%). Location within the field of view had no impact. Scenes where all four lights changed together were noticed with greater frequency than scenes where only pairs of lights changed. It is likely that this was due to the change being twice as large in terms of intensity, as twice as many fixtures were changing.

Overall, participants noticed all rates of color change. The slowest dimming rate of 10 K per second was noticed 46 percent of the time it was presented. This suggests that color tuning in response to an occupant input is not appropriate for shared workspaces, since even slow change rates would be noticed by a significant number of occupants. Based on these results, it is recommended that color tuning for "circadian" lighting in shared spaces be changed at 1 K per second or less to minimize visibility to occupants.

CHAPTER 4: Understanding Current Product Performance

In combination with providing preferred features and useful packaging information, lighting products must deliver on performance claims when used in common applications and over their rated life. Simply having a specific feature at the time of purchase does not ensure that the product will remain installed in the home or workplace. Independent testing and validation is needed to ensure that high-quality LED products are identified and promoted in the California market.

The Voluntary California Quality LED Lamp Specification (Specification) has made great strides in promoting certain types of high-quality LED lamps; however, not all lamp types are addressed in the current version of the specification. In addition, standard test methods do not incorporate tests to understand performance under some typical applications in California buildings. For example, lamps installed in California applications often experience elevated-temperature operating environments due to energy standards requirements related to air circulation and insulation.

To address these gaps and ensure that quality products are brought to market, the CLTC conducted a three-year study to understand and document both initial LED product performance and performance over time. This information, when combined with the consumer preference outcomes presented in Chapters 2 and 3, can be leveraged by manufacturers when developing products to satisfy initial and long-term performance expectations.

Market Assessment

Researchers conducted a market assessment to identify and characterize common LED lamp types and their energy use. Staff inventoried commercially available LED products in the following four product categories: linear LED lamps, omni-directional LED lamps, directional LED lamps, and ceiling-mounted LED kits. This inventory included LED products from 69 manufacturers. The collection did not reflect the whole market but covered the majority of manufacturers offering products in previously referenced categories.

Based on market assessment findings and Specification requirements, three overarching performance criteria were used to narrow the product inventory and select products for evaluation:

- 90 CRI or greater
- Target CCT of falling inside the ANSI bin for manufacturer-claimed performance
- Dimmable

Given these constraints, the research team identified and procured 23 representative LED products for evaluation under the test program. Selection prioritized lamp types that are the largest contributors to national-lighting energy use (Table 11). Composition of selected products was 57 percent linear LED lamps, 41 percent medium screw-base LED lamps, and two percent other categories, as determined appropriate by the project team. System components used in the evaluation included LED lamps, ballasts or drivers depending on product type, and housings or fixtures. Ballast selection was driven by the prevalence of ballasts installed in today's commercial building stock throughout California. Driving factors for housing selection were socket orientation, number of sockets, and trim options.

Table 11: Lamp Type Energy Use

Lamp Type	Annual National Residential Energy Use (GWh)	Annual National Commercial Energy Use (GWh)	Total (GWh)	Lighting Energy Use Contribution (%)
Medium Base Lamp (INC, CFL, Halogen)	158,730	50,166	208,896	41%
Linear Fluorescent	15,658	277,585	293,243	57%
Other (LED, HID, etc.)	1,872	6,689	8,560	2%
TOTAL	**176,260**	**334,440**	**510,700**	**100%**

Table 11 shows national residential and commercial energy use by the lamp type.

Source: California Lighting Technology Center

Life Testing: Products

While certain criteria were prioritized at the time of purchase, only eight commercially available products met the 90-CRI-or-greater requirement. None were linear LED lamps. After selection of all available 90-CRI or-greater products, the remaining budget was used to procure lamps that had less than 90 CRI from prominent manufacturers and at competitive price points, while keeping with the overall sample set with the lamp distribution that mirrored national energy-use distribution data. The full list of products used as part of product life testing is shown in Table 12.

Table 12: Replacement LED Lamps Selected for Testing

Test ID	Product Description	Light Output (lm)	Power (Watt)	Power Factor	CCT (Kelvin)	CRI	Rated Life (Hrs.)
Candle-01	Candelabra, E12 base	350	5	N/A	2,700	90	25,000
Candle-02	Candelabra, E12 base	500	6	0.7	2,700	90	25,000
MSB-01	Directional Flood, E26 base, BR40	1,000	14	N/A	2,700	93	25,000
MSB-02	Directional Narrow Flood, E26 base, BR30	655	9	>0.9	2,700	80	25,000

Test ID	Product Description	Light Output (lm)	Power (Watt)	Power Factor	CCT (Kelvin)	CRI	Rated Life (Hrs.)
MSB-03	Directional Wide Flood, E26 base, PAR20	640	11	N/A	2,700	85	35,000
MSB-04	Filament omnidirectional, E26 base	800	7	N/A	2,700	80	20,000
MSB-05	Omnidirectional, E26 base	800	9.8	N/A	2,700	90	25,000
MSB-06	Omnidirectional, E26 base	800	9	N/A	2,700	92	25,000
MSB-07	Omnidirectional, E26 base	450	7	N/A	2,700	80	25,000
MSB-08	Directional Flood, E26 base, BR30	800	12	N/A	2,700	93	25,000
MSB-09	Directional Narrow Flood, E26 base	800	10.5	N/A	2,700	90	50,000
MSB-10	Omnidirectional, E26 base, PAR20	445	7	0.9	3,000	94	25,000
MSB-11	Directional Flood, E26 base, PAR38	1,200	17	N/A	2,700	82	25,000
MSB-12	Filament omnidirectional, E26 base	500	5	0.9	2,700	80	25,000
MSB-13	Directional Flood, E26 base, PAR30	960	12	>0.9	2,700	75	50,000
MSB-14	Omnidirectional, E26 base	800	8	N/A	2,700	80	25,000
TLED-1	TLED - UL Type C	4,500	44	0.9	3,500	80	50,000
TLED-2	TLED - UL Type A	2,290	22	0.95	3,000	80	50,000
TLED-3	TLED - UL Type B	1,800	15	N/A	3,000	80	50,000
TLED-4	TLED - UL Type B	2,200	18	>0.9	3,500	85	50,000
TLED-5	TLED - UL Type A	2,000	15	N/A	3,000	82	50,000
TLED-6	TLED - UL Type A	1,800	14	N/A	3,000	83	50,000
TLED-7	TLED - UL Type A/B	1,600	15	N/A	3,000	80	50,000

Table 12 shows the replacement LED lamps and their manufacturer claimed performance that were selected for life testing.

Source: California Lighting Technology Center

The research team identified a cross-section of linear LED lamp products: UL Type A, UL Type B, UL Type A/B, and UL Type C. UL Type A products are designed to operate on a linear fluorescent lamp ballast. UL Type B LED lamps use an internal driver and must be connected directly to line voltage for power. These products rely on the fluorescent sockets for support and may also receive power through the socket. UL Type C lamps use an external driver, and systems are designed to replace both the linear fluorescent lamp(s) and the fluorescent lamp ballast. Some commercial linear LED products can operate under multiple configurations. UL Type A/B products can be installed as a plug-and-play replacement of linear fluorescents (UL Type A configuration). Then, when the ballast fails, instead of replacing it, the UL Type A/B products can be wired directly to line voltage (UL Type B configuration).

The research team focused on one-lamp configurations. However, TLED-1 was only available in a two-lamp configuration. The photometric data was tracked for a one-lamp system to compare its performance with one-lamp products.

Interoperability Testing: Products

Four-foot linear luminaires are the most common luminaire type installed in California's commercial buildings. Most installed products use linear fluorescent lamps; however, linear LEDs are quickly replacing fluorescents in many applications. Retrofits may result in installation of incompatible lamp and ballast/driver combinations due to the plethora of products available on the market.

For this study, researchers compiled a list of 78 linear-LED lamp products. Researchers selected 12 products for evaluation based on the three overarching criteria previously described plus UL type, reported efficacy, lumen output, and other criteria aligned with the consumer preference outcomes reported. Four samples of each product were purchased for evaluation. Manufacturer-claimed performance for selected lamps is provided in Table 13.

Associated drivers and ballasts are shown in Table 14.

Table 13: Linear LED Lamp Products Selected for Testing

Product ID	Type of LED	Beam Angle	CRI	CCT (K)	Efficacy (lm/W)	Light Output (lm)	Input Power (Watts)
Product A	Type A	330	>80	4,000	163.34	1,800	11
Product B	Type A	270	80	4,000	120.00	1,800	15
Product C	Type B	240	>83	4,000	131.03	1,900	14.5
Product D	Type B	160	82	4,000	144.83	2,100	14.5
Product E	Type C	270	>80	4,000	140.00	2,100	15
Product F	Type C	240	82	4,100	152.00	2,280	15
Product G	Type AC	220	82	4,100	141.94	2,200	15.5
Product H	Type AC	160	82	4,000	150.00	2,100	14
Product I	Type AB	120	84	4,000	130.00	1,950	15
Product J	Type AB	220	>80	4,000	120.00	1,800	15
Product K	Type B	120	94	4,000	128.89	2,320	18
Product L	Type B	240	>90	4,000	108.33	1,625	15

Table 13 shows linear LED lamp products selected for interoperability testing.

Source: California Lighting Technology Center

Table 14: Ballast and Drivers for Linear LED Lamps Selected for Testing

Product ID	Lamp Number	Type/Dimmability
Driver 1	2	Dimmable
Driver 2	2	No Dimming
Driver 3	2	Dimmable
Driver 4	2	Dimmable
Ballast 1	2	Rapid Start, Dimmable
Ballast 2	1	Program Rapid Start, Dimmable
Ballast 3	2	Instant Start, No Dimming
Ballast 4	2	Program Start, Dimmable

Table 14 shows the ballasts and drivers selected for testing with the linear LED lamps.

Source: California Lighting Technology Center

Test Methodology

The test methodology was developed to evaluate and document LED lamp performance initially, over time, and under installed conditions representative of California's building sector. Test methods for the evaluation of interoperability and electrical and photometric performance over time are shown in the following figure.

Test Rack

A custom test rack was designed and constructed to track product run-time, control run-time duration, and monitor electrical characteristics (Figure 65). The test rack consists of a physical array of sockets mounted on a metal frame that power and support the lamps, control hardware, and measurement devices.

Figure 65: Test Rack Geometry

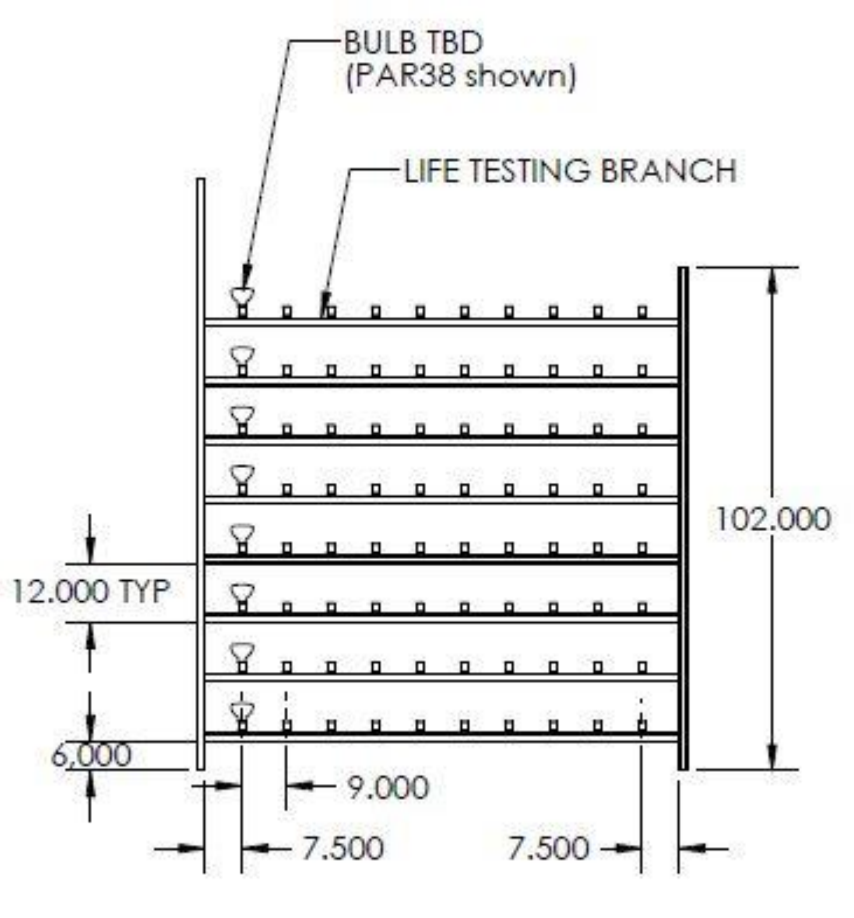


Figure 65 shows the test rack used for life testing. It consists of a physical array of sockets mounted on Unistrut that power and support the lamps, control hardware, and measurement devices.

Source: California Lighting Technology Center

The control and measurement system relied on a National Instruments PXI chassis with a variety of modules for measurement and control. All control and measurement were run via software written in LabVIEW, running on the PXI chassis. This software was built to run continuously throughout the test duration, provide timing for measurement and control, and generate notifications regarding system status. Every 60 seconds, the control software recorded in-situ data of lamp operating conditions, including temperature, current, voltage, photometric, and airflow.

Electrical and Photometric Performance

Laboratory testing included collection of electrical and photometric properties over time. Baseline testing included electrical and photometric testing of all products at full output and selected dimmed levels when controlled by commercially available dimmers.

Life testing was conducted according to IES LM-84-14, which provided electrical and photometric measurements every 1,000 hours of run time for full output, which in turn was used to capture power, current, voltage, power factor, and total harmonic distortion metrics. Photometric data collected simultaneously with electrical data every 1,000 hours of operation was used to calculate luminous flux, chromaticity (CIE 1932 x, y), correlated color temperature (CCT), D_{UV}, CRI, and percent flicker.

Electrical and photometric measurements were made in accordance with the Illuminating Engineering Society LM-79-08 Approved Method: Electric and Photometric Measurements of Solid State Lighting Products. Electrical and photometric metrics were analyzed to categorize the functionality of the products, including electrical harmonic distortion, individual R1–R15 values, flicker index, and percent flicker.

Luminous flux, chromaticity, CCT, D_{UV}, and CRI were calculated from the spectral-power distribution (SPD) as measured with an integrating sphere. Flicker data were also collected in an integrating sphere using custom instrumentation.

System Configuration

The test samples were run in in-situ conditions typical of a California application. The medium screw-base, linear LED replacement lamps, and candelabra lamps each use a different fixture configuration in the run-time test rack.

Medium screw-base lamps were installed in typical California recessed fixtures to understand how this specific, enclosed application affected the lifetime of the lamp. Downlight housings with airtight trims were used for omni-directional products, as shown in Figure 66. These components were chosen to ensure compliance with Section 150.0(k)1C of California’s Building Energy Efficiency Standards. All of the downlight housings were wrapped with R-19 building insulation to simulate typical operating conditions. Directional medium screw-base products were tested in the same housing without the lens.

Four-foot, single lamp, sealed fixtures were identified as the most intensive thermal conditions that a linear LED replacement lamp would experience for indoor applications in California. The instant-start ballast that ships standard with the fixture was used with the UL Type A products. The fixtures were modified to accommodate Type B and Type C replacement products with varying wire and mounting configurations.

Vanity fixtures equipped with candelabra sockets and enclosed globes were identified as being the most intensive thermal conditions that a candelabra lamp would experience for indoor applications in California. The fixtures were mounted with lamps oriented base-up with the globe connecting to the fixture via thumbscrews.

Figure 66: Test Rack Showing Downlights with LED A-Lamps and Linear LED Lamps

Figure 66 shows the test rack with downlight and linear housings installed to duplicate the most intensive thermal conditions where medium screw base and linear lamps are installed in California.

Source: California Lighting Technology Center

Interoperability

For linear LED products, evaluations included interoperability testing to test each product's compatibility with common electrical components selected independent of manufacturer's recommendations. Data was analyzed to understand product performance and safety concerns related to incorrect pairing of linear LED lamps, ballast, drivers, and lamp holders.

The linear LED lamps in Table 13 were tested with each ballast and driver described in Table 14, as well as single-ended and dual-ended UL Type B lamp holder configurations. Lamp performance was rated based on light output delivered and the temperature of the lamp and ballast or driver. The interoperability-testing matrix and order of the testing are provided in Table 15.

Table 15: Product Matrix for Interoperability Testing

Round	Model	Ballast/Driver
1	Product E	Driver 2
1	Product F	Driver 1
1	Product A	Ballast 3
1	Product B	Ballast 2
1	Product I	Ballast 4
1	Product J	Ballast 1
1	Product G	Driver 3
1	Product H	Driver 4
2	Product E	Driver 3
2	Product F	Driver 2
2	Product A	Ballast 2
2	Product B	Ballast 3
2	Product I	Ballast 1
2	Product J	Ballast 4
2	Product G	Driver 4
2	Product H	Driver 1

Table 15 shows the lamp and ballast/driver combinations used for interoperability testing.

Source: California Lighting Technology Center

System Configuration

Interoperability testing was conducted in a dark room measuring 0.008 fc or less of illuminance. A four-foot strip fixture was used for testing that accommodated all wiring requirements for the selected ballast/driver and lamp configurations (Figure 67). Tests included a research-grade illuminance meter attached to the fixture to measure relative light output of each configuration.

Figure 67: Linear LED Fixture with Illuminance Meter

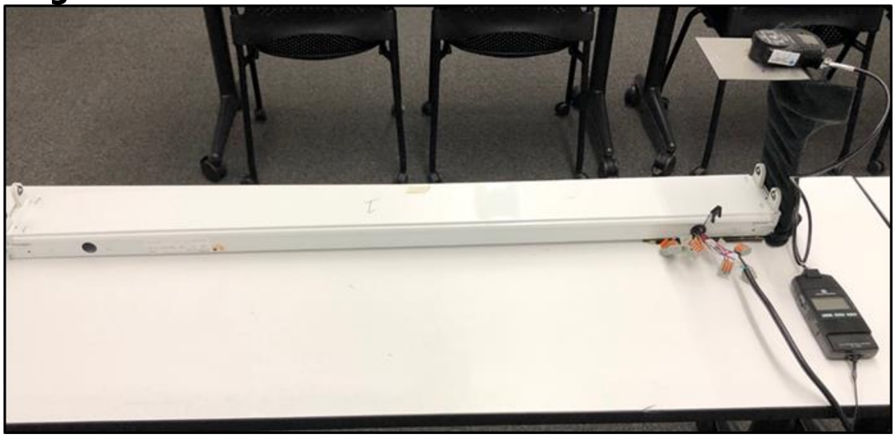


Figure 67 shows a four-foot strip fixture with an illuminance meter used for interoperability testing.

Source: California Lighting Technology Center

In-situ temperature measurements of the ballast/driver housing and the lamp base were collected using a non-contact infrared thermometer-temperature gun directed at ballast/driver housing and socket ends of the replacement lamps.

The interoperability testing was conducted in the following steps:

1. **Baseline testing:** Each product was paired with the manufacturer-approved lamp-holder type and driver/ballast. This provided the relative light output and temperature baseline performance of the product.
2. **Interoperability testing:** Lamps were paired with one of the driver/ballasts from Table 14, or configured as a UL Type B product. The lamp setup was monitored closely for hazard indications including temperature or power spikes. If no hazards were observed, relative light output and temperature measurements were recorded. After each test, lamps and power components were wired in the baseline configuration and retested to compare with relative light output. This assessed any damage resulting from the interoperability testing configurations.

Data was analyzed to understand performance and safety issues associated with each configuration. Configurations were classified as nonoperational or hazardous if the light output was significantly changed from baseline (> 10 percent difference) or temperature if the lamp or the ballast/driver exceeded the manufacturer-rated conditions for the product.

Test Results

The evaluation consists of interoperability data and electrical and photometric data collected initially and every 1,000 hours up to 12,000 hours of total run time. A complete set of summarized performance data is provided in Appendix D.

Directional Medium Screw-Base Lamps

The average directional, medium screw-base lamp data is compiled based on an average of individual sample performance for seven representative products. The seven products are averaged to understand the product category as a whole. Table 16 shows the key performance characteristics for this product category over time.

Table 16: Directional Medium Screw-Base Lamps Average Performance Over Life

	Power (W)	Luminous Output (lm)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)	D_{uv}	Flicker (%)
Manufacturer Claimed	11.7	814	69.0	0.90	87.0	2,743	N/A	N/A
Baseline	11.2	813.1	71.3	0.93	87.0	2,739	–0.000522	13.9
1000 Hour	11.2	806.1	70.5	0.93	86.9	2,740	–0.000491	14.4
2000 Hour	11.2	817.1	71.5	0.93	86.8	2,741	–0.000341	14.3
3000 Hour	11.2	811.0	71.3	0.93	86.7	2,737	–0.000221	14.1
4000 Hour	11.2	819.0	71.8	0.93	86.7	2,724	–0.000295	13.8
5000 Hour	11.2	794.4	69.6	0.93	86.5	2,713	–0.000269	14.8
6000 Hour	11.1	781.4	68.7	0.93	86.6	2,719	–0.000265	14.3
7000 Hour	11.1	776.7	68.4	0.93	86.6	2,720	–0.000206	15.2
8000 Hour	11.1	768.3	67.6	0.93	86.5	2,722	–0.000049	16.9
9000 Hour	11.2	807.7	70.1	0.93	87.6	2,748	–0.000419	14.7
10000 Hour	11.3	817.9	71.3	0.93	87.4	2,765	–0.000082	14.8
11000 Hour	11.2	805.0	70.3	0.93	87.4	2,778	0.000008	14.7
12000 Hour	11.3	805.2	69.9	0.93	87.5	2,768	–0.000094	14.7

Table 16 shows the average performance over life of the tested directional medium screw-base lamps.

Source: California Lighting Technology Center

Regarding power, six of the seven products consumed within one watt of the manufacturer-claimed power rating at the time of the baseline characterization. Product MSB-11 consumed 2.9 watts (or 17 percent) less than the marketing literature indicated. All seven products varied within 0.2 watts for the duration of testing.

With respect to efficacy, the variation in the minimum baseline measurement taken per product as compared to the manufacturer claimed performance ranges from one percent to 33 percent. Product MSB-11 measured at 93.2 lumens per watt for the baseline characterization as compared to 70.6 lumens per watt claimed by the manufacturer. MSB-13 claimed 80 lumens per watt and delivered 33 percent less at 53.3 lumens per watt. All seven products varied within 4.2 lumens per watt for the duration of testing.

The CRI variation between each product's minimum baseline measurement as compared with the manufacturer-claimed performance ranges from 0.1 percent to 13 percent. Product MSB-13 measured at 84.7 for the baseline characterization, as compared with the 75 claimed by the manufacturer. MSB-11 claimed 82 and delivered 0.1 percent more at 82.1. All seven products varied within 1.1 for the duration of testing.

With respect to percent flicker, all seven products varied within 3.0 percent for the duration of testing. Three of the seven directional medium screw-base lamps experienced product failures: MSB-2, MSB-3 and MSB-13. Failure modes varied. See Table 17.

Table 17: Failed Directional Medium Screw-Base Products

Product	Failure Mode	Number of Failed Samples (out of 6 total tested)
MSB-2	LED Array	4
MSB-3	Melted Optic	6
MSB-13	Driver	4

Table 17 shows the number of failed directional medium screw-base products and their failure mode.

Source: California Lighting Technology Center

Table 18: Projected Rated Life (L_{70}) for Directional MSB Lamps

	Manufacturer Claimed Rated Life (hours)	Projected Rated Life (L_{70}) Based on In-Situ Performance (hours)	Manufacturer Recommended Operating Conditions
MSB-1	25,000	>60,000	None provided
MSB-2	25,000	N/A (4 failures)	None provided
MSB-3	35,000	N/A (6 failures)	Recessed downlights
MSB-8	25,000	>60,000	Not for use in enclosed fixtures
MSB-10	25,000	>60,000	Suitable for use in totally enclosed luminaires
MSB-11	25,000	>60,000	UL approved for damp location and enclosed fixtures
MSB-13	50,000	N/A (4 failures)	Operate in fixtures that provide the free flow of air around the lamp heat sink

Table 18 shows the projected rated life of the directional medium-screw base lamps based on the test data collected during the product evaluation. Three of the seven products did not meet the manufacturers' claimed rated life when operating in conditions typical of California buildings.

Source: California Lighting Technology Center

The average luminous output data was used for each product to project the long-term luminous flux maintenance of LED lamps according to IES LM-84 and IES TM-28. Failed lamps were input into the projections for MSB-2, MSB-3, and MSB-13, which affected the ability to project the luminous flux if the number of failed samples reduced the operational sample size to three or less.

Four of the products exceeded the manufacturer-claimed rated life, and three of the products were unable to achieve the manufacturer-claimed rated life when operating in conditions typical of California buildings. Of the three products that were unable to achieve the manufacturer-rated life, one product's specification sheet required that "it operate in fixtures that provide the free flow of air around the lamp heat sink." The operating conditions typical of California buildings do not allow for the free flow of air around the lamp heat sink.

Omni-Directional Medium Screw-Base Lamps

The average omni-directional medium screw-base lamp product evaluated is compiled based on an average of individual sample performance for seven representative products. The seven products are averaged to understand the market vertical as a whole.

Regarding power, six of the seven products consumed within one watt of the manufacturer-claimed power rating at the time of the baseline characterization. Product MSB-4 consumed 1.2 watts (or 17.7 percent) less than the marketing literature indicated. Six of the seven products varied within one watt for the duration of testing, while MSB-7 varied 2.8 watts for the duration of testing.

With respect to efficacy, the variation in the minimum-baseline measurement taken per product, as compared with the manufacturer-claimed performance, ranges from 2.1 percent less to 15.2 percent more. Product MSB-9 measured at 74.6 lumens per watt for the baseline characterization as compared with the 76.2 lumens per watt claimed by the manufacturer. MSB-4 claimed 114.3 lumens per watt and delivered 16 percent more at 131.67 lumens per watt. The seven products varied within 18.3 lumens per watt for the duration of testing. MSB-4 varied 87.4 lumens per watt for the duration of the testing. Table 19 shows the key performance characteristics for the product category over time.

With respect to CRI, the variation in the minimum baseline measurement taken per product, as compared with manufacturer-claimed performances, ranges from one percent less to four percent more. Product MSB-6 measured at 91.5 for the baseline characterization, as compared with the 92 claimed by the manufacturer. MSB-12 claimed 80 and delivered four percent more at 83. Six of the seven products varied within 1.4 for the duration of testing. Product MSB-4 varied by 2.1 over the duration of testing.

Table 19: Omni-Directional Medium Screw-Base Lamps Average Performance Over Life

	Power (W)	Luminous Output (lm)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)	D_{UV}	Flicker (%)
Manufacturer Claimed	8.0	707	89.3	0.90	84.6	2,700	N/A	N/A
Baseline	8.1	730	93.1	0.87	86.0	2,699	0.000608	23.6
1000 Hour	8.1	711	90.5	0.87	86.1	2,704	0.000205	24.1
2000 Hour	8.1	713	90.4	0.87	86.1	2,715	0.000291	24.5
3000 Hour	8.1	688	86.7	0.87	86.1	2,726	0.000320	24.1
4000 Hour	8.1	666	82.7	0.87	86.2	2,736	0.000244	24.8
5000 Hour	8.1	630	77.3	0.87	86.2	2,749	0.000096	24.5
6000 Hour	8.6	660	75.9	0.92	86.6	2,748	0.000523	20.8
7000 Hour	9.1	708	77.8	0.93	87.4	2,713	0.001023	25.0
8000 Hour	9.1	695	76.4	0.93	87.3	2,716	0.001191	31.6
9000 Hour	8.8	681	76.5	0.86	87.4	2,718	0.001359	31.3
10000 Hour	8.8	690	77.6	0.92	87.4	2,733	0.001508	26.6
11000 Hour	9.1	676	76.2	0.93	87.3	2,742	0.001692	26.6
12000 Hour	8.5	657	74.8	0.91	87.4	2,735	0.001863	26.3

Table 19 shows the average performance over life of the tested omni-directional medium screw-base lamps.

Source: California Lighting Technology Center

With respect to percent flicker, products varied within 10.8 percent for the duration of testing. Three of the seven omni-directional medium screw-base lamps experienced product failures: MSB-4, MSB-6, MSB-7, and MSB-12. Failure modes varied. See Table 20.

Table 20: Failed Omni-directional Medium Screw-Base Products

Product	Failure Mode	Number of Failed Samples (out of 6 total tested)
MSB-4	LED filament array	6
MSB-6	Not tested	1
MSB-7	Driver	3
MSB-12	LED filament array	6

Table 20 shows the number of failed samples and failure mode of the tested omni-directional medium screw-base lamps.

Source: California Lighting Technology Center

The average luminous output data was used for each product to project the long-term luminous flux maintenance of LED lamps according to IES LM-84 and IES TM-28. Failed lamps were input into projections for MSB-4, MSB-6, MSB-7, and MSB-12, which affected the ability to project luminous flux if the number of failed samples reduced the operational sample size to three or less.

Table 21: Projected Rated Life (L_{70}) for Omni-directional MSB Lamps

	Manufacturer Claimed Rated Life (hours)	Projected Rated Life (L_{70}) Based on In-Situ Performance (hours)	Manufacturer Recommended Operating Conditions
MSB-4	20,000	N/A (6 failures)	None provided
MSB-5	25,000	>60,000	None provided
MSB-6	25,000	>60,000 (1 failure)	Not intended for use in totally enclosed fixtures
MSB-7	25,000	N/A (3 failure)	None provided
MSB-9	25,000	>60,000	Not for use in totally enclosed luminaires
MSB-12	25,000	N/A (6 failures)	None provided
MSB-14	25,000	>60,000	None provided

Table 21 shows the projected rated life for the tested omni-directional medium screw-base lamps.

Source: California Lighting Technology Center

Four products exceeded the manufacturer-claimed rated life, and three products were unable to achieve the manufacturer-claimed rated life when operating in conditions typical of California buildings. The two products with six failed samples used LED filament designs. For these two products, no operating requirements or recommendations were provided in the product literature.

Linear LED Replacement Lamps

The average linear LED replacement lamp product evaluated is compiled based on an average of individual sample performance for seven representative products. The seven products are averaged to understand the market vertical as a whole. Table 22 shows key performance characteristics for the product category over time.

Regarding power, two of the seven products consumed within one watt of the manufacturer claimed power rating at the time of the baseline characterization. TLED-2 consumed 5.6 watts (or 26 percent) less than the marketing literature indicated. TLED-6 consumed 12.7 watts (or 90 percent) more than the marketing literature indicated. The average product varied within 4.7 watts for the duration of testing. TLED-2 varied 6.1 watts over the duration of testing and TLED-7 in UL Type A configuration varied 17.7 watts over the duration of testing.

Table 22: Linear LED Replacement Lamp Average Performance Over Life

	Power (W)	Luminous Output (lm)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)	D_{uv}	Flicker (%)
Manufacturer Claimed	20.4	1991	109.4	0.92	81.4	3,143	N/A	N/A
Baseline	24.1	1981	96.0	0.98	83.6	3,183	–0.000924	15.4
1000 Hour	24.1	1994	96.6	0.99	83.5	3,192	–0.000905	17.1
2000 Hour	23.9	2001	97.7	0.98	83.5	3,200	–0.000896	13.5
3000 Hour	24.1	2001	97.0	0.98	83.5	3,209	–0.000906	15.4
4000 Hour	24.2	2001	97.1	0.98	83.5	3,210	–0.000821	14.9
5000 Hour	19.5	2001	107.9	0.95	83.6	3,210	–0.000950	14.6
6000 Hour	20.5	2001	95.9	0.99	83.6	3,163	–0.000900	17.2
7000 Hour	19.8	2001	91.9	0.98	83.7	3,169	–0.000921	18.3
8000 Hour	20.5	2001	94.6	0.99	83.6	3,174	–0.000977	N/A
9000 Hour	20.5	2001	95.3	0.99	83.7	3,178	–0.000992	N/A
10000 Hour	20.6	1964	97.0	0.98	83.8	3,208	–0.001045	24.4
11000 Hour	20.2	1916	96.2	0.98	83.8	3,209	–0.001060	19.1
12000 Hour	20.5	1902	94.2	0.98	83.8	3,207	–0.000920	20.1

Table 22 shows the average performance over life of the tested linear LED replacement lamps.

Source: California Lighting Technology Center

With respect to efficacy, the variation in the minimum baseline measurement taken per product as compared with the manufacturer-claimed performance ranges from seven percent to 32 percent less. Product TLED-4 measured at 113.3 lumens per watt for the baseline characterization as compared with the 122.2 lumens per watt claimed by the manufacturer. TLED-7 in UL Type A configuration claimed 106.7 lumens per watt and delivered 31 percent less at 72.7 lumens per watt. The seven products varied within 15.9 lumens per watts for the duration of testing.

With respect to CRI, the variation in the minimum baseline measurement taken per product, as compared with the manufacturer-claimed performance, ranges from one percent less to 7 percent more. Product TLED-4 measured at 84.4 for the baseline characterization as compared with the 85 claimed by the manufacturer. TLED-2 claimed 80 and delivered 7 percent more at 85.2. The seven products varied within 0.3 for the duration of testing.

With respect to percent flicker, two of the seven products varied within 0.4 percent for the duration of testing. TLED-5 varied 5.0 percent for the duration of testing. Four of the seven products varied from 10.5 percent to 17.3 percent for the duration of testing.

Three of the seven linear LED replacement lamps experienced product failures: TLED-1, TLED-5, and TLED-7. Failure modes varied: see Table 23. One sample of TLED-5 failed during the

1,000-hour characterization. The testing operator discharged the lamp from the warming rack with energized lamp holders and mounted in the sphere with energized lamp holders.

Table 23: Failed Linear LED Replacement Lamp Products

Product	Failure Mode	Number of Failed Samples (out of 6 total tested)
TLED-1	Connections	6
TLED-5	Driver	1
TLED-7	Resistor	4

Table 23 shows number of failed samples and the failure mode of the tested linear LED replacement lamps.

Source: California Lighting Technology Center

Table 24: Projected Rated Life (L_{70}) for Linear LED Replacement Lamps

	Manufacturer Claimed Rated Life (hours)	Projected Rated Life (L_{70}) Based on In-Situ Performance (hours)	Manufacturer Recommended Operating Conditions
TLED-1	50,000	N/A (6 failures)	Existing dry or damp rated linear fluorescent fixtures including troffers, parabolics, strips, wraps, volumetric/baskets and industrials; not intended for use in vapor tight fixtures
TLED-2	50,000	>60,000	Capable of indoor usage in -5ºF to 115ºF temperature range
TLED-3	50,000	>60,000	None provided
TLED-4	50,000	>60,000	Suitable for enclosed fixture
TLED-5	50,000	>60,000 (1 failure)	Suitable for use in fixtures where ambient temperature is between -4°F (-20°C) and 113°F (45°C)
TLED-6	50,000	>60,000	Not rated for use in fully enclosed fixtures
TLED-7	50,000	>N/A (4 failures)	None provided

Table 24 shows projected rated life for the tested linear LED replacement lamps.

Source: California Lighting Technology Center

The average luminous output data was used for each product to project the long-term luminous flux maintenance of LED lamps according to IES LM-84 and IES TM-28. Failed lamps were input into the projections for TLED-1, TLED-5, and TLED-7, which affected the ability to project the luminous flux if the number of failed samples reduced the operational sample size to three or less.

The research team evaluated one UL Type A/B product, TLED-7. The electrical and photometric performance of TLED-7 was captured for the baseline performance in both UL Type A and UL Type B configurations and is provided. Table 25 shows the key performance characteristics for the product category over time, comparing UL Type A configuration to UL Type B configuration, and includes the manufacturer-claimed performance for reference.

Table 25: Linear LED Replacement Lamp UL Type A vs. UL Type B Performance for TLED-7

	Power (W)	Luminous Output (lm)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)	Duv	Flicker (%)
Manufacturer Claimed	15	1,600	106.7	N/A	80	3,000	N/A	N/A
UL Type A	21.3	1,560	73.2	1.0	81.8	2,949	–0.00069	17.0
UL Type B	15.1	1,525	101.0	0.95	81.9	2,945	–0.00068	27.6

Table 25 shows the performance for the TLED-7 linear LED replacement lamp that can be operated in UL Type A or UL Type B configurations.

Source: California Lighting Technology Center

The TLED-7 product in UL Type A configuration performed generally as claimed by manufacturers for luminous output, CRI, and CCT. The UL Type A configuration consumed more power than claimed, resulting in a lower efficacy than claimed by the manufacturers. Generally, the TLED-7 product in UL Type B configuration performed as claimed by manufacturers for all performance criteria analyzed.

The minimum baseline measurement for power of the TLED-7 product tested in UL Type A configuration was initially 21.3 watts and 15.1 watts in the UL Type B configuration. The UL Type B configuration consumes 6.2 watts less than the UL Type A configuration, or 28.5 percent less.

The minimum baseline measurement for efficacy of the average TLED-7 product tested in UL Type A configuration was initially 73.2 lumens per watt and 101.0 lumens per watt in the UL Type B configuration. The UL Type B configuration increases the efficacy by 27.8 lumens per watt as compared with the UL Type A configuration, or a 38 percent increase.

The minimum baseline measurement for CRI of the average TLED-7 product tested in UL Type A configuration was initially 81.8 and 81.9 in the UL Type B configuration. The UL Type B configuration CRI is 0.01 less than the UL Type A configuration, or 0.01 percent less. The minimum baseline measurement for percent flicker of the average TLED-7 product tested in UL Type A configuration was initially 17 percent and 26.8 percent in the UL Type B configuration. The UL Type B configuration percent flicker is 9.7 percent greater than the UL Type A configuration.

Candelabra Lamps

The average candelabra LED lamp product evaluated is compiled based on an average of individual sample performance for two representative products. The two products are averaged to understand the product category as a whole. Table 26 shows the key performance characteristics for the product category over time.

Table 26: Candelabra LED Lamp Average Performance Over Life

	Power (W)	Luminous Output (lm)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)	D_{UV}	Flicker (%)
Manufacturer Claimed	5.5	425	76.7	0.70	90.0	2,700	N/A	N/A
Baseline	5.6	372	66.5	0.81	90.3	2,780	0.002759	12.2
1000 Hour	5.6	390	69.8	0.81	89.9	2,779	0.002272	13.2
2000 Hour	5.6	396	70.6	0.81	90.2	2,770	0.002214	12.3
3000 Hour	5.6	373	66.7	0.81	90.1	2,782	0.002069	11.5
4000 Hour	5.6	374	66.8	0.81	90.6	2,780	0.001600	12.0
5000 Hour	5.6	357	63.9	0.81	91.0	2,765	0.001076	12.0
6000 Hour	5.6	350	62.7	0.81	91.6	2,753	0.000587	13.5
7000 Hour	5.6	341	61.1	0.81	92.0	2,751	0.000331	12.0
8000 Hour	5.6	336	60.3	0.81	91.9	2,742	-0.000146	5.1
9000 Hour	5.6	322	57.5	0.81	92.3	2,733	-0.000801	5.4
10000 Hour	4.9	297	60.5	0.76	93.2	2,786	-0.000466	15.9
11000 Hour	5.8	344	59.0	0.69	94.1	2,816	-0.001416	4.8
12000 Hour	5.8	336	57.7	0.69	94.2	2,817	-0.001643	4.8

Table 26 shows the average performance over life of the tested candelabra LED lamps.

Source: California Lighting Technology Center

Regarding power, both products consumed within 0.2 watts of the manufacturer-claimed power rating at the time of the baseline characterization. Candle-2 consumed 0.2 watts (or four percent) less than the marketing literature indicated. Candle-1 consumed 0.2 watts (or four percent) more than the marketing literature indicated. Both products varied within 1.3 watts for the duration of testing.

With respect to efficacy, the variation in the minimum baseline measurement taken per product as compared with the manufacturer-claimed performance ranges from eight percent to 27 percent less. Product Candle-1 measured at 51.8 lumens per watt for the baseline characterization as compared with the 70 lumens per watt claimed by the manufacturer (27 percent less). Candle-2 claimed 83.3 lumens per watt and delivered eight percent less at 76.5 lumens per watt. The average product varied within 13.2 lumens per watt for the duration of testing.

With respect to CRI, the variation in the minimum baseline measurement taken per product as compared with the manufacturer-claimed performance ranges from 1.2 percent less to 0.2 percent more. Product Candle-1 measured at 90.2 for the baseline characterization, as compared with the 90 claimed by the manufacturer. Candle-2 claimed 90 and delivered 1.2 percent less at 88.9. Both products varied within 5.1 for the duration of testing.

With respect to percent flicker, both products varied within 13.3 percent for the duration of testing. Candle-1 varied 13.3 percent for the duration of testing. Candle-2 varied 1.8 percent for the duration of testing.

One of the two candelabra LED replacement lamps experienced six sample failures. The failure mode was a non-functioning LED array.

The average luminous output data was used for each product to project the long-term luminous flux maintenance of LED lamps according to IES LM-84 and IES TM-28. Failed lamps were input into the projections for Candle-1, which affected the ability to project the luminous flux as the number of failed samples reduced the operational sample size to three or less.

Table 27: Projected Rated Life (L_{70}) for Candelabra LED Replacement Lamps

	Manufacturer Claimed Rated Life (hours)	Projected Rated Life (L_{70}) Based on In-Situ Performance (hours)	Manufacturer Recommended Operating Conditions
Candle-1	25,000	N/A (6 failures)	None provided
Candle-2	25,000	>60,000	None provided

Table 27 shows projected rated life for the tested candelabra LED replacement lamps.

Source: California Lighting Technology Center

Interoperability

Results from the interoperability testing reveal that a significant amount of UL Type A and UL Type C combinations resulted in no light output or significantly reduced light output; however, no combination caused a hazard. Driver and ballast temperatures were within reason as compared to the baseline, and the power draw did not cause any issues.

When testing UL Type B configurations, most products failed to turn on. Some configurations caused hazards in addition to failing to illuminate. Temperature measurements of Product H reached 158 degrees Fahrenheit after five minutes of operation. Product E in a single-ended UL Type B configuration failed during testing. Electrical discharge, or "sparking," was visible at the lamp holder, followed immediately by additional electrical discharge inside the lamp.

When comparing results from the product testing to the best-in-class specification developed based on consumer preference outcomes and CQVS requirements, no single commercially available product was able to meet the dimming, color quality, and efficacy performance thresholds. Product H performed closest to specification but failed to achieve the necessary color-quality goals. The products that met the color quality were not dimmable and did not meet the light-output and efficacy goals. A summary of product performance in terms of select performance characteristics is shown in Table 28.

Table 28: Best-in-Class Specification Criteria Met by Each Tested Linear LED Product

Product ID	Type - Config	Dimmable	Light Output	Efficacy	Power Factor	CRI
Product A	Type A	Yes	No	No	Yes	No
Product B	Type A	Yes	No	No	Yes	No
Product C	Type B	Yes	No	Yes	Yes	No
Product D	Type B	No	No	Yes	Yes	No
Product E	Type C	Yes	No	Yes	Yes	No
Product F	Type C	Yes	No	Yes	Yes	No
Product G	Type AC	Yes	No	No	Yes	No
Product H	Type AC	Yes	Yes	Yes	Yes	No
Product I	Type AB	No	No	Yes	Yes	No
Product J	Type AB	No	No	No	Yes	No
Product K	Type B	No	No	No	No	Yes
Product L	Type B	No	No	No	Yes	Yes

Table 28 shows which metrics of the best-in-class specification the linear LED lamps met.

Source: California Lighting Technology Center

Photometric and Electrical Performance

Photometric and electrical performance test results for all product combinations at full output are shown in Table 29.

Table 29: Photometric and Electrical Test Results of Linear LED Products and Ballast/Driver Combinations at Full Output

Product ID	Type - Config	Lumen/Lamp	CCT	efficacy	Watt/Lamp	Power Factor	CRI
Product A	Type A	1942	3944	110.15	17.63	0.9959	84.46
Product B	Type A	1922	3989	111.00	17.32	0.9986	83.29
Product C	Type B	2028	3981	133.56	15.18	0.9796	84.76
Product D	Type B	2097	3981	145.02	14.46	0.9816	84.16
Product E	Type C	1797	3962	119.92	14.99	0.9941	82.99
Product F	Type C	2080	3999	143.15	14.53	0.9884	83.40
Product G	Type AC-C	1745	4034	108.66	16.05	0.9970	85.04
	Type AC-A	1123	4131	85.18	13.18	0.9992	84.63
Product H	Type AC-A	2084	3919	118.89	17.53	0.9958	83.70
	Type AC-C	2555	4032	133.99	19.07	0.9915	83.73
Product I	Type AB-B	1779	4061	122.44	14.53	0.9595	82.99
	Type AB-A	1105	4066	103.72	10.65	0.9954	82.47
Product J	Type AB-B	1908	4014	130.95	14.57	0.9811	84.16
	Type AB-A	1933	3948	112.88	17.12	0.9975	83.42
Product K	Type B	1995	3992	116.80	17.08	0.4875	92.83
Product L	Type B	1627	3916	106.15	15.33	0.9735	93.20

Table 29 shows the photometric and electrical test results of the linear LED products combined with varying ballast/driver combinations when operated at full output.

Source: California Lighting Technology Center

Values highlighted in deep green meet CLTC's recommended specification for linear LED lamps. Values highlighted in light green show values that are within 10 percent of the specification. If the lamp and driver/ballast combination allowed for dimming, measurements were captured at 100 percent, 50 percent, 25 percent, and minimum load values. Test results for dimmed states are shown in Table 30.

Table 30: Photometric and Electrical Test Results for Dimmable Lamp and Ballast/Driver Combinations

Product ID	Type - Config		Lumen/Lamp	CCT	efficacy	Watt/Lamp	Power Factor	CRI
Product A	Type A	100%	1942	3944	110.15	17.63	0.9959	84.46
		50%	944	3923	109.52	8.62	0.9818	84.68
		25%	309	3908	82.61	3.74	0.9267	84.90
		min	79	3895	38.97	2.02	0.9535	84.85
Product B	Type A	100%	1922	3989	111.00	17.32	0.9986	83.29
		50%	842	3977	97.06	8.68	0.9958	83.59
		25%	282	3977	64.83	4.36	0.9873	83.67
		min	244	3975	61.46	3.97	0.9854	83.67
Product C	Type B	no dimmer	2028	3981	133.56	15.18	0.9796	84.76
		100%	1787	3981	134.12	13.32	0.9099	84.80
		50%	983	3974	139.49	7.05	0.7388	85.33
		25%	458	3979	134.77	3.40	0.6357	85.75
		0%	85	3989	110.29	0.77	0.4436	86.75
Product E	Type C	100%	1797	3962	119.92	14.99	0.9941	82.99
		50%	871	3949	116.68	7.47	0.9861	82.95
		25%	396	3939	105.42	3.75	0.9515	82.95
		min	126	3928	76.10	1.66	0.9083	82.93
Product F	Type C	100%	2080	3999	143.15	14.53	0.9884	83.40
		50%	1063	3999	147.11	7.23	0.9825	83.64
		25%	509	3997	141.62	3.59	0.9521	83.79
		min	198	3999	120.21	1.65	0.8202	84.16
Product G	Type AC-A	100%	1123	4131	85.18	13.18	0.9992	84.63
		50%	505	4065	76.54	6.59	0.9978	85.20
		25%	169	4047	49.84	3.40	0.9867	85.75
		min	45	4053	19.16	2.35	0.9756	86.34
Product H	Type AC-A	100%	2084	3919	118.89	17.53	0.9958	83.70
		50%	1044	3899	124.95	8.35	0.9830	83.97
		25%	370	3889	105.17	3.52	0.9162	84.32
		min	94	3871	54.66	1.72	0.9638	84.31
	Type AC-C	100%	2555	4032	133.99	19.07	0.9915	83.73
		50%	1371	4003	143.66	9.54	0.9821	83.89
		25%	591	3989	125.11	4.72	0.8544	84.12
		min	101	3983	58.32	1.73	0.8299	84.45

Table 30 shows the photometric and electrical test results for the linear LED lamp and ballast/driver combinations that are dimmable.

Source: California Lighting Technology Center

Test results for lamp and ballast/driver combinations that did not meet manufacturer recommendations are shown in the next table for UL Types A, B, and C. Information on incompatibility and relative light output provided by the combination, as compared with the baseline combination performance, is provided using a color scale:

- Cells highlighted in red with the abbreviation "DNF" represent a combination that does not function. No light output was emitted by this product combination.

- Cells highlighted with orange and yellow values, with negative percent values, dictate a reduction in light output compared with baseline. Orange cells have a relative percentage difference >10 percent while yellow cells have percentages <10 percent.
- Cells highlighted with light green and dark green, with positive percent values, dictate an increase in light output compared with baseline. Dark-green cells have relative percentage differences >10 percent while light-green cells have percentages <10 percent.

Table 31: Results of Interoperability Testing, UL Type C Fixture Compatibility

	Drivers			
Product ID	Driver 1	Driver 2	Driver 3	Driver 4
Product A	DNF	-19.06% @ 83°F	0.34% @ 82°F	DNF
Product B	DNF	-6.53 @ 82°F	22.09% @ 87°F	DNF
Product C	DNF	DNF	DNF	DNF
Product D	DNF	DNF	DNF	DNF
Product E	Baseline	-64.93% @ 81°F	-97.69% @ 81°F	-12.28% @ 79°F
Product F	DNF	DNF	DNF	Baseline
Product G	DNF	Baseline	27.03% @ 87°F	DNF
Product H	DNF	-13.18% @ 81°F	Baseline	DNF
Product I	DNF	-16.15% @ 81°F	-31.16% @ 87°F	DNF
Product J	DNF	1.69% @ 81°F	-0.39% @84°F	DNF
Product K	DNF	DNF	DNF	DNF
Product L	DNF	DNF	DNF	DNF

Table 31 shows the results of the interoperability testing for the UL Type C linear LED lamps when combined with four varying drivers.

Source: California Lighting Technology Center

Table 32: Results of Interoperability Testing, UL Type A Fixture Compatibility

	Ballast			
Product ID	Ballast 1	Ballast 2	Ballast 3	Ballast 4
Product A	-1.96% @ 83°F	2.04% @ 90°F	-8.64 @ 83°F	Baseline
Product B	Baseline	DNF	9.06% @ 82°F	16.37% @ 92°F
Product C	DNF	DNF	DNF	DNF
Product D	DNF	DNF	DNF	DNF
Product E	-53.42% @ 81°F	DNF	-57.62% @ 86°F	-52.77% @ 88°F
Product F	DNF	DNF	DNF	DNF
Product G	7.4% @ 83°F	Baseline	12.18% @ 82°F	18.07% @ 94°F
Product H	-7.58% @ 82°F	DNF	-3.56% @ 84°F	Baseline
Product I	-18.49 @ 81°F	DNF	Baseline	15.18% @ 87°F
Product J	-28.8% @ 81°F	DNF	Baseline	DNF
Product K	DNF	DNF	DNF	DNF
Product L	DNF	DNF	DNF	DNF

Table 32 shows the results of the interoperability testing for the UL Type A linear LED lamps when combined with four varying ballasts.

Source: California Lighting Technology Center

While a significant number of UL Type A and UL Type C combinations resulted in either no or significantly reduced light output, no combination caused a hazard. Driver and ballast temperatures were within reason as compared with the baseline, and the power draw did not cause any issues.

Table 33: Results of Interoperability Testing, UL Type B Fixture Compatibility

	Line Voltage	
Product ID	Single-Ended	Double-Ended
Product A	DNF	DNF
Product B	DNF	DNF
Product C	Baseline	DNF
Product D	DNF	Baseline
Product E	DNF, Sparks	DNF
Product F	N/A	N/A
Product G	DNF	DNF
Product H	DNF @ 158°F	DNF
Product I	Baseline	DNF
Product J	Baseline	DNF
Product K	Baseline	DNF
Product L	Baseline	DNF

Table 33 shows the UL Type B interoperability testing results.

Source: California Lighting Technology Center

When testing UL Type B configurations, most products failed to turn on. Some configurations caused hazards in addition to failing to illuminate. Temperature measurements of Product H reached 158 degrees Fahrenheit after five minutes of operation. CLTC staff smelled burning plastic during this test and turned off the power. The lamp was rewired in its baseline configuration and retested. Product H was unable to turn on after this test. Product E in a single-ended UL Type B configuration failed during testing. Electrical discharge, or sparking, was visible at the lamp holder followed immediately by additional electrical discharge inside the lamp.

Figure 68: Product E Electrical Discharge at Lamp Holder (Left), and Inside the Lamp (Right)

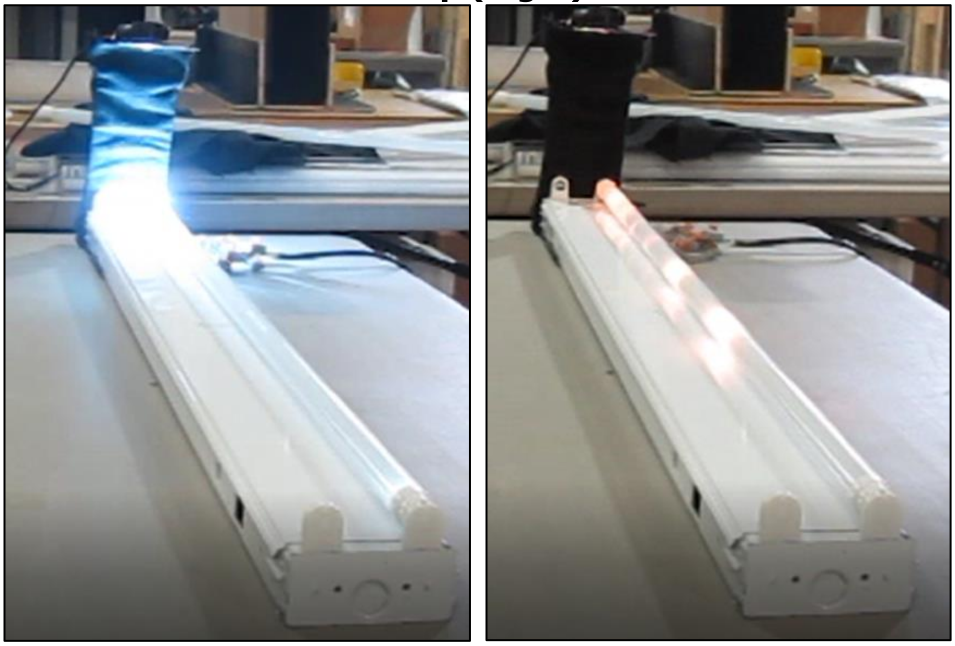


Figure 68 shows the electrical discharge during testing of Product E.

Source: California Lighting Technology Center

Conclusions and Recommendations

Of the 23 evaluated products, only eight fulfilled the full set of criteria with the limiting factor of a CRI of 90 or greater. Approximately 35 percent of the market met the Voluntary California LED Quality LED Lamp Specification at the time of procurement.

The evaluation results generally show that LED replacement lamps performed as claimed by manufacturers for the majority of performance criteria considered; however, no single commercially available product was able to meet all dimming, color quality, and efficacy performance thresholds. Product H performed closest to specification but failed to achieve the necessary color-quality goals. The products that met the color quality were not dimmable and did not meet light output and efficacy goals.

Medium screw-base lamps performed as claimed for all performance criteria analyzed. Linear LED (TLED) replacement lamps performed as claimed for luminous output, CRI, and CCT. On average over the first 2,000 hours of operation, the TLED replacement-lamp category consumed more power than claimed, under delivered on efficacy, and had a higher power factor than marketed. Candelabra LED lamps performed as claimed by manufacturers for power, CRI, and CCT. On average, the candelabra-LED lamp category produced less luminous output than claimed, under delivered on efficacy, and had a higher power factor than marketed.

In addition, the research team compared the initial performance of linear LED replacement lamps marketed for use as either UL Type A (paired with a fluorescent ballast) or UL Type B (line voltage run to lamp holders) to understand the performance of both available configuration options. The UL Type B configuration consumed 6.2 watts less than the UL Type A configuration, or 28.5 percent less. Due to this reduced power, the UL Type B configuration has an increased efficacy as compared with the UL Type A configuration of 27.8 lumens per watt, or a 38 percent increase. However, the UL Type B flicker is 9.7 percent greater than the UL Type A.

Lifetime Performance

Medium screw-base lamps and linear LED replacement lamps varied the most for efficacy and flicker during the first 2,000 hours of runtime testing. For candelabra LED lamps, the power factor varied the most over the 2,000-hour period of evaluation.

The original sample set was composed of six lamps each of 23 lighting products, resulting in 138 lamps. Forty-nine individual lamps failed to turn on over the duration of the 12,000-hour. This is a 36-percent failure rate for the sample set.

Projected rated life (L_{70}) calculations using IES LM-84-14 and TM-28-14 determined that nine of the 23 products were unable to meet the manufacturer-claimed rated life when operated in conditions typical of California buildings. This is a 39-percent failure rate of the products tested.

It is important to note that one of the nine products that did not meet manufacturer-claimed rated life was operated in conditions outside manufacturer recommendations. When omitting this product from the analysis, 36-percent of the products tested fail to meet the manufacturer-claimed rated life.

Product Safety and Reliability

No safety concerns were encountered over the course of the evaluation. No issues regarding safety markings were identified for evaluated lamps. The evaluation confirmed that readily available lamps marketed for the four-reviewed product categories available complied with industry-standard safety markings and compatibility labeling.

Two out of six samples of a medium screw base (MSB) product failed prior to reaching 1,000 hours of run time during round-one testing. This product utilizes a filament-style LED design, intended to emulate the look of traditional filament lamps. The other filament-style lamp reviewed as part of the MSB sample set experienced the most lumen depreciation over 2,000 hours of run time. The luminous output decreased 92 lumens, or 11 percent.

All samples of two filament-style omni-directional LED design MSB lamps failed over the course of the 12,000-hour life testing. This indicates that while the filament-style lamp design is aesthetically pleasing, further product development is needed to improve its reliability for the California consumer.

One sample of a linear LED (TLED) lamp failed during characterization due to improper installation by the test operator. The installation guide from the manufacturer states that the installer should install the LED T8 tube and then switch on the power. The operator removed the lamp from energized lamp holders used as a warming rack and installed it in energized lamp holders mounted in the integrating sphere. This action resulted in a failed lamp. For facilities re-lamping existing luminaires with LED replacement lamps, it critical that this product-specific information be communicated in order to maintain the life of the product. Additional product marking for specific installation requirements is recommended.

Recommendations

Results from the Consumer Preference and Lamp Characterization studies were used to inform recommendations for the next update of the Voluntary California LED Quality LED Lamp Specification (Specification). The recommendations and justifications for the recommendations are summarized here:

- Expand the eligible light-source language in the Specification to include linear light-source applications, such as the medium bi-pin base (G13) commonly used for T8 and T12 lamps, and the miniature bi-pin base (G5), commonly used for T5 lamps.
- Align the minimum luminous efficacy requirements for the Specification with the 2020 efficacy projections made by the US Department of Energy (DOE). This includes the addition of multiple lamp product categories, as well as an increase in required efficacy.
- Offer the option of color fidelity index (Rf) in addition to the CRI to comply with the color rendering requirements in the Specification.
- Include requirements for the electrical architectures of the linear LED replacement lamps.

Revise the chromaticity and color consistency requirements according to the data in Table 34 and Table 35.

Table 34: Proposed Chromaticity Bins

	2,700 K		4,000 K	
Perception Goal	**CCT Shift**	**D_{uv} Shift**	**CCT Shift**	**D_{uv} Shift**
95% Undetectable	± 22 CCT	± 0.2e-3 Duv	± 43 CCT	± 0.3e-3 Duv

Table 34 shows the proposed chromaticity bins derived from the consumer preference studies.

Source: California Lighting Technology Center

Table 35: Chromaticity Bin Corner Locations for 1964 10 Degree Standard Observer Color Space

	u'				v'			
Corner #	1	2	3	4	1	2	3	4
95% Undetectable	0.2654	0.2635	0.2636	0.2655	0.5276	0.5267	0.5261	0.5270
	x				**y**			
	1	2	3	4	1	2	3	4
	0.4637	0.4601	0.4594	0.4630	0.4096	0.4088	0.4076	0.4084
	u'				**v'**			
Corner #	1	2	3	4	1	2	3	4
95% Undetectable	0.2274	0.2257	0.2260	0.2277	0.5042	0.5027	0.5020	0.5035

Table 35 shows the coordinates of the chromaticity bin corners for the proposed chromaticity bins derived from the consumer preference studies.

Source: California Lighting Technology Center

CHAPTER 5:
LED Product Development

Results from the consumer preference studies for sources and controls, as well as outcomes from the assessment of current commercially available products, were incorporated into multiple product prototypes designed and developed as part of this research program. A summary of key outcomes is provided below.

Table 36: Key Research Outcomes

Outcome	Description
Consumer preferred attributes for LED sources	Minimum 92 R_f ensures most consumers' acceptance regarding color fidelity
	Current ANSI LED color bins are inadequate for accurately characterizing LED color; bins' shape and size must be reconsidered if goal is to ensure LEDs from the same bin appear to be the same color
	Higher R_f translates to lower lumen output needs
	Color fidelity impacts visual acuity for color-based tasks
Current state of LED lamp life	Significant portion (36%) of currently available LED lamps do not meet manufacturer claimed rated life; early failure
	All tested filament style LED lamps failed early; not a stable architecture for ensuring long-term performance
Consumer preferred attributes for lighting controls	Consumers prefer analog control interfaces
	Smart phone apps to control lighting are highly desired, yet current solutions do not deliver common, preferred features
	Digital control interfaces are difficult and frustrating for consumers to use
	Flicker is a significant issue and current CA requirements are insufficient in ensuring consumer acceptance
	Consumers would pay a premium for lighting packages that include compatible sources and controls
Circadian Design	High color fidelity translates to increased melanopic efficacy
Lamp Packaging and Consumer Information	Most warranty information confuses consumers; manufacturers should provide information tailored to commercial and residential applications
	People do not understand life ratings or failure mechanisms

Table 36 shows the key research outcomes used to inform LED product development recommendations.

Source: California Lighting Technology Center

Linear LED Lamps

Linear fluorescent lamps can be replaced with linear LEDs, but large majorities of today's commercially available linear LED lamps do not compete with fluorescent technology in terms of efficacy, light distribution, product cost, and safety.

Linear LED replacement lamps require a different electrical system compared to fluorescent. For fluorescent systems undergoing a retrofit to LED, an electronic driver must be introduced to the system to provide the proper voltage and current for LED operation. Depending on the type of LED replacement selected, different rewiring of the fixture may be needed to accommodate the driver. The electrical differences between linear fluorescent lamps and linear LED lamps constitute an important safety issue facing California consumers, an issue which will severely limit sustained market adoption of linear LED lamp products if unaddressed by a simple and safe linear LED lamp solution.

Performance Specifications for General Purpose Linear LED Lamps

CLTC developed a linear LED lamp product specification that provides guidelines for creating a simple and safe retrofit solution for linear fluorescent retrofit applications. Areas included in the specification include electrical architecture, light source binning, color fidelity, controllability, light output, light distribution, and system efficacy.

The final specification is provided here:

- Electrical architecture, UL Type C
- Light output, bare single lamp light output of 2,250 lumens for 4' lamps
- System efficacy, at least 120 lumens per watt (system includes lamp and driver)
- Distribution, beam angle of at least 220 degrees with no less than 20 percent of total flux emitted in the 100–180 degree zone
- Color fidelity, Rf value greater than 92 +/- 2 measured by IES TM-30-18
- Light source binning, align with findings on just-noticeable difference
- Controllability, minimum dimming level of at least 10 percent power
- All else, meet DLC minimum criteria

Linear LED Lamp Prototypes

Market assessment and prototyping activities demonstrated that, while no commercially available linear LED lamps are available that meet the best-in-class linear LED lamp specification completely, all the criteria was achievable individually using lighting components available today.

Amber Linear LED Lamp Prototype

CLTC developed a linear LED lamp that utilizes amber LED components in place of existing full spectrum, white LED components. The prototype was created by replacing the LED components in a commercially available Type AC linear LED lamp with amber LEDs. After all white LEDs were replaced with amber LEDs the lamp was tested to understand the prototype's electrical and photometric performance.

The prototype was tested with no dimmer and with a dimmer at five output levels (100 percent, 50 percent, 25 percent, 10 percent, and minimum light output). The amber linear LED replacement lamp prototype was powered by a Mark X Powerline ballast. Summary results are provided in Table 37.

Figure 69: Linear LED Replacement Lamp Test

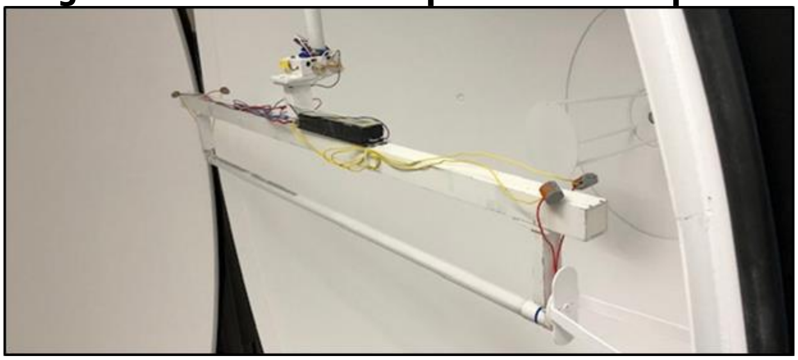


Figure 69 shows linear LED replacement lamp prototype mounted in integrating sphere for photometric and electrical characterization.

Source: California Lighting Technology Center

Dimming performance of the prototype did not satisfy the criteria for the best-in-class linear LED lamp product category. The amber LED used in the prototype had similar power requirements to the white LEDs that they replaced and had even light distribution at full output; however, the amber LED struggled at low dim levels under ~15 percent full output.

The amber linear LED prototype produced 1,386 lumens with an efficacy of 78.35 lm/W at 100 percent output. The total energy draw of the lamp was 17.69 W with a power factor (PF) of 0.998 (Table 37).

Table 37: Summary Performance Results for the Amber Linear LED Lamp Prototype

Power %	Power (Watts)	Light Output (lumens)	CCT (K)	CRI	Efficacy (lm/W)
No Dimmer	17.69	1,386	1,779	55.36	78.35
100	17.67	1,384	1,779	55.38	78.32
50	8.90	765	1,777	55.57	85.93
25	3.94	317	1,774	55.59	80.33
10	1.99	126	1,763	55.12	63.32
Minimum	1.73	93	1,757	54.79	53.54

Table 37 shows the summary performance results for the amber linear LED lamp prototype.

Source: California Lighting Technology Center

Furthermore, testing showed the prototype had uneven light output from individual LEDs when operating at the two lower dimming levels (10 percent and minimum). One of the two circuit legs of the circuit board supplies more power while the other does not receive adequate power. The legs of the LED transition every six LEDs, where six LEDs will be brighter followed by six LEDs that are less bright. This creates the uneven light output at the lower dim levels seen in Figure 70.

Figure 70: Uneven Lighting Distribution at Low Dim Level in the Amber Linear LED Prototype

Figure 70 shows uneven distribution at low dim level in the amber linear LED prototype.

Source: California Lighting Technology Center

Dual-Channel White/Amber Linear LED Lamp Prototype

CLTC also developed a dual-channel linear LED lamp to combine high fidelity white LED and phosphor-converted amber LED into a single product. The design approach for the dual-mode white/amber linear LED lamp prototype was to utilize one lamp with both amber and white channels in the same tube. This dual-channel lamp presents more technical challenges to develop with respect to electrical and thermal design but results in a direct replacement lamp for retrofitting existing fixtures.

The dual-channel linear LED replacement lamp was paired with a 700 mA constant current driver with 0-10 V dimming to power the white and the amber channels individually. Researchers evaluated the prototype under multiple loading scenarios: 100 percent, 20 percent, and 10 percent. The white channel of the dual-channel linear LED prototype produced 2,044 lumens and an efficacy of 83.6 lm/W. In comparison, the amber channel produced 2,020 lumens and an efficacy of 87.4 lm/W. Full results from photometric testing of the dual-channel linear LED prototype are provided in Table 38.

Table 38: Summary Sphere Results for the Dual-Channel Linear LED Prototype

Channel	Power %	Power (W)	Light Output (lumens)	CCT (K)	CRI	Efficacy (lm/W)
White	No Dimmer	24.45	2,044	3,889	92.09	86.60
White	20	4.87	529.7	3,834	92.35	108.77
White	10	2.48	243.8	3,826	92.26	98.31
Amber	No Dimmer	23.11	2,020	1,752	54.62	87.41
Amber	20	4.52	445.4	1,751	55.18	98.54
Amber	10	2.33	201.5	1,751	55.34	86.48

Table 38 shows the photometric and electrical test results for the dual-channel (white and amber) linear LED prototype.

Source: California Lighting Technology Center

Measurements at 100 percent load showed that:

- The white channel of the prototype produced 2,044 lumens and the amber channel produced 2,020 lumens.
- The white channel CRI value was measured at 92, and temperature within the lamp was very stable.
- Efficacy of both channels was improved from the amber linear LED lamp prototype to 83.6 lm/W for white channel and 87.4 lm/W for amber channel.
- Efficacy improved when dimming each LED channel.

Spectrally Optimized LED Lighting

LED sources that produce light in specific parts of the visible spectrum allow for development of light sources with non-continuous spectral power distributions (SPDs). Producing optimized SPDs for specific functions and end-user tasks can maximize the luminous efficacy of emitted radiation. For example, combinations of light intensities from LED sources of different wavelengths can produce an optimized spectrum appropriate for a variety of biological and psychological functions, such as visual activities and circadian rhythms.

CLTC incorporated results from the consumer preference study into the spectrally optimized specification to ensure consumer buy-in of the next generation of LED lighting systems. The specification can be developed due to two technologies that are readily available today:

1. LED light sources able to produce light in specific wavelengths of the visible spectrum.
2. Control systems able to dynamically tune light sources and be customized as needed.

Performance Specification for General Purpose Luminaires

CLTC developed a performance specification for spectrally optimized, general-purpose luminaires. Areas included in the specification include electrical architecture, light source binning, color fidelity, controllability, light output, light distribution, and system efficacy.

Color Binning

Luminaries must be binned in quadrangles of not more than three steps along the Planckian Locus and not more than one and one half (1.5) steps across the Planckian Locus. If the luminaire is tunable and interprets a signal to produce a specific white light, it is recommended that the resultant chromaticity be within this range of the target chromaticity.

Color Rendering Metrics

For general-purpose lighting, luminaires must have a minimum fidelity, R_f, of 92 determined according to CIE 224-17 or TM-30-15.

Visual Acuity

Lighting designed to increase visual acuity should be considered general-purpose lighting for color binning and color rendering purposes. To maximize visual acuity, maximize the ratio of melanopic equivalent lux to photopic lux for the light produced by the luminaire.

Circadian Rhythm Impact

Low-impact circadian affective lighting for nighttime illumination must meet the following requirements:

- Have a ratio of cyanotic equivalent lux to photopic lux less than 25 percent.
- Have a ratio of melanopic equivalent lux to photopic lux less than 10 percent.

An alternate route to providing low-impact circadian affective lighting is to specify that the luminaire be dimmable to 1 percent or less light output. This will enable the luminaire to be included in a lighting design that is able to dim below photopic luminance levels, thereby limiting the impact of the lighting on the circadian system.

It is recommended that low-impact circadian affective luminaires be paired with high-impact affective circadian luminaires for daytime illumination or be capable of providing the same themselves. High-impact circadian affective lighting should be considered general-purpose lighting for color binning and color rendering purposes. To maximize impact on the circadian system, luminaires should maximize the amount of light between 410 nm and 525 nm while still achieving design CCT and color fidelity targets.

Color Tuning

Light Efficacy of Radiation for Non-Tunable Fixtures

To increase the luminaire light efficacy of radiation (LER), the luminaire must limit light produced outside the range of 380 to 780 nm. Due to the overlapping nature of the cone sensitivities, it is not possible to recommend specific wavelength ranges within their sensitivities that can be ignored without potential loss of fidelity.

Control Architecture for Tunable Lighting

Due to lack of precision in analog controls and potential for voltage drop on long analog signal cabling runs, tunable luminaires should be controlled by a digital protocol, such as DMX512 or DALI. Additionally, it may be appropriate to include the ability to control specific characteristics via analog signals such as dimming and CCT.

Proximately Occupied Space Lighting for Tunable Luminaires

To enable proximately occupied space lighting, the luminaire must be tunable in such a way that the same chromaticity can be reached in multiple ways, one of which maximizes color fidelity and one that maximizes the efficacy of the luminaire.

The luminaire must be able to be switched between the two modes. The commissioning documentation should explicitly list how to switch between modes for commissioning and operation audiences. The default mode for the luminaire should be the occupied state.

Spectrally Optimized Luminaire Prototypes

CLTC developed spectrally optimized luminaire prototypes based on the aforementioned performance specification. The prototype luminaires include:

- General features, which make them capable of being optimized for SPD in real time or in-situ
- High-fidelity, red-enhanced diodes for enabling enhanced color discrimination in dermatology offices

- A "Zeitgeber" control strategy for a multi-spectral luminaire to support the 'sensation of the passage of time and connection with the outside world' in enclosed spaces
- A dual-channel approach

CLTC performed application-specific optimizations using a custom algorithm to specify the SPD of each prototype fixture. The optimizations focused on stimulating specific biological and/or psychological responses in humans.

Evaluations of all spectrally optimized prototype fixtures were conducted in the laboratory using a variety of test methods.

Photometric testing of the spectrally optimized luminaires was performed in an integrating sphere. The purpose of the photometric testing was twofold:

1. Gather the SPD of each LED channel to use in the matching algorithm's calculations; and
2. Validate the SPD measurements created by a custom algorithm

The luminaire was mounted in an integrating sphere, as shown in Figure 71. The integrating sphere's vertical support was adjusted so that the luminaire was positioned at the midpoint of the sphere. A 600 W auxiliary lamp and a high-sensitivity multi-channel spectrometer were mounted at separate ports. Power was supplied to the luminaire and the auxiliary lamp by programmable AC source.

Figure 71: The Spectrally Tunable Luminaire Mounted in an Integrating Sphere

Figure 71 shows the spectrally tunable luminaire mounted in the integrating sphere for photometric and electrical characterization.

Source: California Lighting Technology Center

The luminaire was characterized using the following test protocol:

1. Set the luminaire's light output to a white light (approximately 4,000 K). Allow the LED luminaire to stabilize thermally according to IES LM-79-08.
2. Set all LED channel intensities to zero. Set channel of interest to 100 percent intensity. Scan and collect the spectral data of the LED channel.

3. Scan and collect the spectral data of the LED channel at 50 percent, 25 percent, 10 percent, 5 percent, and 1 percent intensity. Do not perform IES LM-79-08 stabilizations in between scans.
4. Reset the luminaire to a white light and stabilize according to IES LM-79-08.
5. Repeat the process in Steps 1 through 4 for each of the eight LED channels.

The SPDs of each channel were used in a custom spectral matching algorithm written in the MATLAB programming language. With the experimental values incorporated into the matching algorithm, the code was run several times while varying the photometric inputs. The purpose of this exercise was to confirm that the light produced by the tunable luminaire matched the target photometric properties. The photometric inputs included permutations of CCT, D_{UV}, CRI, melanopsin expression, and luminous flux to test the complete functionality of the code.

The protocol for the test points was similar to the procedure outlined above with a few modifications. First, it was not necessary to repeat the auxiliary correction step because the luminaire remained fixed in the integrating sphere. Second, spectral data was collected from each test point in succession after a single stabilization at 4,000 K.

General Spectrally Optimized Luminaire

Various SPD optimizations were tested to evaluate the results of the spectral matching algorithm. The results from the integrating sphere measurements are presented in Table 39 and organized by optimization factors. Each row in Table 39 through Table 42, below is a photometric parameter used as an input in the matching algorithm. The algorithm attempts to match the photometric parameter while optimizing CRI.

Table 39: Tested Performance of Various Spectral Designs Optimized for CRI Considering CCT Matching with CRI Optimization
CRI > 94.9, DUV = 0.000, Luminous Flux = 1500 lm

Target	Measured			
CCT	CCT	D_{UV}	Lumen	CRI
2000	2003	0.0002	1502	96.5
3000	3001	0.0001	1503	97.2
4000	4001	0.0003	1503	96.9
5000	4998	0.0002	1502	96.9

Source: California Lighting Technology Center

Table 40: Tested Performance of Various Spectral Designs Optimized for CRI Considering D_{uv} Matching with CRI Optimization
CRI > 65, CCT = 3000 K, Luminous Flux = 1500 lm

Target	Measured			
D_{UV}	D_{UV}	CCT	Lumen	CRI
0.010	0.0104	3006	1501	78.2
0.005	0.0055	3006	1500	78.1
0.001	0.0015	3012	1500	78.0
-0.001	-0.0007	3013	1500	77.9
-0.005	-0.0045	3014	1500	77.9
-0.010	-0.0097	3009	1501	77.7

Source: California Lighting Technology Center

Table 41: Tested Performance of Various Spectral Designs Optimized for CRI Considering Melanopsin and CRI Optimization
CRI > 70, CCT = 3000 K, D_{UV} = 0.000, Luminous Flux = 1500 lm

Target	Measured				
Melanopsin	CCT	D_{UV}	Lumen	CRI	Melanopsin (W)
Maximized	3009	0.0005	1501	71.0	1.34
Minimized	3030	0.0008	1498	71.7	0.97

Source: California Lighting Technology Center

Table 42: Tested Performance of Various Spectral Designs Optimized for CRI Considering Melanopsin and CRI Optimization
CRI > 70, CCT = 4000 K, D_{UV} = 0.000, Luminous Flux = 1500 lm

Target	Measured				
Melanopsin	CCT	D_{UV}	Lumen	CRI	Melanopsin (W)
Maximized	4016	0.0003	1499	73.7	1.67
Minimized	4002	0.0003	1498	87.7	1.25

Source: California Lighting Technology Center

The spectral matching algorithm met the CCT targets with very high accuracy while keeping D_{UV} and luminous flux constant. There was greater discrepancy between the spectral matching algorithm and the experimental data when the target D_{UV} was changed while keeping CCT and luminous flux constant.

The spectral matching algorithm successfully optimized the CCT and D_{UV} test points for the given CRI metric. During the CCT matching, the algorithm consistently found a solution yielding a CRI greater than 94.9. Likewise, the CRI values in the D_{UV} matching test exceed the CRI limit of 65.

Red-Enhanced Luminaires for Dermatology Applications

A commercially available fixture was retrofitted with three sets of LED chips to create three different spectral distributions while maintaining the same CCT and light output. The three sets of LED chips were controlled with separate switches to allow for three light scenes. Prior to installation in the test room, the luminaire's photometric and electrical performance was evaluated at the CLTC laboratory to verify the photometric power, CCT, light output, and SPD.

A preliminary evaluation of the dermatological benefits of the three LED channels were conducted at CLTC using six CLTC employees. The luminaire was mounted in the center of a room with a mirror, small desk, desk chair, and three control switches (Figure 72).

Each participant completed two tests. During the first test, the test administrator set the lighting in the room to each of the three different light settings and participants evaluated their own complexion, hands, and arms using a Likert scale response.

During the second test, participants were allowed to flip through each of the three light settings on their own and asked to evaluate the color of their complexion, hands, and arms. The questions for the second test were similar in topic to the first test. However, each of the light settings were ranked one, two, or three according to their comparative performance.

Figure 72: Skin Inspection Test (Left) Luminaire Illuminates the Task Space (Right)

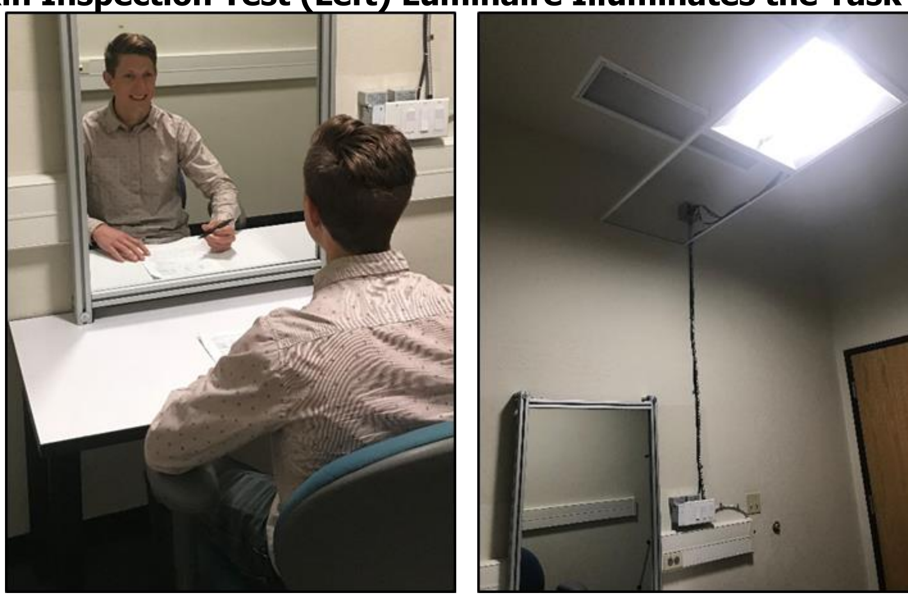


Figure 72 shows a CLTC researcher participating in the skin inspection test (left) and the ambient luminaire in the space above the mirror (right).

Source: California Lighting Technology Center

Red-Enhanced Luminaires

Results from the participants at CLTC showed that the 95 CRI and 95 CRI+Red light settings were more effective for inspecting their skin than the 82 CRI light setting. However, conflicting answers were obtained to what light source creates the most color contrast, is the most natural, performs the best, and ultimately is most desired for use in participant's homes.

Participants indicated that the 95 CRI+Red light provided them with the most color contrast when they changed back and forth between the light sources themselves, but when the same participant inspected their skin in each of the three light settings randomly, they found the 95 CRI+Red and the 95 CRI light to have the same color contrast.

Commercialization Activities

CLTC worked with multiple industry partners to commercialize the spectrally optimized luminaires and components developed over the duration of this effort.

Commercialized Luminaire for Dermatology Study

CLTC collaborated with two manufacturers to develop single-die emitters with the red-enhanced phosphor and integrate the sources into existing product lines. The commercialized fixture for the dermatology study is a modified tunable white 2'x4' recessed troffer, shown in Figure 73. The team also developed a three-channel LED board populated with three different mid-powered LEDs with the following specifications for each channel:

- Channel A: 32 W, 4300 lm, 80 CRI
- Channel B: 42 W, 4600 lm, 97 CRI
- Channel C: 50 W, 4500 lm, 95 CRI (red enhanced)

Figure 73: Three-Channel Luminaire

Figure 73 shows a three-channel luminaire where each channel varies in wattage, luminous output and CRI.

Source: California Lighting Technology Center

Dual-Channel Circadian Lighting Fixtures

CLTC collaborated with the same fixture manufacturer to develop a health-centric circadian lighting system. The manufacturer introduced a phosphor-converted amber LED channel into their healthcare product line. The circadian lighting fixture design consists of two LED channels: 3,500 K and PC amber. These are on two separate arrays, as shown in Figure 74. The goal of this collaboration was to develop a lighting system that would minimize the occupant's circadian response from exposure to blue light in the morning and evening. The development team also produced a dual-channel circadian lighting fixture for corridor applications (Figure 75). This fixture includes two separately controlled LED arrays, one with white diodes and the other with phosphor-converted amber diodes. This fixture is now commercially available.

Figure 74: White and PC Amber Arrays Installed in the Dual-Channel Circadian Lighting Fixture

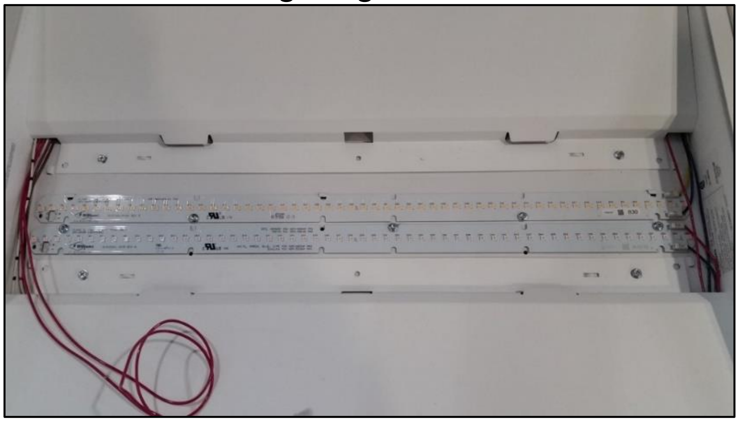


Figure 74 shows white and PC amber arrays installed in the dual-channel circadian lighting fixture.

Source: California Lighting Technology Center

Figure 75: Recessed Dual-Channel Circadian Lighting Fixture for Corridor Applications

Figure 75 shows a recessed dual-channel circadian lighting fixture for corridors.

Source: California Lighting Technology Center

CHAPTER 6: Technology Transfer

A critical component of successful technology transfer is clearly articulating all of the additional value associated with use of high-efficiency LED lighting technology that goes beyond energy savings. Improved visual environments, color discrimination, product longevity, controllability, sustainability, and ease-of-use all add value.

The overall goal of the *New Generation of LED Light Sources* was to promote best practices for the construction and operation of sustainable commercial- and residential-lighting systems. Best practices leverage energy-saving technology and additional benefits from their use. Tools that communicate the benefits and better ensure continued product use such as design guidelines, lighting standards, and appliance regulations help to assist and nurture progressive product concepts by making them part of the mainstream built environment. Additionally, new ideas and application of emerging technologies help drive new and insightful designs, which ultimately lead to wider adoption of progressive building standards and regulations. This section provides an overview of the technology-transfer activities that have reinforced the benefits of existing regulations and introduced new opportunities to improve California's new and existing buildings.

New Products and Systems

CLTC identified new commercial opportunism and developed products that will form the basis of energy-efficient lighting designs for the next decade. Novel concepts were demonstrated in working environments with UC campus and UC Medical Center partners. Many of its research activities were part of the pre-commercial development cycle and included collaboration with multiple industry partners, including manufacturers and early-adopting host sites.

Specific examples illustrating CLTC's technology transfer activities are provided in the following sections including color-quality evaluations, application of laboratory outcomes to commercial applications including healthcare, launch of the Million LED Challenge, and development of exterior lighting color-quality standards.

Future Regulations, Standards, and Guidelines

CLTC developed and tested new lighting technologies and strategies with the potential to integrate and support future updates to California's Building Energy Efficiency Standards (Title 24), Appliance Efficiency Regulations (Title 20), and the Voluntary California Quality LED Lamp Specification. Specifically, CLTC leveraged the University of California (UC) campus network, UC Medical Center network, the State of California's Department of General Services, the California State University (CSU) network, and the Foundation for California Community Colleges as a living laboratory for testing new LED lighting strategies and technologies.

Current Applications

CLTC technology transfer activities supported the necessary foundation and development activities associated with updating the 2016 and 2019 Energy Standards (Title 24), various updates of the Appliance Efficiency Regulations (Title 20), and the Voluntary California Quality LED Lamp Specification. Outcomes are expected to influence additional updates to the energy standards as part of the 2022 rulemaking process.

Color Quality Study

CLTC's laboratory-based, user-preference studies that evaluated preferences for specific lighting characteristics and functional attributes formed a significant foundational element of the program's product development portfolio. As previously discussed, CLTC completed a series of experiments with approximately 200 study participants to understand consumer preferences for a variety of performance metrics and product attributes including color, warranty, dimming functionality, lamp shape, and product packaging.

With respect to color, a key research objective was to understand perceptible differences and preference between high- and low-CRI-light sources when used in a variety of applications. Studies consistently demonstrated that high color quality provided by broad-spectrum light sources is preferred. Additionally, related lighting control evaluations indicated user preferences for reduced light levels when using high fidelity sources. This demonstrates the potential for tailoring spectrums to achieve additional energy savings.

Looking at existing programs and policies, CLTC's research reinforces the foundational concept behind the Voluntary California Quality LED Lamp Specification. The Specification is based on the idea that improving overall lamp quality translates to increased initial and sustained use of LED lighting, which in turn creates long-term energy benefits for California. CLTC's research outcomes provide direct data to support this position. Additionally, this research supports the high color-quality specification in the current Energy Standards, joint appendix 8 (JA8), which mandates high-efficacy, high color-quality light sources for residential buildings. These regulatory activities have also contributed to updates to the Appliance Efficiency Regulations (Title 20), which add color-quality requirements for certain lamp products sold in California, starting in 2016.

Each of these regulations and requirements has led to the development of a broad array of high-quality products for California's residential lighting market. This includes a variety of medium-screw-base products, retrofit kits, and downlights. For example, a recent Department of Energy report on the LED marketplace indicated that over 50 percent of today's retrofit-kit downlight products are between 90-100 CRI (R_a) nationwide.[10] CLTC considers this trend one of the major successes of its color research portfolio. CLTC continues to refine color-quality specifications focused on application-specific, color-rendering requirements and color-space definitions.

[10] US Department of Energy. *CALiPER Snapshot Downlights Report*. June 12, 2017.

Figure 76: Percent of Downlight Products by CRI

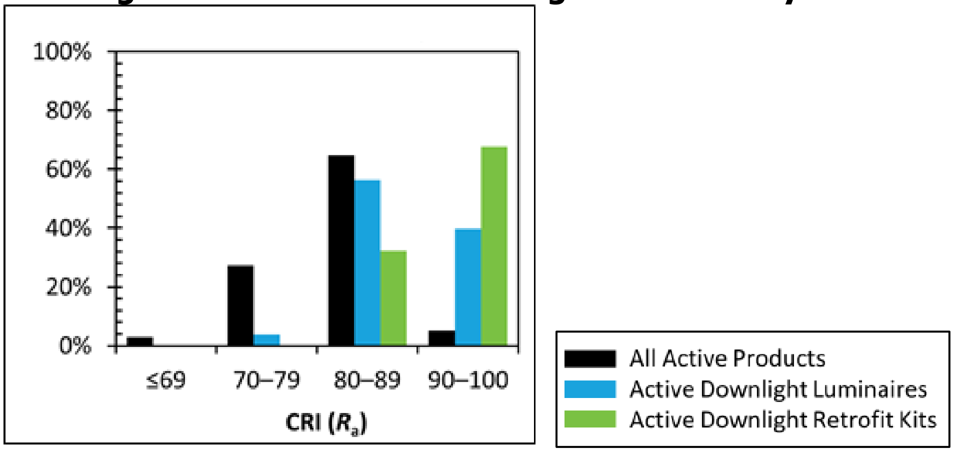


Figure 76 shows that over 50 percent of today's retrofit-kit downlight products are between 90-100 CRI (R_a) nationwide.

Source: US Department of Energy. CALiPER Snapshot Downlights Report.

Lighting Quality for Targeted Markets

High-quality color can significantly affect LED market adoption in commercial applications such as healthcare where few color quality requirements currently exist. In these target markets, workers depend heavily on visual acuity so quality lighting is paramount. The impact of such future regulations, however, can be estimated by looking to the residential sector, where quality guidelines have positively affected consumer satisfaction and led to increased use of energy-saving LED alternatives. For example, residential stakeholders can achieve deep, persistent energy savings by using Title 24-compliant, JA8 high-color quality light sources as replacements for incandescent and halogen. Standards and required labeling make these products easy to find and occupants are assured that their use will provide good visual environments with respect to light quality and color.

To help increase market adoption of LED sources among target commercial applications, CLTC developed and demonstrated a series of LED lighting solutions to evaluate and document its non-energy benefits. When combined with well-documented information on energy savings, validated non-energy benefits will help increase the rate of market adoption of LED technology.

CLTC focused on documenting the benefits of improved visual environments in medical, healthcare, and educational environments. Each is an application that relies heavily on visual perception and acuity to achieve successful outcomes. For its research, CLTC selected color rendering as its primary performance attribute to evaluate. CLTC worked with UC Davis Student Housing and the UC medical centers to implement solutions with high color rendering and collect feedback from users. Specifically, work was conducted with UC Irvine's dermatology department, where clinical decisions are often based on or directly impacted by the perceived color of objects (e.g., test samples, skin color).

CLTC developed a comprehensive series of experiments and demonstrations with UC Irvine clinical staff and researchers to evaluate the impacts of a high-color-quality design strategy. The ultimate objective of these studies was to provide empirical evidence to support a statewide lighting specification for medical applications.

Within a medical context, a specification must include:

- Naturalness: The lighting environment should render colors consistently as compared to incandescent or daylight sources.
- Color discrimination: The lighting environment should allow clinicians to discern small color differences to aid diagnosis of skin conditions.

CLTC developed and leveraged a relationship with the University of California's Office of the President via its Carbon Neutrality Initiative to deploy a color-quality lighting specification for its UC medical centers. This healthcare demonstration work is also an example of how the specification can translate into ongoing improvements to California's energy standards as they relate to healthcare facilities and the need to balance energy goals with visual needs.

Healthcare Applications

CLTC collaborated with the UC Irvine Department of Dermatology and facilities team to evaluate the impact of color fidelity on diagnoses and evaluations related to common skin conditions and the overall visual comfort of patients and staff working under various color-fidelity environments. Researchers developed two double-blind experiments to answer the following questions:

1. Is the low- or high-color fidelity more effective for skin evaluations?
2. Do different color-fidelity light sources affect the visual comfort of dermatologists and patients?
3. Is there any significance between alopecia skin evaluations and other skin conditions evaluated under the same light sources?

Study Hypothesis

It was hypothesized that the high-color-quality light settings would be perceived as more natural, effective, and comfortable (and therefore preferable) than the low-color-quality light settings. Additionally, it was hypothesized that the lighting performance evaluations collected while viewing a patient with Alopecia would be similar to those of patients with red skin conditions, but different from people with other skin conditions.

Study Design

The first color-fidelity experiment was a longitudinal study in which two to thirteen dermatologists split into small groups and visited patients during the dermatology department's grand rounds. Grand rounds traditionally represent a biweekly group evaluation of a patient with a medical condition that requires extra thought and attention. In this case, two patients were viewed during three separate grand rounds that occurred at least one month apart. Dermatologists used both low- and high-color-fidelity light settings to inspect at least one of the two patients located in the patient's assigned room.

The second color-fidelity experiment was a longer longitudinal study in which three dermatologists evaluated the lighting during a subset of their normal daily patient visits. Dermatologists individually evaluated the lighting during between seventeen and twenty-three patient consultations over the course of several months.

Each experiment completed by a dermatologist was led by a test administrator to ensure that a repeatable procedure was followed, provided in Appendix 7. The test administrator controlled the light settings and read the script as the test progressed.

Before the dermatologist(s) viewed a patient under each light setting, a 30-second adaptation period was required. During that time, the dermatologist was asked to look away from the patient to allow their eyes to adjust to the new SPD of the light setting. Then, dermatologists inspected their patient's skin condition and evaluated the lighting performance.

The test administrator would then call out the light setting being used, "Light Setting A" or "Light Setting B." Light settings were shown in a randomized order according to a patient number. Although "Light Setting A" was called out, it may correspond to either the high-color-fidelity light or the low-color-fidelity light. No light settings were repeated.

After viewing the patient's skin while illuminated with Light Setting A or B, dermatologists were asked to rate the performance of the light setting on a Likert scale from zero to four. Dermatologists were provided the following questions:

- How natural does the patient's skin appear under this light setting? (Note: Skin color appears most natural under sunlight)
  - Unnatural, Somewhat Natural, Neutral/ Unsure, Somewhat Natural, Natural
- How effective is this light setting for inspecting the patient's skin condition?
  - Not effective (0) – Very Effective (4)
- How comfortable is this space when illuminated with this light setting?
  - Uncomfortable, Somewhat Comfortable, Neutral/ Unsure, Somewhat Comfortable, Comfortable

Patients were also asked to rate the visual comfort of the dermatology room while illuminated with this light setting and answer the same comfort question as the dermatologist(s).

Next, the test administrator instructed the dermatologist(s) to look away from the patient for another 30- second adaption period after the light setting was changed. Then, the dermatologist was asked to evaluate the new light setting. After answering the naturalness, effectiveness, and comfort questions, the dermatologists were asked about their lighting preferences with the following question:

- What light setting would you like to use for the rest of your consultation with this patient?
  - Open response

Again, patients were asked to rate the visual comfort of the dermatology room and answer the same comfort question the dermatologist was asked.

Experimental Setup

Lighting Systems

Researchers installed prototype LED luminaires to evaluate the impact of color fidelity on the dermatologists' clinical evaluations and patient's comfort. Each luminaire housed a set of low-color-fidelity (82 CRI) LED sources and a set of high-color-fidelity (97 CRI) LED sources, each with the same CCT. Three luminaires were tested at CLTC, prior to their use in this study, to determine the SPD of each channel and allow for normalization of the photopic light output of low- and high-CRI channels. The average SPD for each channel is shown in Figure 77.

Figure 77: Spectral Power Distribution of the Two Channels of LEDs in the Luminaire Prototype

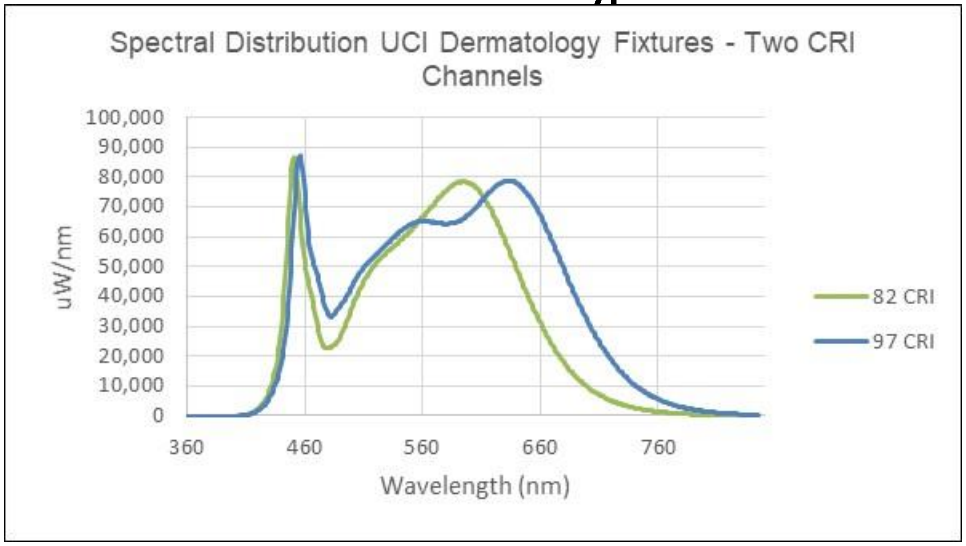


Figure 77 shows the spectral power distribution of the two-channel LED luminaire installed at the UC Irvine clinic.

Source: California Lighting Technology Center

Thirty-two multi-channel fixtures were installed in 15 rooms within the UC Irvine Gottschalk Medical Plaza Dermatology Clinic. A floorplan of the installed lighting is shown in Figure 79.

Figure 78: The Color Fidelity Study Encompassed 15 Rooms at the UC Irvine Gottschalk Medical Plaza's Dermatology Clinic

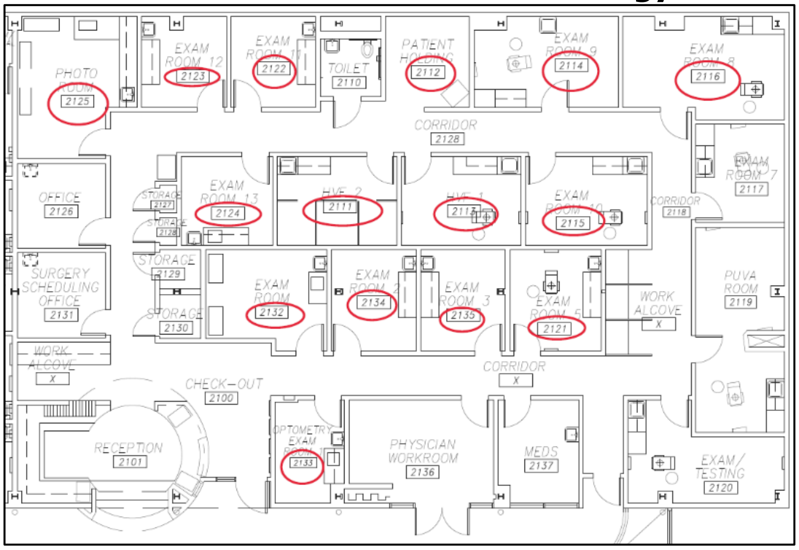


Figure 78 shows the locations where the two-channel luminaires were installed at the UC Irvine clinic, circled in red.

Source: California Lighting Technology Center

Thirteen of the rooms have two 2-foot by 4-foot recessed troffer luminaires. The thirteen rooms have a similar layout as the room shown in Figure 79. The remaining two rooms have a slightly different layout with three luminaires.

Figure 79: Patient Room Retrofitted With the Two-Channel LED Luminaire

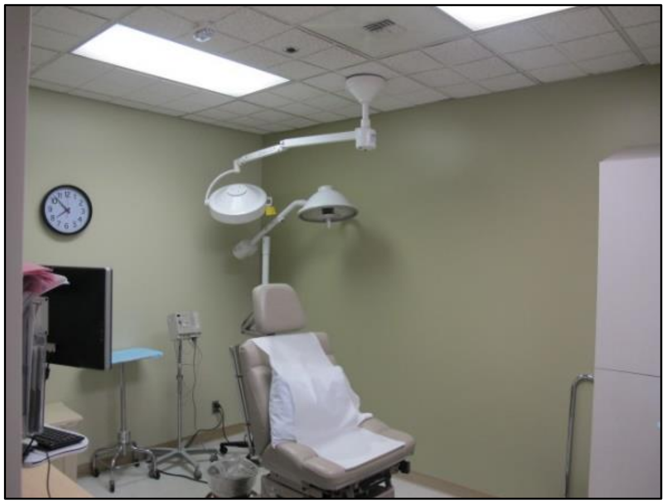


Figure 79 shows a patient room retrofitted with the two-channel LED luminaire.

Source: California Lighting Technology Center

Study Participants

Participants in both experiments included both dermatologists and patients. Of the 50 useable dermatologist responses collected from the first experiment's grand rounds, the reported age of respondents ranged from 24 to 64 years, with an average of 35 years. Thirty-six respondents were female and 14 were male. More than half, 29 of respondents, answered "Yes" to wearing glasses or correctional lenses, leaving 21 who marked "No" and did not wear glasses or correctional lenses.

Two patients were seen during each grand rounds lighting experiment, but the number of dermatologists who inspected these patients varied from two to thirteen. During the first grand rounds, both patients had red rashes. More specifically, one patient had atopic dermatitis while the other patient had psoriasis. Eleven and 13 dermatologists, respectively, viewed these patients and participated in the lighting experiment. One month later during the second grand rounds, nine dermatologists inspected one patient with alopecia areata and nine dermatologists inspected another patient with ephelides and participated in the lighting experiment. During the third grand rounds, two months after the second grand rounds, dermatologists inspected two patients with cosmetic conditions. Eight dermatologists viewed the first patient and two dermatologists viewed the second patient.

Of the three dermatologists who participated in the second experiment, the reported age of respondents ranged from 41 to greater than 60 years of age for an average age of greater than 54 years. One dermatologist was female, while the other two were male. Two dermatologists reported wearing glasses or correctional lenses, leaving one who did not. None of the dermatologists reported being colorblind.

In the second experiment, lighting evaluations were completed during 60 patient visits. A quantity of 23, 17 and 20 of the responses were collected from dermatologist one, two and three respectively. The patients had a wide variety of diagnosis including acne, alopecia, areas of cosmetic concern, moles, psoriasis, rosacea, and rashes for people with various Fitzpatrick skin types or shades of skin.

Among the patient sample population, there were 58 useable responses. The reported age of patient respondents ranged from 15 to 85 years of age with an average of 48 years. Thirty-five respondents were female and 23 were male. More than half, 33 of respondents answered "Yes" to wearing glasses or correctional lenses, leaving 25 who marked "No" and did not wear glasses or correctional lenses.

Results

In the first experiment, 55 responses were collected from the UC Irvine Dermatology Department's grand rounds. These responses came from dermatologists and other medical professionals with various levels of clinical experience including medical students, interns, residents, fellows, and others. Five responses were removed because four people marked "Other" and one person reported being colorblind. It is assumed that the participants who marked "Other" were not dermatologists. In addition, it should be noted that one of the respondents did not answer the naturalness question.

Six patients were seen by small groups of dermatologists during the first lighting experiment. The average lighting evaluation rating for each patient is shown in Table 44.

Table 43: Average Ratings of Dermatologists Evaluating the Lighting Performance

Grand Round (GR) No. – Patient Diagnosis	Color Fidelity	Natural-ness Rating (0-4)	Effective-ness Rating (0-4)	Comfort Rating (0-4)	Percent of Times Selected as Preferred Light for Consultation[1] (%)
GR1 – Atopic Dermatitis (N=11) [2]	Low (82 CRI)	1.9	2.2	2.8	25
	High (97 CRI)	2.7	2.8	3.1	75
GR1 – Psoriasis (N=13)	Low (82 CRI)	2.4	2.5	2.7	33
	High (97 CRI)	3.4	3.0	3.2	66
GR2 – Alopecia Areata (N=9)	Low (82 CRI)	1.4	2.0	2.2	0
	High (97 CRI)	2.7	2.8	3.0	100
GR2 – Ephelides (N=9)	Low (82 CRI)	2.4	2.5	2.5	33
	High (97 CRI)	2.5	2.6	2.4	66
GR3 – Cosmetic (N=8)	Low (82 CRI)	1.9	2.4	3.3	0
	High (97 CRI)	3.0	3.3	3.4	100
GR3 – Cosmetic (N=2)	Low (82 CRI)	3.5	3.5	4.0	100
	High (97 CRI)	3.0	3.5	3.5	0

[1] This percentage is based upon only participants that selected the high color fidelity light setting or the low color fidelity light setting. Missing responses or other responses are not included in this calculation.

[2] Number of dermatologists that inspected this patient and completed the lighting survey.

Source: California Lighting Technology Center

To compare the perceived performance of each lighting color fidelity during the first experiment, the average performance rating for each light source is shown in Table 44. The average of 50 dermatologist-performance ratings for each color fidelity indicate that the high-color-fidelity light caused patient's skin to look more natural, was more effective, and thus more preferred for use for the rest of the consultation.

Table 44: Average Ratings of 50 Dermatologists Evaluating the Lighting During Grand Rounds in the First Experiment

Experiment No.	Color Fidelity	Naturalness Rating (0-4)	Effectiveness Rating (0-4)	Comfort Rating (0-4)	Percent of Times Selected as Preferred Light for Consultation[1] (%)
1	Low (82 CRI)	2.1	2.4	2.7	29
	High (97 CRI)	2.9	2.9	3.0	71
	P-value[2]	0.000	0.000	0.075	—

[1] This percentage is based upon only participants that selected the high color fidelity light setting or the low color fidelity light setting. Missing responses or other responses are not included in this calculation.

[2] A two sample paired t-test was used to evaluate whether the mean scores for each light setting would reject the null hypothesis. The null hypothesis in this case is that there is zero difference between means. This analysis was evaluated using a 95 percent confidence interval, thus all p-values less than 0.05 are considered statistically significant and will reject the null hypothesis.

Source: California Lighting Technology Center

In the second experiment, three dermatologists combined completed lighting evaluations during 60 patient visits. To compare the perceived performance of each lighting color fidelity during the second experiment, the average performance rating for each light source is shown in Table 45.

Table 45: Average Rating for Dermatologists Evaluating the Lighting and During Patient Consultations in the Second Experiment

Experiment No.	Color Fidelity	Naturalness Rating (0-4)	Effectiveness Rating (0-4)	Comfort Rating (0-4)	Percent of Times Selected as Preferred Light for Consultation[1] (%)
2	Low (82 CRI)	1.8	1.9	1.8	0
	High (97 CRI)	3.3	3.4	3.3	100
	P-value[2]	0.000	0.000	0.000	—

[1] This percentage is based upon only participants that selected the high color fidelity light setting or the low color fidelity light setting. Missing responses or other responses are not included in this calculation.

[2] A two sample paired t-test was used to evaluate whether the mean scores for each light setting would reject the null hypothesis. The null hypothesis in this case is that there is zero difference between means. This analysis was evaluated using a 95 percent confidence interval, thus all p-values less than 0.05 are considered statistically significant and will reject the null hypothesis.

Source: California Lighting Technology Center

The average of 60 performance ratings for each color fidelity indicate that high-color-fidelity light caused patients' skin to look more natural and was more effective, more visually comfortable, and preferred for the rest of the consultation. It should be noted that one of the respondents did not answer the color fidelity-preference question.

In the second experiment, 60 dermatology patients evaluated the comfort of their rooms while illuminated with each light setting in this study. Two responses were removed because these patients indicated being color blind. To compare the perceived visual comfort of each lighting color fidelity, the average of 58 patient comfort ratings for each light source is shown in Table 46. The average ratings for each color fidelity indicates that high-color-fidelity light was more visually comfortable.

Table 46: Average Rating for Dermatology Patients Evaluated the Lighting During Their Consultations in the Second Experiment

Experiment No.	Color Fidelity	Comfort Rating (0-4)
2	Low (82 CRI)	2.5
	High (97 CRI)	2.6
	P-value[1]	0.735

[1] A two sample paired t-test was used to evaluate whether the mean scores for each light setting would reject the null hypothesis. The null hypothesis in this case is that there is zero difference between means. This analysis was evaluated using a 95 percent confidence interval, thus all p-values less than 0.05 are considered statistically significant and will reject the null hypothesis.

Source: California Lighting Technology Center

Discussion

Both experiment one and two confirm the hypothesis that the high color fidelity lighting (97 CRI) outperforms low color fidelity lighting (82 CRI) in dermatology offices concerning naturalness and effectiveness. Dermatologists preferred to use high color fidelity lighting for the remainder of their consultations. More specifically, there is statistically significant evidence on a 95 percent confidence interval that the average rating for high color fidelity lighting is different from the low color fidelity lighting and is perceived as more natural and effective. Additionally, both experiments confirm that the high color fidelity sources were chosen more times than the low color fidelity sources. Seventy-one percent and 100 percent of dermatologists selecting high color fidelity lighting for the remainder of the consultation in the first and second experiments respectively.

Both experiments fail to confirm the hypothesis that high color fidelity improves the visual comfort of a dermatology office. Although both experiments indicate a higher average comfort rating for the high color fidelity lighting as compared to the low color fidelity lighting, only the dermatologists in the second experiment indicated that there is a statistical difference between these averages according to a two-sample paired t-test using a 95 percent confidence interval. The dermatologists in experiment one and the patients in experiment two fail to meet the maximum p-value of 0.05, therefore there is no statistical difference between the means of the high and low color fidelity light channels for visual comfort. It should be noted that the average comfort rating for the high and low color fidelity lighting in the first experiment might have been statistically different if there was a larger sample size.

Experiment 1 partially confirms the hypothesis that the lighting performance evaluations collected while viewing a patient with Alopecia would be similar to that of patients with red skin conditions. A nonparametric Mann-Whitney and Kruskal-Wallis test were used to determine whether there was a significant difference between means and determine if one of the samples comes from a different population for lighting performance ratings while inspecting patients during the first grand rounds. Each patient from the first grand rounds was compared to the patient with Alopecia on a 95 percent confidence interval. Only the naturalness rating of the low color fidelity setting for the second patient in the first grand rounds and the patient with Alopecia are statistically different.

Experiment 1 fails to confirm the hypothesis that the lighting performance evaluations collected while viewing a patient with Alopecia would be different from people with skin conditions that are not red. The same statistical approaches described above were used to determine if there were a significant difference between means and determine if one of the samples comes from a different population for patients diagnosed with Alopecia when compared to patients from the third grand rounds and the second patient in the second grand rounds on a 95 percent confidence interval. However, the comfort rating of the low color fidelity setting and the preference selection for the second patient within the third grand rounds and the patient with Alopecia are statistically different. Additionally, the naturalness rating of the low color fidelity setting and the preference selection for the second patient within the second grand rounds are statistically different from the patient with Alopecia.

Conclusions

Results from both double-blind color fidelity lighting experiments indicate that dermatologists in a clinical setting prefer high color fidelity light sources to low color fidelity light sources. On average, dermatologists indicated that high color fidelity light is more effective for skin evaluations and allows skin to appear more natural than low color fidelity light. However, both dermatologists and patients indicated that color fidelity did not significantly improve their visual comfort.

It was also found that lighting performance ratings for Alopecia skin conditions are similar to other skin conditions according to the six-patient sample size in this study; however, the preferred light settings for specific skin conditions can vary.

Future Work

The comfort and effectiveness of LED light sources are important factors in the market adoption and retention of LED products. CLTC is interested in extending color fidelity studies to other healthcare applications such as cardiology, neonatal and intensive care units (ICU) among others. Additionally, CLTC is interested in gathering lighting performance evaluations for specific skin conditions like cyanosis for example and from larger samples of people.

Education Facilities

CLTC also explored enhanced color in educational and teaching environments to determine if enhanced and/or improved lighting supports learning objectives. CLTC initially explored the application of high color quality in the teaching of art and design at the university level. CLTC had discussions with individuals in the design and art environments who indicated strong preference for full spectrum white sources and higher color rendering. A series of full color displays were developed to display the color quality differences.

Moving forward, CLTC will be launching a series of research demonstrations with two UC campuses to explore the application of enhanced-color light sources in teaching environments (studios, labs, and classrooms). This development has garnered significant interest within the academic community and a classroom initiative with University of California is being put in place to transform this marketplace to high-color quality. CLTC anticipates broad statewide support on this through the University of California Million LED Challenge.

Million LED Challenge

To support the rapid uptake of high-color-quality lighting systems, CLTC launched a program called the Million LED Challenge, which seeks to align the state's universities, colleges, and the Department of General Services into a purchasing collaborative to negotiate bulk pricing. The objective of the Million LED Challenge is to accelerate uptake of the products in the market in preparation for the inclusion of these concepts in the regulatory process. The first phase of the Million LED Challenge leveraged the requirements from the Voluntary California Quality LED Lamp Specification, Version 3.0 for medium screw base lamps.

Now, the program is being expanded (Phase 2), with a focus on educational and commercial market spaces that use linear LED retrofit solutions. The performance requirements for Phase 2 were informed by the technical research conducted as part of this effort. CLTC is working actively with the Title 20, Title 24, and Voluntary California Quality LED Lamp Specification teams at the California Energy Commission to ensure appropriate and supportive alignment for future specifications and regulations.

This program is one of the best examples of how research, specifications, codes, and standards all serve to support technology transfer.

Exterior Lighting Color Quality and its Transition to California's Green Building Standards

CLTC participated in the 2019 Title 24, Part 11 CALGreen code-development process to incorporate lower CCT standards for certain outdoor lighting applications. CLTC provided key testimony and support during public meetings in support of this specification.

Considerable scientific data currently exists indicating that light at night can be a significant issue in terms of circadian disruption leading to poor health and wellness outcomes. Two well-recognized organizations, the International Dark Sky Association and the American Medical Association (AMA) have adopted recommendations for 3,000 K outdoor lighting. After much criticism and discussion, the AMA reaffirmed this position.

In terms of near-term practical experience with the issues associated with color temperature, CLTC collaborated with the City of Davis, by request, in its streetlight retrofit effort to move from high-pressure sodium (HPS) to LED technology. This relighting effort initially focused on higher color temperatures (4,000/4,500+ K) driven largely by energy savings considerations. As this relighting effort moved forward, significant issues arose due to glare, poor optics, light distribution characteristics, and stray light, resulting in a considerable level of community concern. CLTC was asked to look into the issues with the objective of identifying a potential course of action to address the community concerns that arose after the first deployment of high-CCT outdoor lighting.

The primary objective was to move to a much lower-color temperature, 2,700 K, which reduced the potential for direct glare, as well as sky glow resulting from blue light scattering. This effort involved a series of demonstrations, community surveys, and site visits. Overall, community support was quite high for the lower-color-temperature lighting, 2,700 K, which residents found to be generally less intrusive and harsh when compared to the original high-color-temperature deployment by the city. While not perfect, this was a positive move forward. Numerous cities have followed up with the City of Davis leadership team on exploring similar approaches within their own municipalities.

Apart from this project, CLTC was involved with the City of Davis bicycle paths and parkway lighting that now use a 2,700 K LED lighting system in combination with adaptive controls to reduce light during periods of inactivity. This was also received well by the community, with no reports of accidents or other related issues associated with either the light sources or controls.

The University of California, Davis also committed to relighting efforts, moving from a 4,000 K to a 3,000 K maximum for all area, pathway, building perimeter (wall packs), and associated lighting. UC Davis is the largest fully networked campus in the United States, working to reduce both energy and light pollution through use of adaptive controls. UC Davis is deeply committed to providing safe nighttime environment and mitigating environmental impacts in terms of light pollution and circadian disruption.

As part of this effort, CLTC examined the CCT issue relative to visual acuity and color rendering for a broad range of CCTs. The objective was to support Title 24 CALGreen updates by understanding and addressing the visual acuity and color quality issues, given that both the attribution and cost issues have largely gone away. During CLTC laboratory activities, a broad range of products between 2,200 K and 6,500 K has demonstrated that similar color rendering, discrimination, and visual acuity can be achieved. The potential advantage is that at 2,200 K, people significantly reduce melatonin suppression relative to typical 4,000 K light sources. In addition, CLTC identified a potential opportunity to increase the amount of horizontal illuminance at 2,200 K, thereby enhancing the opportunity for visual acuity.

CLTC is currently conducting a series of studies at the UC Davis campus with 2,200 K light sources in parking applications. The studies are in collaboration with the campus security team to help understand the safety security issues associated with reduced CCT light sources. In this study, CLTC will examine color fidelity and color distortion issues associated with the reduced CCT.

Currently, UC Davis has established a 3,000 K building specification in alignment with Title 24 CALGreen. CLTC anticipates that the regulations and standards for exterior lighting will navigate to at least 2,700 K within the next five years. Based on the findings of the research conducted as part of this effort, CLTC is actively working with California Energy Commission to advance the Title 24 CALGreen 3,000 K standard into the Title 24 mandatory requirements. CLTC advocates for building lighting, pathway wall packs, parking lots, and all other building lighting regulated within Title 24 to navigate to 3,000 K. CLTC expects that this approach will ultimately affect roadway and other related municipal applications that are not regulated under Title 24.

CLTC worked closely with its manufacturing, education, and other industry partners to bridge the gap between research and commercialization. To facilitate technology and research knowledge transfer, CLTC developed a Technology and Knowledge Transfer Plan to engage and inform key stakeholders of the project outcomes. This section details the major topic areas that are addressed as part of the technology transfer activities, including several specific activities designed to map research outcomes to commercial products for the California market.

Other Technology Transfer Activities

CLTC leveraged multiple advocacy tools to make the knowledge gained, experimental results, and lessons learned from this effort available to the public and key decision makers. Examples of advocacy tools include:

- Technical Advisory Committee
- Outreach Portals and Materials
- Education and Workforce Development
- Rebates and Incentive Programs
- Targeted Market Adoption Programs
- Policy Support

Technical Advisory Committee

The New Generation of LED Lighting Solutions effort used a Technical Advisory Committee (TAC) consisting of key stakeholders who are a cross section of professionals related to the research topic. Members of the New Generation of LED Lighting Solutions TAC were from the following areas of expertise:

- Partners in manufacturing
- Researchers in the same field as the research effort
- Members of trades that will apply the results of the project
- Public interest market transformation implementers
- Product developers relevant to the project
- Experts from agencies relevant to project
- Public interest environmental groups
- Utility representatives
- Members of relevant technical society committees

The TAC's purpose was to provide guidance and project direction to the research team. The research team leveraged the TAC's technical area expertise, knowledge of market applications, and links with industry to inform various stages of the research.

The research team collaborated with the TAC members by hosting annual TAC meetings. During these meetings, the research team updated the TAC on project progress and solicited their input on outstanding questions being resolved at the time of the meeting. Additionally, the research team reached out to individual TAC members to solicit input on specific questions and methods leveraged to execute the research.

Outreach Portals and Materials

A variety of outreach portals and materials was used to inform key stakeholders and the public on how to participate in the research, gain public exposure, and accelerate adoption of resulting technologies and strategies. Outreach portals and materials include:

- Attending lighting-industry conferences to present findings of research efforts and incorporate new products into ongoing research.
- Website and newsletter announcements of findings and opportunities for public and manufacturers to participate in research.
- Tours at CLTC for key stakeholders and the public of research test areas.
- Publishing fact sheets, journal articles, press releases, and other documents on research findings on CLTC website (https://cltc.ucdavis.edu).
- Social media updates on project-related topics using Facebook and Twitter platforms.

Education and Workforce Development

CLTC developed education and workforce materials by writing research articles for lighting-industry publications and teaching lighting fundamentals courses. Efforts include:

- Contributing content to the Illuminating Engineering Society's industry publication, LD+A Magazine, in their *Research* column.
- Providing lighting educational courses for investor-owned utility partners and energy-efficiency associations. Curriculum for the courses includes information about ongoing research from this effort.
- Presenting on an Emerging Technology webinar hosted by Bonneville Power Administration on linear LED replacement lamps and their relevance to the residential market.
- Teaching lighting education courses on behalf of Southern California Edison, focusing on the Building Energy Efficiency Standards (Title 24) and new technology updates for commercial and residential applications.
- Hosting the monthly event twice for the Northern California chapter of the Association of Energy Engineers (AEE) in February 2017 and January 2018 with a special focus on the New Generation of LED Lighting Solutions research topics.

Rebates and Incentives Program

CLTC partnered with the University of California's Office of the President (UCOP) to develop a new LED light-source purchasing program called the Million LED Challenge (MLC). The MLC aids the UCOP's Carbon Neutrality Initiative (CNI) by creating a simple, cost-effective means of reducing greenhouse gas (GHG) emissions through persistent energy savings, recycling provisions, and process efficiencies associated with LED lighting retrofits. Discounted, bulk pricing was negotiated for the program to promote the purchase and installation of the high-quality LED lighting products.

The main purpose of the MLC is to generate rapid transformation from incumbent lighting technology to high quality, high-efficiency LED technology for two key audiences: 1) the UC campus facilities and 2) the UC community. Additionally, the program is being leveraged by UC partners, including California's universities, colleges, community colleges, and Department of General Services.

A dedicated website and purchasing platform were developed to educate consumers on how to choose the right light and support the CNI long-term. In addition to supporting the CNI, the MLC contributes directly to California's statewide efficiency and decarbonization goals.

Market Adoption

CLTC used multiple methods to accelerate market adoption of the products developed as part of this effort:

- CLTC collaborated with manufacturers with established market channels to increase market penetration of the new products.
- CLTC implemented proof-of-concept installations of the new products in real-world applications where the products are best suited to gather end-user feedback and collect energy use data.
- CLTC collaborated with policy groups to establish the new products as a best-in-class option for both quality and energy efficiency.

Combined, these three channels will help to reduce the cost of the product and ensure a competitive market.

Policy Support

California has statutory mandates to reduce lighting electricity consumption in the residential (25 percent savings goal) and commercial sectors (50 percent savings goal) by 2018 (Assembly Bill 1109, Statutes of 2007). In addition, under the *Clean Energy and Pollution Reduction Act* of 2015, the state is required to achieve a doubling of energy efficiency savings for retail customers by 2030.

CLTC actively communicates with the policy groups at the California Energy Commission. In 2016, CLTC drafted a recommendations report for Specification version 3.0. The recommendations developed in this study will draw on lessons learned from that activity and confirm the importance of select recommendations that were not incorporated in Version 3.0. Similarly, Title 24 JA8 thresholds are being evaluated with respect to impacts on consumer preference. This is specifically focused on color fidelity and its importance in residential applications. The CLTC transferred this knowledge to concurrent work to assist with the development of the 2022 version of Title 24 JA8.

GLOSSARY

Term/Acronym	Definition
American National Standards Institute (ANSI)	The American National Standards Institute is a private non-profit organization that oversees the development of voluntary consensus standards for products, services, processes, systems, and personnel in the United States. The organization publishes the most notable chromaticity binning standards.
American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)	A professional association that publishes federal regulations for building energy efficiency performance. States are required to certify that their commercial energy code meets or exceeds ASHRAE 90.1-2013.
chromaticity	An objective measure of color, independent of brightness. It is typically represented as a set of coordinates, one representing color hue and the other color saturation.
chromaticity binning	A defined process where light sources are grouped, or "binned", according to the chromaticity of the light produced by the device. It is based, in part, on the "just-noticeable color difference" research published in 1942 by Dr. Davis Lewis MacAdam. When two light sources are grouped within the same bin, they are considered to have the same nominal chromaticity, even though their wavelength spectrum (color) may be different.
circadian lighting	Health-centric lighting systems that are designed with, and take into account, biological human factors.
color fidelity	A measure of how "true" the colors illuminated by the light appear as compared to a reference standard. The reference standards for defining "trueness" are daylight for high color temperature light sources and blackbody radiators for low color temperature light sources.
color rendering index (CRI)	The metric most commonly used to communicate a light source's color fidelity. The maximum CRI value is 100.
correlated color temperature (CCT)	A specification of the color appearance of light emitted by a lamp, relating its color to the color of light from a source when heated to a particular temperature. Low CCT indicates a warmer (more red) hue while high CCT denotes a cooler (more blue) appearance.
efficacy	The amount of light produced by a lamp or luminaire relative to the amount of electrical power it draws (lm/W). To calculate lamp efficacy, divide the lamp's rated initial lumens (lm) by the rated lamp power (watts) without including auxiliaries such as ballasts, transformers and power supplies.

Term/Acronym	Definition
EPIC (Electric Program Investment Charge)	The Electric Program Investment Charge, created by the California Public Utilities Commission in December 2011, supports investments in clean energy technologies that benefit electricity ratepayers of Pacific Gas and Electric Company, Southern California Edison Company, and San Diego Gas & Electric Company.
illuminance	A measure of the density of incident luminous flux on a surface, i.e., lumens per area; the unit is lux (lx) when the area is measured in square meters and foot-candle (fc) when the area is measured in square feet.
Institute of Electrical and Electronics Engineers (IEEE)	A technical professional association that publishes notable technological standards adhered to in practice by the lighting industry.
interoperability	The compatibility of lighting products to work with common electrical components.
just-noticeable difference	The minimum amount by which stimulus intensity must be changed to produce a noticeable variation in sensory experience.
Likert scale	A linear rating scale that measures participant feeling or experience. An example is a 5-step continuum from strongly disagree to strongly agree.
melanopic stimulus	The amount of light-induced stimulation of melanopsin, the intrinsic photopigment of the human intrinsically photosensitive retinal ganglion cells (ipRGCs). This stimulation correlates to the magnitude of effect that light has on the human circadian system.
percent modulation	Also referred to as 'percent flicker,' a measure of the amount of flicker present in a waveform. It is calculated as the ratio of the maximum, minus the minimum value, divided by the maximum plus the minimum. This results in a value between zero and one hundred percent. A higher percent modulation correlates to higher visibility for each waveform shape.
Planckian locus	The locus of points on a chromaticity diagram representing the chromaticity of blackbodies having various (color) temperatures.
Planckian radiator	Objects heated to the point of incandescence.
power factor	The ratio of the real power absorbed by the load as compared to the apparent power flowing in the circuit.
PXI chassis	A modular electronic instrumentation platform used in automation and testing. In this study, it was used to control and measure LED performance during the testing stage.
Snellen visual acuity	The standard "20/20" metric of visual acuity. It is the ratio of normal distance that the test is made (20 feet) to the distance that a standard observer would see the resultant line. For example, a Snellen visual acuity of 20/40 indicates that what the observer was able to discern at 20 feet, a standard observer would be able to see at 40 feet.

Term/Acronym	Definition
spectral power distribution	The radiant power emitted by a light source over a range of specified wavelengths, typically the visible range (approximately 360 nm to 830 nm).

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APPENDIX A:
Consumer Preference Study Details

The sample size for each of the consumer preference studies varied by phase and round. Most studies were conducted in multiple rounds, across many phases. The total sample size for each is shown in Table A-1.

Table A-1: Consumer Preference Studies – Individual Study Sample Size

Task	Round	Phase	Study name	Number of Participants
2	1		Chromaticity Perception and Preference Test	50
2	1		Color Fidelity Trade-Off Study	50
2	1		Lighting Service Delivered Test	50
4			Amber Corridor Lighting Study	50
4			User Interface Study	50
2 & 4	1		Consumer Preference Survey	50
2	2	A	Consumer Preference of Intentional Color Shift During Dimming	50
2	2	A	Multi-spectral Melanopic Lighting Perception Tests	37
4	2		Perception of Visible Flicker Study	36
4	2		Perceptibility of Color tuning	44
2 & 4	2	A	Survey	65
2	2	B	Consumer Preference of Intentional Color Shift During Dimming	106
2	2	B	Multi-spectral Melanopic Lighting Perception Tests	99
2 & 4	2	B	Survey	149

Table A-1 shows the individual study sample size for the consumer preference studies.

Source: California Lighting Technology Center

APPENDIX B: Lighting Survey Details

Metric Questions

Participants were presented with the LED Lighting Facts label, which provides a basic level of education on lighting terminology. The label is shown in Figure B-1. Participants were then asked a series of related questions.

Q1. Imagine that you are purchasing a new lamp at the store and you are choosing between the following three lamps. Which would you expect to last the longest?

- 7 people (14%) selected – "A LED lamp with a rated life of 25,000 hours"
- 37 people (74%) selected – "A LED lamp with a rated life of 22.8 years"
- 6 people (12%) selected – "A LED lamp with a warranty of 5 years"

Figure B-1: Lighting Facts Label Info Graphic

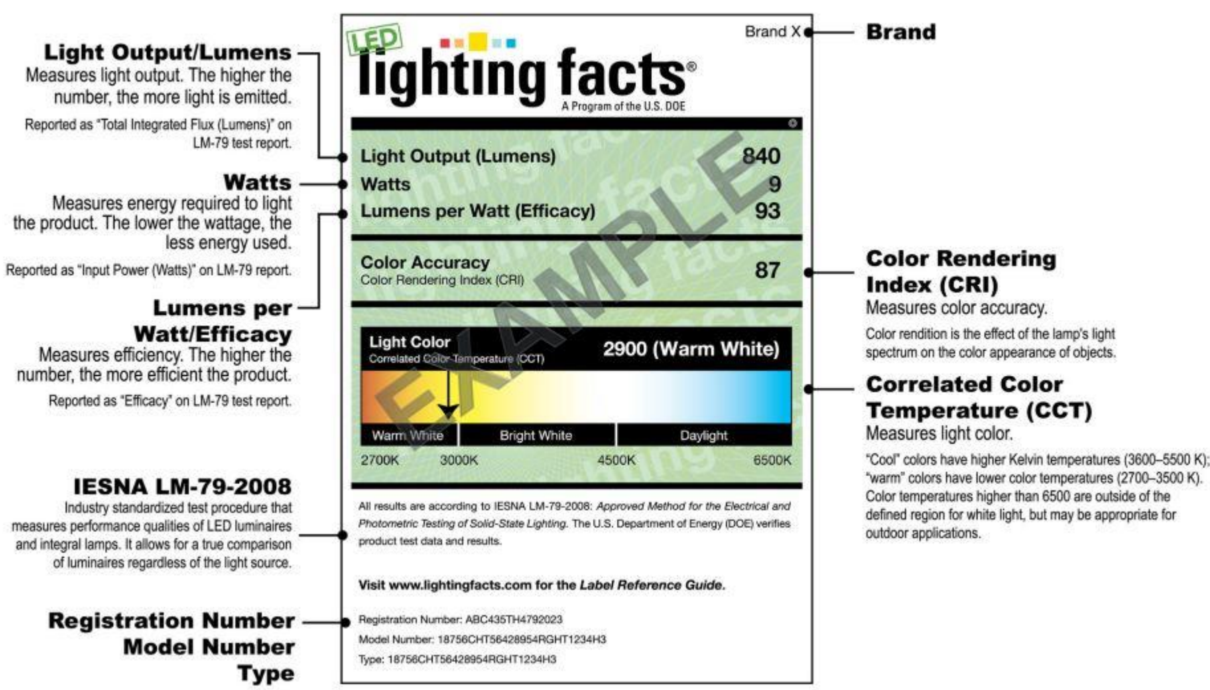

Figure B-1 shows the Lighting Facts label.

Source: U.S. Department of Energy

Q2. In a few words, please describe how you expect a lamp with a rated life of 25,000 hours to behave at the end of its life? Written responses were grouped into to the following categories. Note that many responses fell into multiple categories.

- 25 people (50%) said the lamp would "Die"
- 23 people (46%) said the lamp would "Dim", e.g. "Fade", "Dim", "Less bright", etc.
- 10 people (20%) said the lamp would "Flicker"

- 6 people (12%) said the lamp would "Degrade", e.g. "Dull", "Less efficient", "Yellow", etc.
- 6 people (12%) said the lamp would "not change" at the end of its life, e.g. "as normal", "same", etc.

Q3. Please rank the importance of the following lamp characteristics when purchasing a replacement lamp (Where 1 is the most important)." They were also allowed to select "Not Applicable". Order of characteristics was randomized for each participant.

- "Cost" was rated 3.53 with 1 N/A
- "Light Output (Lumens)" was rated 3.58 with 2 N/A
- "Power (Watts)" was rated 4.43 with 1 N/A
- "Light Color Appearance (Correlated Color Temperature)" was rated 4.44 with 2 N/A
- "Efficacy (Lumens per Watt)" was rated 4.71 with 2 N/A
- "Warranty" was rated 5.30 with 3 N/A
- "Replacement Wattage (e.g. "60W Replacement Lamp")" was rated 5.30 with 3 N/A
- "Color Fidelity (Color Rendering Index)" was rated 5.58 with 2 N/A
- "Brand (Manufacturer)" was rated 6.81 with 3 N/A

Q4. Please check any of the following lamp warranty terms that are unacceptable to you.

- 36 people (72%) selected - "Cost of returning lamp is to be paid by customer."
- 29 people (58%) selected - "This warranty only applies to lamps operating on a burn cycle of 12 hours or more per start and operated a maximum of 4400 hours per year."
- 19 people (38%) selected - "Lamp must be returned with proof of purchase or cashiers receipt to receive a refund or replacement."
- 19 people (38%) selected - "To obtain coverage under this warranty, customer must complete and deliver to the manufacturer a "Warranty Form" form within 30 days of product installation."
- 13 people (26%) selected - "Manufacturer may issue a partial refund (cost of original purchase reduced by duration of use) or send you a replacement lamp."
- 13 people (26%) selected - "Lamp must be returned to place of purchase for a refund if it fails."
- 11 people (22%) selected - "Lamp must be properly installed, wired, and operated or the warranty is void."
- 2 people (4%) selected - "These are all appropriate terms"

Packaging

To gauge the effects of lamp packaging on conveying common lighting features and information, participants were asked to compare the three lamps shown in Figure B-2 and answer a series of related questions.

Figure B-2: Lighting Packaging Shown in Survey

Figure B-2 shows the lighting packaging used in the consumer preference survey.

Source: California Lighting Technology Center

Q5. Please rank the lamps according to your preference (where one is most preferred). The weighted score of each lamp is shown below:

- Lamp A was rated 2.16
- Lamp B was rated 2.04
- Lamp C was rated 1.80

Q6. Please order the following factors by the influence they had on your ranking in the previous question (where one is most influential). They were also allowed to select "Not Applicable". Order of factors was randomized for each participant. Weighted scores are shown below.

- "Lighting facts label" was rated 3.29 with 5 N/A
- "Package design aesthetics" was rated 3.37 with 1 N/A
- "Lamp specifications" was rated 3.40 with 3 N/A
- "Energy Star label" was rated 3.61 with 4 N/A
- "Lamp aesthetics, shape or form" was rated 4.00 with 2 N/A
- "Package colors" was rated 4.60 with 3 N/A
- "Brand name" was rated 4.83 with 8 N/A

Q7. How strong is your preference for your top-ranked lamp compared with the second- and third-ranked choices?

Participants given a one tailed, 5 point Likert scale with rankings 1 - "No strong preference", 2 - "A slight preference", 3 - "A somewhat strong preference", 4 - "A very strong preference", and 5 - "An extremely strong preference". The average rating for each comparison was:

- For "Top-ranked Compared With Second-ranked": 2.39
- For "Top-ranked Compared With Third-ranked": 2.75

APPENDIX C: Consumer Preference Study Details – Lighting Controls

Literature Review

For select target market and technology sectors, CLTC conducted a literature review of mandatory lighting regulations and lighting research studies to identify lighting control performance characteristics determined 'critical' to transforming the target lighting product categories, including consumer perception of metrics such as dimming thresholds and dimming rate of change. Relevant lighting research studies helped researchers identify and document relevant gaps and associated study questions to include in the NGLS program.

CLTC found that very little information existed on consumer expectations for lighting control functionality. Therefore, CLTC developed its user preference studies around the following basic question, "What is the typical consumer's expectation and preference for lighting controls functionality following proper installation?"

Lighting Control Regulations and Standards

CLTC conducted a review of historic, current, and proposed building codes, appliance regulations, and other related standards to assess the baseline lighting control performance characteristics that consumers experience in typical commercial buildings. This review guided CLTC's evaluation of existing and emerging lighting controls for commercial and residential applications.

National Regulations and Standards

The research team compiled the history of the development of national regulations and standards related to lighting controls. National regulations and standards include Energy Standard for Buildings (ASHRAE/IECC 90.1) and Federal Energy Conservation Standards (Title 42 U.S.C. §6295).

ASHRAE/IECC 90.1

The International Energy Conservation Code (IECC) and ASHRAE Standard 90.1 Energy Standard for Buildings except Low-Rise Residential regulate building energy efficiency performance and are adopted by many states within the U.S. States are required to certify that their commercial energy code meets or exceeds ASHRAE 90.1-2013 starting on September 26, 2016.

Federal Energy Conservation Standards - Title 42 U.S.C. §6295

In 1992, the United States Congress passed the Energy Policy Act of 1992 that wrote Title 42 U.S. Code § 6295 into national law. Title 42 U.S. Code § 6295 provides federal energy conservation standards applicable to lighting products. Title 42 U.S. Code § 6295 mandated the minimum efficacy of fluorescent and incandescent reflector lamps. In 2007, Congress passed the Energy Independence and Security Act of 2007 which expanded the Energy Conservation Standards in Title 42 U.S. Code § 6295 and added additional standards. These changes expanded the range of regulated lamps and increased the requirements to include a 25% increase in lamp efficiency by 2013 and a 200% increase in lamp efficiency by 2020.

California Regulations and Standards

The Energy Commission has implemented additional lighting standards that exceed national standards. California regulations and standards included in the literature review are California Building Energy Efficiency Standards (Energy Code) and California Appliance Efficiency Regulations (Title 20, Section 1601–1608).

California Building Energy Efficiency Standards

The Energy Code contains requirements for building energy efficiency performance of new construction, additions, and qualifying alterations to existing buildings. For lighting, the Energy Code focuses on regulation of lighting power density and lighting controls. The 2016 version of the Energy Code is the current version and has been effective since January 1, 2017. Specifically applicable to this research program, certain LED lamps must meet minimum efficacy ratings found in the current Joint Appendix 8 (JA-8) to be categorized as high efficacy. The most significant efficiency improvements in the 2016 Energy Code include standards to address attics, walls, water heating, and lighting in residential applications. For non-residential applications, the Energy Code language now aligns with ASHRAE 90.1 2013 standards and includes more stringent lighting power density limits for many indoor and outdoor spaces. Updates enhance and simplify many aspects of the 2013 requirements, including lighting control requirements for indoor new construction and alterations. For the 2016 updates to the JA-8, the scope and depth has greatly increased, now being a standard for all light source types.

California Appliance Efficiency Regulations

California Appliance Efficiency Regulations (Title 20, Section 1601–1608) regulate the efficiency of appliances sold within California, including lamps and luminaires. California's Appliance Efficiency Regulations were established in 1976 in response to a legislative mandate to reduce California's energy consumption. The regulations are updated periodically to allow consideration and possible incorporation of new energy efficiency technologies and methods.[11] The current version of Title 20, Sections 1601–1608 was adopted in 2015 and effective since January 1, 2016.

The 2016 amendment to the regulations increases efficiency requirements for lamps and luminaires, as well as regulates performance metrics including color rendering, light distribution, and stand-by power. The amendment became effective January 1, 2018 for LED lamps.

Regulation and Standard Summary

Table C-1 summarizes control functionalities required under the reviewed regulations for commercial applications. Note that not all control functionalities are required in all spaces.

[11] California Code of Regulations. Title 20, Division 2. California Energy Commission. 2016.

Table C-1: Building Code Control Functionality Requirements per Space Type by Code

Control Type	Control Requirements	CA Title 24 – 2013	CA Title 24 – 2016	ASHRAE 90.1	2012 IECC C405	2015 IECC C405
All	Max Indicator Light Power	X	X			
	Instructions for Install and Calibration	X	X	X		
	Control System Operation Narrative			X		
Manual	Manual Control			X	X	X
	Manual ON and OFF controls	X	X			
	Reduce Light in Zone by at Least 50%				X	X
Occupancy Sensing	Delayed Auto-OFF after Space is Vacated	X	X	X	X	X
	Allow Manual Override	X	X	X		X
	Partial-OFF Requirements	X	X			X
	Max Auto-ON Percent Power		X	X	X	X
	No Auto-ON for Vacancy Sensors	X	X	X	X	X
Dimming	Min. Power Reduction at Lowest Level	X	X			
	Max. Standby Power	X	X			
	Low Flicker Operation	X	X			
	NEMA SSL 7A Compliance		X			
	Dim and Raise Rate			X[1]		
Daylight	Calibration Settings Readily Accessible			X	X	X
	Reduce Electric Light in Response to Available Daylight	X	X	X	X	X
	Separate Control of Secondary Daylight Zones	X	X	X		X
	Not Over-Dim the Lighting	X	X			

Control Type	Control Requirements	CA Title 24 – 2013	CA Title 24 – 2016	ASHRAE 90.1	2012 IECC C405	2015 IECC C405
	At least two control points between 1% and 99%	X	X	X	X	X
	Able to fully turn off lights			X		X
Scheduling	Control no more than a set size of zone	X	X	X		
	Shall account for weekends and holidays	X	X	X		X
	Limit on length of override	X	X	X	X	X
	Have backup capabilities	X	X			X

[1] **ASHRAE 90.1 allows an additional power allowance if additional controls are installed with specific functionality**

Source: California Lighting Technology Center

Research Objectives

Goals for the consumer preference lighting control studies focused on understanding how consumers and occupants expect advanced lighting controls to operate under ideal conditions and what their preferences are for specific control device settings. To accomplish these goals, the research team identified three objectives that form a picture of consumer and occupant expectations and requirements:

Objective 1: Understand the user experience associated with lighting controls that result in successful market adoption. Industry needs to understand how a user expects lighting to be controlled to provide the best lighting control solution to their customers.

Objective 2: Understand occupant preference for various control device settings. The goal of typical commercial lighting control systems is to provide user amenity while reducing lighting energy consumption. If the user is not satisfied with the light levels or system performance, there is risk of the system being disabled and potential energy savings lost.

Objective 3: Understand occupant tolerance for reduced light levels during a Demand Response event. Understand how demand response events are viewed by lighting system users.

Research Questions

The research team conducted a lighting preference literature review to identify existing research. Detailed results from the lighting preference literature review are provided below by objective and question.

Objective 1. Understand the User Experience that Results in Successful Market Transformation

Question 1. What factors influence user satisfaction with advanced lighting controls in commercial applications?

Installation requirements, status quo, fear that the system will reduce quantity and quality of lighting in the space, and lack of consumer understanding of advanced lighting control technologies are all factors that prevent successful market adoption of advanced lighting control systems. However, many building and appliance code requirements are easiest to address by using an advanced system for new construction and retrofit scenarios.

This question aims to understand consumer awareness of lighting control system benefits and the influence these have on the acceptance of advanced lighting controls. The research team did not identify studies documenting factors that drive market penetration of control devices or systems in the literature. As such, the research team proposed a survey asking what two factors, from a list of relevant factors (energy saving, better controllability, system cost, installation difficulties, improvement over current controls, code requirements), were most significant to a consumer's lighting control experience.

Question 2. Do consumers have a preference between analog and digital lighting control user interfaces?

User preference for lighting control devices with analog interfaces versus digital interfaces will influence individual experiences with installations of advanced lighting control systems. Understanding if there is a preference will assist in successful market transformation by providing design guidance to manufacturers and specifiers based on the knowledge gained during this study. The research team did not identify studies documenting consumer preference for lighting control system interfaces during the literature review.

The research team proposed a laboratory evaluation to address these issues. A selection of dimming control devices was presented to study participants, who were asked to use the devices to control the light in a mock-up space. Participants rate the controls in terms of how easy it was to reach desired light levels, how much control they felt they had over the lights through the controller, and how they liked the aesthetics/feel of the controller.

Objective 2. Understanding Occupant Preference for Control Device Settings

Question 1. What is a user's preference for dimming ramp rates (i.e. continuous, instantaneous step)?

Digital wall controllers typically have a "push-and-hold" operation design that slowly increases the lights until the occupant releases the paddle or button. Some controllers have a single speed at which the lights change, while others accelerate the speed the longer the button is held, or increase the light in steps, remaining at each illuminance level for a brief moment before moving to the next. There is variance between different controllers on how quickly or slowly the lights dim. Consumer preference of how digital controls should operate is not well understood and will help in the design of consumer centric control design.

The research team did not identify studies documenting consumer preference for specific dimming rates during the literature review; however, studies have indicated that occupants are unlikely to complain with dimming rates as low as 10 percent per second and that there may be slight energy savings as the system is less likely over-brightened.[12]

To evaluate consumer expectations for digital dimming ramp settings, the research team will ask study participants to dim lights in a laboratory or mock-up space several times with randomly ordered dimming rates, and participants are asked if each dimming rate is appropriate and if they feel they have control over the lights.

Question 2. What is the acceptable position delay for an occupancy sensor to trigger a light on when a building occupant enters a vacant area?

Proper placement of occupancy sensors affects device performance and user acceptance of the device. One of the primary complaints about occupancy sensor installations is that the lights do not respond quickly enough to satisfy an occupant entering the space. It is unknown what the limits of acceptable delay are and whether this would change based on the occupant's technical knowledge or the light levels in the space prior to the occupancy event.

The research team did not identify studies documenting consumer preference for occupancy sensor response time delays during the literature review.

To evaluate the acceptability of different lengths of delay for the primary lighting in a space to respond via occupancy sensing, test subjects will be asked to enter a mock-up space and perform simple tasks as might be required at the beginning of a day, such as plugging in a computer or selecting a book and reading a line. The test space will be constructed with variable ambient lighting. The space will be monitored to capture time delay between when the subject enters the space and the lights turn on. This task will be performed multiple times, with varying delays for the lights to come on and varying ambient light levels. After each time, the test subject will be asked to rate the responsiveness of the room and the acceptability of the delay.

Question 3. What is the acceptable occupancy sensor sensitivity threshold for building occupants while they occupy an area for a sustained period of time?

Occupancy sensor sensitivity settings can affect the user experience by either providing the appropriate timeout setting associated with the appropriate motion trigger for a positive experience or by providing settings intended for other space types for a negative experience. If a sensor is commissioned with the wrong settings, the space will not function as intended and will result in the user sitting in dark spaces or in lost energy savings by providing light to an empty space after the occupant leaves.

The research team did not identify studies documenting consumer expectations of occupancy sensor sensitivity during the literature review.

The research team proposes a study in a mock-up space where test subjects will be informed that there is a motion sensor in the room controlling the lights and then set to perform a simple task. The lights will turn off either suddenly or with a ramp rate of 1 minute. The occupants' initial response and motion used to trigger the sensor will be noted, and the lights will turn back on. The occupant will then be asked how distracting the lights turning off was

[12] Juslén, Henri, Marius Wouters, and Ariadne Tenner. "The Influence of Controllable Task-lighting on Productivity: A Field Study in a Factory." Applied Ergonomics 38.1 (2007): 39-44.

and if they would deem an occupancy sensor that behaved in the fashion depicted as appropriate.

Question 4. How quickly do consumers expect a daylight sensor to respond to changes in a room for continuous dimming? For step dimming?

Daylight is variable, such as on a day with scattered clouds. A properly designed daylight sensor will vary the electric lights in response to the variable daylight entering the space. To date, research has not shown if it is preferred by users to have the electric light augment the varying daylight immediately in a step function, or continuously to provide no change in light levels on the task plane. For electric light installations with step dimming, only a rapid change in daylight may cause the electric lights to cycle. On the other hand, if the system responds too slowly, it is possible that the occupant will consider the lights in the room too bright or dim and override the daylight sensor, which may reduce realization of energy savings.

The research team did not identify studies documenting consumer preference for daylight sensor response rates during the literature review.

To evaluate the acceptability of varying response rates for daylight sensors, the research team proposes to have test subjects perform a task, such as reading in a mock-up space with controllable primary and ambient lighting. The ambient light will be caused to change and then the primary lighting will respond by either quickly following the ambient lighting, slowly changing over the course of a minute to its new set level, or switching to the new set level either quickly or after a brief delay. Test subjects will be asked after each scenario if they noticed the lighting in the room change and how distracting the change was; then, the test will repeat with a new response.

Objective 3 – Understanding Occupancy Tolerance for Reduced Light Levels During a Demand Response Event

Objective 3 was adequately addressed in published research at the time of this report. The research team identified multiple studies evaluating accepted dimming from the perspective of use as part of a demand response plan. Two studies showed that occupants did generally not notice a 20 percent reduction of light level. Current applicability of these studies may be limited, as both were performed in modeled office spaces lit with 400 lux at work plane level, which is greater than the currently recommended light level of 300 lux for most common office tasks.

Study Administration

The administration process for the experimental methodology adheres to the federal regulations implemented to protect the rights and welfare of human subjects involved in research conducted under the auspices of the University of California, Davis that is enforced by the Institutional Review Board (IRB). Definitions and guidelines to be used during the administration of this study are provided for the following study parameters: inclusion/exclusion criteria, number of study participants, recruitment methods, compensation to the study participants, study endpoints, withdrawal of the study participants, risks to the study participants, sharing of results with study participants, provisions to protect the privacy interests of study participants, compensation for research-related injury, economic burden to study participants, consent process, process to document consent in writing, and drugs or devices.

Inclusion and Exclusion Criteria

A third-party study participant-recruitment agency will use screener questions to determine the potential study participant's eligibility for this study. Eligible study participants should have relatively good eyesight—no corrective lenses (glasses or contact lenses), no eye conditions (e.g. glaucoma, cataracts, etc.), or have not undergone laser eye surgery. In addition, study participants from the following groups will not be included:

- Adults unable to consent
- Individuals who are not yet adults (infants, children, teenagers)
- Pregnant women
- Prisoners

Number of Study Participants

No charts/records or specimens will be collected/obtained as part of this study. All study participants will be enrolled locally. There will be 50 study participants for this study, five male and five female per age group. The age groups are:

- 20–29
- 30–39
- 40–49
- 50–59
- 60–69

Recruitment Methods

The research team contracted with a third-party study participant-recruitment agency. The agency identified potentially eligible study participants from their pre-existing database of local, Sacramento-area research participants. The recruiting team ran through the screener and, if they qualify, will assist the research team in scheduling the study participants to participate in this study. The agency will be contacting potential participants via phone and not employ any additional advertising methods to recruit study participants.

If possible, study participants screened for the Consumer Lighting Preference Study will be asked to participate in this study in parallel.

Compensation to the Study Participants

Study participants were compensated for their participation in the study. Each participant received $100 following the completion of the test session (two sessions total). If a participant fails to complete a session, no compensation for that session will be provided. The compensation will be distributed by the Agency as cash, check, or Visa debit cards (the method that adheres to IRB regulations).

Study Endpoints

Each study participant was required to participate in two one-hour sessions. Study participant recruitment began in March 2016 and completed by June 2016. Session 1 began in June 2016 and concluded in August 2016. Session 2 began in October 2017 and concluded in December 2018.

Data and/or Specimen Management and Confidentiality

Each study participant was assigned a study participant identification number, particularly noting the study participant's age and gender. This ID was used to label the preferences to ensure study participant identity confidentiality.

After each session, the research team collected the data from the laboratory and mock-up evaluations regarding their preferences and compiled the data in an Excel file, noting the filename with the study participant ID number. Likewise, any video recording was logged with the study participant ID number stored in a local and archived backup folder.

Withdrawal of Study Participants

Possible reasons for removal from the study include failure to arrive for the scheduled session twice, color blindness, vision-impairing conditions (such as cataracts, glaucoma, macular degeneration), or determination that the study participant's eyes could not react naturally to changes in light levels.

Disqualified study participants were notified by the Agency and a replacement found within 30 days. Participants were also able to stop any of the tests, mid-procedure.

Should the test be terminated mid-procedure at the request of the study participant, the research team will stop the test and ask the study participant if they would like to continue the test at a different scheduled time or if they would prefer to be withdrawn from the test. The research team will reschedule or withdraw the study participant accordingly, working with the Agency to handle logistics.

Risks to Study Participants

There are no known risks to the study participants. The exposure to the four different white light sources will be at the same intensity as the recommended illumination for reading and writing, approximately at 50 foot-candles at the floor of the viewing booth.

Sharing of Results with Study Participants

The collected results of this study will be shared with the research sponsor, California Energy Commission, without information that could be used to identify the study participants.

Provisions to Protect the Privacy Interests of Study Participants

To protect each study participant's privacy interests, each study participant will be assigned a study participant identification number particularly noting the study participant's age and gender. This ID will be used to label the preferences to ensure study participant identity confidentiality.

The research team will obtain data by following the pre-approved questions to guide the data collection; only questions relevant to the key research question will be asked to make the study participants feel at ease with the research situation.

Data will be compiled in an Excel file and stored at CLTC. Access to shared resources on computer servers is controlled by using Active Directory Local Groups. Each account follows strict Campus password policies. The servers are kept in a secured room with limited access. The servers are behind a firewall to protect against outside attacks; furthermore, intrusion detection software is utilized to generate alerts to any attempts to access CLTC computing resources. For personal computers, access is restricted to those with campus provided accounts. Laptops are kept with the assigned employee or in a locked location. The data will be stored as archived files on the CLTC servers indefinitely.

Economic Burden to Study Participants

Study participant will be responsible for transportation costs to CLTC facility. These costs may be offset in whole or part by compensation made to the study participant after completion of each test session (2 sessions total).

Consent Process

The Agency will receive verbal consent from the study participant during the initial recruitment phone call for proceeding with the eligibility questionnaire and agreeing to schedule test sessions at CLTC.

The research team obtained study participant consent in writing. The consent process began following a full review of the research provided to each study participant over the phone by the Agency during the recruitment interview. When the study participant arrived at CLTC for their first session, the research team provided the study participant with the printed consent form to complete.

Drugs or Devices

The experimental methodology did not utilize drugs or devices.

Methodology Details

Two evaluation types are required to address the research questions identified in Chapter 2 of this report: laboratory and mock-up (Table C-2).

Table C-2: Research Question Evaluation Type

Research Question	Laboratory Evaluation	Mock-Up Evaluation
1.1	X	
1.2	X	
2.1		X
2.2		X
2.3		X
2.4		X

Table C-2 shows which evaluation type was used to address each research question

Source: California Lighting Technology Center

Laboratory Evaluation

The experimental methodology required to assess absolute perception and preference differences using a strictly artificial setting is provided in this section. Research questions 1.1 and 1.2 were answered in the laboratory environment using the following test setup and procedure.

Test Setup Components

The test setup was comprised of a viewing booth and viewing window. The booth was illuminated from the top by light sources with varying characteristics. The research team was in the room with the study participant, controlling light switching and recording study participant responses to questions.

The test setup was made up of the following components:

- **Viewing Booth:** The viewing booth allows light sources to be viewed side-by-side, and/or consecutively using a combination of switches and/or mirrors.
- **Light sources:** Light sources were mounted to the top of the booth and shielded from the participants' field of view.
- **Light controls:** Lighting controls were mounted near the booth and allowed control of the associated sources. Examples of light controls provided include occupancy sensors, daylight sensors, and dimmer switches.
- **Furniture and Room Ambiance:** The test setup was placed on a table along with the laptop controlling the light sources. The study participant was seated such that their eyes aligned with the viewing window. Ambient lighting was provided at a lower level than that of the viewing booth.

Test Procedure

The research team completed the following procedure for each study participant:

1. **Study participant arrives at test facility**
   Study participants were greeted upon arrival and allowed 10 minutes of acclimation to indoor lighting conditions prior to start of any tests.
2. **Research team escorts study participant to test space**
   Following the acclimation period, participants were instructed to silence cell phones and stow any other electronic devices to minimize stray light during the tests.
3. **Pretest evaluation and explanations**
   To ensure that the study participant was not colorblind or had other conditions that would have caused them to be withdrawn from the study, the study participant was asked to take the Ishihara color blindness test on a laptop in the test room (http://www.color-blindness.com/ishihara-38-plates-cvd-test).

- Once the participant passed the exam, the research team continued with the test protocol. If the study participant was found to be colorblind or have other degenerative eye disorders, they were withdrawn from the study.
- During this time, the research team explained the purpose and length of each test and answered any questions.

4. **Study participant is instructed to sit in front of the test setup**
   The study participant will use the adjustable chair to line their eyes to the arrow markings on the view opening of the booth.
5. **Study participant is instructed to look at the first light source setup to evaluate preference**
   The research team will configure the first light source in the viewing booth. The research team will instruct the study participant to look down towards the point of interest on the floor of the viewing booth. The study participant will be allowed to adjust their head so they are focused on the color swatch.

6. **Research team will turn on light sources with varying performance metrics in viewing booth**
   The research team will provide light sources with varying performance metrics and study participants will evaluate light sources, point of interest, and light controls to answer questions outlined in Chapter 2 of this report. Questions will be provided in a digital survey for the study participant to complete while in front of the viewing booth with no time limitation. Study participants will be able to experience the lighting performance multiple times until they are able to answer the survey questions.
7. **Research team will notify the study participant they have concluded the laboratory evaluation**
   The research team will notify the study participant they have completed the test and ask if they are ready to proceed to the next test.
8. **Closing Statements**
   The research team thanked the study participant and asked if they have any questions or comments about the test. The research team then escorted the study participant to the lobby.

Mock-Up Evaluation

The test setup used in this research is comprised of a full-size immersion build out that allows the study participant to experience and evaluate lighting control performance metrics in typical commercial scenarios. The booth is illuminated with light sources of typical performance metrics designed according to recommended practices by the Illuminating Engineering Society (IES). The booth is controlled by lighting controls of varying performance metrics. Research questions 2.1, 2.2, 2.3, and 2.4 will be answered in the mock-up environment using the following test setup and procedure.

The test will be conducted at the California Lighting Technology Center of the University of California, Davis. The research team will be outside the full-size immersion build out, controlling light switching and recording notes regarding study participant responses to questions.

The test setup is made up of the following components:

- **Furniture and Room Ambiance:** The full-size immersion build out will be designed according to standard interior design practices for typical commercial applications, such as kitchen, vanity, and office scenarios including furniture and typical items that are found in each space type. The study participant will perform a typical task, such as typing at a desk in an office space. The ambient lighting outside the test setup will be lower than the light level in the full-size immersion build out. The full-size vignettes allowed users to view light sources side-by-side, and/or consecutively using a combination of controls.
- **Light sources:** Light sources were designed and mounted according to recommended practices for each application scenario.
- **Light controls:** Various commercially available controls were used for all light sources.

Test Setup Preparation

Tasks to be performed before the study participant arrives:

1. **Turn the test setup ON**
   Note the time when the test setup is turned ON to make sure that the light source is fully warmed up when the test begins. The light source needs to be turned on 30 minutes before the beginning of the test to stabilize performance.
2. **Check the switching interface for proper operation.**
   Test the manual light controls to cycle through the light sources. Cycle through all set ups to ensure the process is working properly.
3. **Arrange furniture.**
   Set the furniture and items in a repeatable way to be duplicated for each study participant.

Test Procedure

The research team completed the following procedure for each study participant:

1. **Study participant arrives at test facility**
   The receptionist will greet the study participant and note the time the study participant arrives. This noted time begins the study participant's required 10 minutes of acclimatization to indoor light. The receptionist will notify the research team that the study participant has arrived. The receptionist will also provide the study participant with the consent form.
2. **Research team escorts study participant to test space**
   The study participant will be instructed to silence their cell phones and refrain from using it throughout the duration of the acclimation process and the test, as the light may affect their vision and the results of the test.
3. **Study participant acclimates to indoor light**
   During this time, the research team will explain how many tests will be conducted and for what purpose the tests are being implemented. After this explanation, the research team will ask the study participant if they have any questions about the process before the test begins.
4. **Study participant is instructed to execute typical task for space type**
   The study participant will execute the typical task for space type, such as typing at a desk in an office space.
5. **Study participant is instructed to look at the first light source setup to** evaluate preference
   The research team will instruct the study participant to look towards the point of interest inside the full-size immersion build out. The study participant will be allowed to adjust their head so they are focused on the point of interest before evaluating the point of interest.
6. **Research team will turn on light sources using controls with varying performance metrics in full-immersion build out**
   The research team will provide light sources paired with lighting controls of varying performance metrics and study participants will evaluate the lighting control functionality to answer questions outlined in Chapter 2 of this report. Questions will be provided in a digital survey for the study participant to complete while in front of the viewing booth with no time limitation. Study participants will be able to experience the lighting performance multiple times until they are able to answer the survey questions.

7. **Research team will notify the study participant they have concluded the mock-up evaluation**
   The research team will notify the study participant they have completed the test.
8. **Closing Statements**
   The research team will thank the study participant and ask if they have any questions or comments about the test. The research team will escort the study participant to the lobby and provide information about *Session 2* as appropriate.

APPENDIX D:
Life Testing Performance Data

The summary photometric and electrical test results for all 23 LED products are provided in this section. Results contain performance information for operations from zero up to 12,000 hours of operation. Detailed results for each sample of all products is available upon request through 12,000 hours of operation. Summary performance metrics include power, luminous output, efficacy, power factor, CRI, CCT, chromaticity, D_{UV}, and flicker.

Summary results are presented in two separate tables to provide data for each product and for the product category as a whole.

The minimum sample measured data is included to describe 'worst case' performance of each specific product.

The average sample measured performance data is included to describe the average of the six samples for each measurement for each specific product.

For each results table, the minimum and maximum values are provided to describe product category variation. Additionally, data analysis is provided to understand how much variation occurred over lifetime for both the individual product and the product category.

If all six samples of the product failed before the runtime was reached, the cell is marked as 'dead'. The cell is marked as 'N/A' if at least one sample was still running, but the data file was corrupted after the measurements were taken. The cell is marked with 'omit' if data analysis determined there was operator error during test.

Directional Medium Screw-base Products

The research team evaluated seven directional medium screw-base products. Two of the products are PAR20 lamps; three of the products are PAR30 lamps; one product is a BR40 lamp; and one product is a PAR38 lamp.

Power

The baseline (zero hour) average power of all directional LED medium screw-base products tested was 11.1 W. For the average product, baseline power ranged from a low of 7.4 W to a high of 14.3 W (Tables D-1 and D-2).

Table D-1: Power of Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**
MSB-1	14.0	13.42	13.37	13.37	13.35	13.35	13.34	13.33	13.32	13.31	13.31	13.33	13.31	13.30	**0.1**
MSB-2	9.0	8.44	8.43	8.44	8.43	8.44	8.44	8.44	8.44	8.44	8.44	8.45	8.44	8.44	**0.0**
MSB-3	11.0	10.20	10.21	10.22	10.15	10.13	10.08	9.99	10.08	10.21	dead	dead	dead	dead	**0.2**
MSB-8	12.0	11.74	11.78	11.79	11.83	11.85	11.84	11.85	11.84	11.84	11.84	11.86	11.66	11.84	**0.2**
MSB-10	7.0	7.13	7.21	7.22	7.18	7.22	7.16	7.18	7.17	7.19	7.19	7.09	7.13	7.14	**0.1**
MSB-11	17.0	14.09	14.09	14.10	14.08	14.10	14.05	14.08	14.08	14.07	14.07	14.08	14.07	14.06	**0.0**
MSB-13	12.0	11.09	11.22	11.21	11.21	11.03	11.19	11.18	11.02	11.18	11.01	11.19	11.19	11.39	**0.4**
Minimum	**7.00**	**7.13**	**7.21**	**7.22**	**7.18**	**7.22**	**7.16**	**7.18**	**7.17**	**7.19**	**7.19**	**7.09**	**7.13**	**7.14**	**0.02**
Maximum	**17.00**	**14.09**	**14.09**	**14.10**	**14.08**	**14.10**	**14.05**	**14.08**	**14.08**	**14.07**	**14.07**	**14.08**	**14.07**	**14.06**	**0.38**
Average	**11.71**	**10.87**	**10.90**	**10.91**	**10.89**	**10.87**	**10.87**	**10.86**	**10.85**	**10.89**	**10.98**	**11.00**	**10.97**	**11.03**	**0.16**
Median	**12.00**	**11.09**	**11.22**	**11.21**	**11.21**	**11.03**	**11.19**	**11.18**	**11.02**	**11.18**	**11.43**	**11.53**	**11.43**	**11.62**	**0.13**
Std. Dev.	**3.01**	**2.33**	**2.31**	**2.31**	**2.32**	**2.31**	**2.32**	**2.32**	**2.31**	**2.30**	**2.47**	**2.50**	**2.48**	**2.48**	**0.11**

Table D-1 provides the power of directional LED medium screw-base products for the minimum sample measured.

Source: California Lighting Technology Center

Table D-2: Power of Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**
MSB-1	14.0	13.42	13.37	13.37	13.35	13.35	13.34	13.33	13.32	13.31	13.31	13.99	13.96	13.93	**0.1**
MSB-2	9.0	8.44	8.43	8.44	8.43	8.44	8.44	8.44	8.44	8.44	8.44	8.46	8.45	8.45	**0.2**
MSB-3	11.0	10.20	10.21	10.22	10.15	10.13	10.08	9.99	10.08	10.21	dead	dead	dead	dead	**0.2**
MSB-8	12.0	11.74	11.78	11.79	11.83	11.85	11.84	11.85	11.84	11.84	11.84	12.01	11.93	11.98	**0.1**
MSB-10	7.0	7.13	7.21	7.22	7.18	7.22	7.16	7.18	7.17	7.19	7.19	7.39	7.40	7.42	**0.1**
MSB-11	17.0	14.09	14.09	14.10	14.08	14.10	14.05	14.08	14.08	14.07	14.07	14.27	14.27	14.24	**0.0**
MSB-13	12.0	11.09	11.22	11.21	11.21	11.03	11.19	11.18	11.02	11.18	11.01	11.42	11.42	11.52	**0.2**
Minimum	**7.00**	**7.13**	**7.21**	**7.22**	**7.18**	**7.22**	**7.16**	**7.18**	**7.17**	**7.19**	**7.19**	**7.39**	**7.40**	**7.42**	**0.04**
Maximum	**17.00**	**14.09**	**14.09**	**14.10**	**14.08**	**14.10**	**14.05**	**14.08**	**14.08**	**14.07**	**14.07**	**14.27**	**14.27**	**14.24**	**0.24**
Average	**11.71**	**10.87**	**10.90**	**10.91**	**10.89**	**10.87**	**10.87**	**10.86**	**10.85**	**10.89**	**10.98**	**11.26**	**11.24**	**11.26**	**0.15**
Median	**12.00**	**11.09**	**11.22**	**11.21**	**11.21**	**11.03**	**11.19**	**11.18**	**11.02**	**11.18**	**11.43**	**11.72**	**11.68**	**11.75**	**0.13**
Std. Dev.	**3.01**	**2.33**	**2.31**	**2.31**	**2.32**	**2.31**	**2.32**	**2.32**	**2.31**	**2.30**	**2.47**	**2.58**	**2.57**	**2.56**	**0.07**

Table D-2 provides the power of directional LED medium screw-base products for the average sample measured.

Source: California Lighting Technology Center

Luminous Output

The baseline average luminous output of all directional LED medium screw-base products tested was 813.1 lumens. For the average baseline product, luminous output ranged from a low of 461 lumens to a high of 1,351 lumens (Tables D-3 and D-4).

Table D-3: Luminous Output of Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**
MSB-1	1,000	1,056	1,030	1,060	1,047	1,076	1,054	1,039	1,047	1,030	1,039	1,067	1,025	1,063	**51**
MSB-2	655	603	590	599	601	605	590	595	587	591	601	611	607	601	**24**
MSB-3	640	646	594	595	569	565	383	526	512	557	dead	dead	dead	dead	**263**
MSB-8	800	883	885	920	917	923	892	894	877	865	870	885	874	861	**62**
MSB-10	445	442	435	450	444	466	446	434	445	432	436	458	442	439	**34**
MSB-11	1,200	1,321	1,330	1,300	1,303	1,311	1,317	1,277	1,300	1,281	1,296	1,322	1,308	1,287	**53**
MSB-13	960	609	624	649	646	620	589	544	528	495	491	489	477	472	**177**
Minimum	**445**	**442**	**435**	**450**	**444**	**466**	**383**	**434**	**445**	**432**	**436**	**458**	**442**	**439**	**24**
Maximum	**1,200**	**1,321**	**1,330**	**1,300**	**1,303**	**1,311**	**1,317**	**1,277**	**1,300**	**1,281**	**1,296**	**1,322**	**1,308**	**1,287**	**263**
Average	**814**	**794**	**784**	**796**	**790**	**795**	**753**	**758**	**757**	**750**	**789**	**805**	**789**	**787**	**95**
Median	**800**	**646**	**624**	**649**	**646**	**620**	**590**	**595**	**587**	**591**	**736**	**748**	**741**	**731**	**53**
Std. Dev.	**238**	**286**	**290**	**283**	**285**	**290**	**319**	**292**	**300**	**293**	**310**	**316**	**312**	**313**	**83**

Table D-3 shows the luminous output of directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-4: Luminous Output of Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Outpu t (lm)**	**Outpu t (lm)**	**Outpu t (lm)**	**Outpu t (lm)**	**Outpu t (lm)**	**Outpu t (lm)**	**Outpu t (lm)**	**Outpu t (lm)**	**Output (lm)**	**Output (lm)**
MSB-1	51.0	1,080	1,064	1,086	1,074	1,107	1,087	1,064	1,071	1,053	1,064	1,090	1,042	1,082	**65.0**
MSB-2	24.3	627	607	627	629	634	617	618	601	605	615	626	623	616	**33.0**
MSB-3	263.0	659	624	617	597	597	541	554	541	557	dead	dead	dead	dead	**118.0**
MSB-8	62.0	889	897	931	928	933	904	905	892	884	885	900	889	872	**60.6**
MSB-10	34.0	461	455	465	460	476	464	449	459	450	449	438	457	456	**37.7**
MSB-11	53.0	1,351	1,354	1,327	1,332	1,341	1,339	1,313	1,328	1,319	1,327	1,355	1,335	1,326	**41.7**
MSB-13	177.3	625	642	667	657	645	609	567	545	510	506	498	484	479	**188.4**
Minimum	**24**	**461**	**455**	**465**	**460**	**476**	**464**	**449**	**459**	**450**	**449**	**438**	**457**	**456**	**33**
Maximum	**263**	**1,351**	**1,354**	**1,327**	**1,332**	**1,341**	**1,339**	**1,313**	**1,328**	**1,319**	**1,327**	**1,355**	**1,335**	**1,326**	**188**
Average	**95**	**813**	**806**	**817**	**811**	**819**	**794**	**781**	**777**	**768**	**808**	**818**	**805**	**805**	**78**
Median	**53**	**659**	**642**	**667**	**657**	**645**	**617**	**618**	**601**	**605**	**750**	**763**	**756**	**744**	**61**
Std. Dev.	**83**	**289**	**292**	**285**	**288**	**293**	**301**	**296**	**304**	**302**	**316**	**330**	**316**	**321**	**52**

Table D-4 shows the luminous output of directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Efficacy

The baseline average efficacy of all directional LED medium screw-base products tested was 71.3 lumens per watt (lm/W). For the average product, efficacy ranged from a low of 54.9 lm/W to a high of 94.7 lm/W for baseline measurements (Tables D-5 and D-6).

Table D-5: Efficacy of Directional LED Medium Screw-Base Products – Minimum Measured Sample

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**
MSB-1	71.4	75.6	74.8	76.2	75.5	76.8	76.3	74.7	74.9	74.1	74.4	76.0	70.4	75.7	6.4
MSB-2	72.8	71.1	68.8	70.5	70.9	71.7	69.9	70.4	69.6	70.1	71.2	72.3	71.9	71.3	3.6
MSB-3	58.2	59.2	56.3	57.0	56.0	54.8	33.3	52.6	50.8	54.6	dead	dead	dead	dead	25.9
MSB-8	66.7	74.2	74.9	77.8	77.2	77.6	75.3	75.2	73.6	73.0	73.3	74.6	73.8	72.6	5.2
MSB-10	63.6	60.8	59.6	60.9	61.7	62.3	61.1	59.4	60.6	59.4	59.2	60.7	60.6	60.0	3.1
MSB-11	70.6	93.2	93.6	91.4	92.4	92.7	92.9	90.6	91.8	90.9	91.9	93.7	91.9	90.9	3.1
MSB-13	80.0	53.3	55.1	57.4	56.8	54.3	50.4	47.7	46.3	43.4	43.1	42.0	40.9	40.5	16.9
Minimum	**58.2**	**53.3**	**55.1**	**57.0**	**56.0**	**54.3**	**33.3**	**47.7**	**46.3**	**43.4**	**43.1**	**42.0**	**40.9**	**40.5**	**3.1**
Maximum	**80.0**	**93.2**	**93.6**	**91.4**	**92.4**	**92.7**	**92.9**	**90.6**	**91.8**	**90.9**	**91.9**	**93.7**	**91.9**	**90.9**	**25.9**
Average	**69.0**	**69.6**	**69.0**	**70.2**	**70.1**	**70.0**	**65.6**	**67.2**	**66.8**	**66.5**	**68.9**	**69.9**	**68.2**	**68.5**	**9.2**
Median	**70.6**	**71.1**	**68.8**	**70.5**	**70.9**	**71.7**	**69.9**	**70.4**	**69.6**	**70.1**	**72.3**	**73.5**	**71.2**	**71.9**	**5.2**
Std. Dev.	**6.5**	**12.4**	**12.6**	**11.8**	**12.1**	**12.9**	**18.0**	**13.8**	**14.4**	**14.3**	**15.0**	**15.8**	**15.3**	**15.5**	**8.2**

Table D-5 shows the efficacy of directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-6: Efficacy of Directional LED Medium Screw-Base Products – Average Measured Sample

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**
MSB-1	71.4	76.9	76.0	77.6	76.8	79.2	77.8	76.2	76.7	75.5	76.3	78.0	75.6	77.8	**3.7**
MSB-2	72.8	72.5	70.2	72.3	72.7	73.4	71.7	72.1	71.2	71.6	72.9	74.1	73.7	72.9	**3.9**
MSB-3	58.2	63.4	60.1	59.3	58.5	57.6	52.4	54.5	53.3	54.6	dead	dead	dead	dead	**11.0**
MSB-8	66.7	74.9	75.3	78.1	77.6	77.9	75.5	75.6	74.2	73.8	73.8	74.9	74.5	72.8	**5.2**
MSB-10	63.6	61.9	60.7	62.1	61.9	63.7	62.3	60.3	61.7	60.3	60.3	61.9	61.8	61.4	**3.4**
MSB-11	70.6	94.7	94.9	93.0	93.4	94.0	94.1	92.2	93.2	92.5	93.1	94.9	93.5	93.1	**2.8**
MSB-13	80.0	54.9	56.2	58.5	57.9	56.7	53.3	49.9	48.2	44.9	44.5	43.7	42.4	41.6	**16.9**
Minimum	**58.2**	**54.9**	**56.2**	**58.5**	**57.9**	**56.7**	**52.4**	**49.9**	**48.2**	**44.9**	**44.5**	**43.7**	**42.4**	**41.6**	**2.8**
Maximum	**80.0**	**94.7**	**94.9**	**93.0**	**93.4**	**94.0**	**94.1**	**92.2**	**93.2**	**92.5**	**93.1**	**94.9**	**93.5**	**93.1**	**16.9**
Average	**69.0**	**71.3**	**70.5**	**71.5**	**71.3**	**71.8**	**69.6**	**68.7**	**68.4**	**67.6**	**70.1**	**71.3**	**70.3**	**69.9**	**6.7**
Median	**70.6**	**72.5**	**70.2**	**72.3**	**72.7**	**73.4**	**71.7**	**72.1**	**71.2**	**71.6**	**73.3**	**74.5**	**74.1**	**72.9**	**3.9**
Std. Dev.	**6.5**	**12.0**	**12.3**	**11.6**	**11.9**	**12.4**	**13.7**	**13.6**	**14.2**	**14.5**	**14.9**	**15.7**	**15.5**	**15.8**	**4.9**

Table D-6 shows the efficacy of directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Power Factor

The average power factor of all directional LED medium screw-base products tested at the baseline was 0.93. For the average baseline product, power factor ranged from a low of 0.85 to a high of 0.97 (Tables D-7 and D-8).

Table D-7: Power Factor of Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**
MSB-1	N/A	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	**0.0**
MSB-2	0.90	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.97	0.96	0.96	0.96	0.96	**0.0**
MSB-3	N/A	0.92	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	dead	dead	dead	dead	**0.0**
MSB-8	N/A	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.85	0.91	**0.1**
MSB-10	0.90	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	**0.0**
MSB-11	N/A	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	**0.0**
MSB-13	0.90	0.85	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	**0.0**
Minimu m	**0.90**	**0.85**	**0.83**	**0.83**	**0.83**	**0.83**	**0.83**	**0.83**	**0.83**	**0.83**	**0.83**	**0.83**	**0.83**	**0.83**	**0.00**
Maximum	**0.90**	**0.96**	**0.96**	**0.96**	**0.96**	**0.96**	**0.96**	**0.96**	**0.96**	**0.97**	**0.96**	**0.96**	**0.96**	**0.96**	**0.06**
Average	**0.90**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.92**	**0.93**	**0.02**
Median	**0.90**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.95**	**0.94**	**0.94**	**0.94**	**0.01**
Std. Dev.	**0.00**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.05**	**0.05**	**0.05**	**0.05**	**0.02**

Table D-7 shows the power factor of directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-8: Power Factor of Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**
MSB-1	N/A	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	**0.0**
MSB-2	0.90	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	**0.0**
MSB-3	N/A	0.93	0.94	0.94	0.94	0.94	0.94	0.94	0.93	0.93	dead	dead	dead	dead	**0.0**
MSB-8	N/A	0.91	0.91	0.92	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.90	0.92	**0.0**
MSB-10	0.90	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	**0.0**
MSB-11	N/A	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	**0.0**
MSB-13	0.90	0.85	0.85	0.85	0.84	0.84	0.84	0.84	0.84	0.84	0.85	0.84	0.84	0.84	**0.0**
Minimum	**0.90**	**0.85**	**0.85**	**0.85**	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**	**0.85**	**0.84**	**0.84**	**0.84**	**0.00**
Maximum	**0.90**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.02**
Average	**0.90**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.93**	**0.01**
Median	**0.90**	**0.94**	**0.94**	**0.94**	**0.94**	**0.94**	**0.94**	**0.94**	**0.94**	**0.94**	**0.95**	**0.95**	**0.95**	**0.95**	**0.00**
Std. Dev.	**0.00**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.05**	**0.04**	**0.01**

Table D-8 shows the power factor of directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Color Rendering Index

The baseline average CRI of all directional LED medium screw-base products tested was 87.0. For the average baseline product, CRI ranged from a low of 81.1 to a high of 92.9.

Table D-9: CRI of Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**
MSB-1	93.0	91.7	91.8	91.7	91.7	91.9	91.6	91.6	91.6	91.5	91.6	91.6	91.2	91.6	0.7
MSB-2	80.0	80.9	81.0	81.2	81.2	81.3	81.2	81.2	81.7	81.7	81.8	81.8	81.8	81.8	1.0
MSB-3	85.0	82.7	82.7	82.5	81.9	81.8	79.4	81.3	81.2	80.8	dead	dead	dead	dead	3.3
MSB-8	93.0	92.5	92.3	92.4	92.3	92.3	92.3	92.3	92.4	92.5	92.5	92.4	92.3	92.5	0.2
MSB-10	94.0	92.6	92.5	92.6	92.6	92.6	92.6	92.6	92.7	92.5	92.7	92.7	92.9	92.7	0.4
MSB-11	82.0	82.1	82.4	82.0	82.1	82.1	81.9	82.2	82.2	82.1	82.2	81.8	82.1	82.2	0.6
MSB-13	75.0	84.7	83.8	83.4	83.2	83.1	83.0	83.1	83.2	83.0	83.1	82.9	82.8	82.9	1.8
Minimum	**75.0**	**80.9**	**81.0**	**81.2**	**81.2**	**81.3**	**79.4**	**81.2**	**81.2**	**80.8**	**81.8**	**81.8**	**81.8**	**81.8**	**0.2**
Maximum	**94.0**	**92.6**	**92.5**	**92.6**	**92.6**	**92.6**	**92.6**	**92.6**	**92.7**	**92.5**	**92.7**	**92.7**	**92.9**	**92.7**	**3.3**
Average	**86.0**	**86.7**	**86.6**	**86.5**	**86.4**	**86.4**	**86.0**	**86.3**	**86.4**	**86.3**	**87.3**	**87.2**	**87.2**	**87.3**	**1.1**
Median	**85.0**	**84.7**	**83.8**	**83.4**	**83.2**	**83.1**	**83.0**	**83.1**	**83.2**	**83.0**	**87.4**	**87.3**	**87.0**	**87.3**	**0.7**
Std. Dev.	**6.9**	**4.9**	**4.9**	**5.0**	**5.0**	**5.1**	**5.4**	**5.1**	**5.1**	**5.1**	**5.0**	**5.1**	**5.0**	**5.0**	**1.0**

Table D-9 shows the CRI of directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-10: CRI of Directional LED Medium Screw-Base Products – Average Sample Measured

Product Tested	Manufacturer Claimed Performance	Average Sample Measured: Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	Difference Between Min. and Max. Runtime Data
	CRI	CRI	CRI	CRI	CRI	CRI	CRI	CRI	CRI	CRI	CRI	CRI	CRI	CRI	CRI
MSB-1	93.0	91.8	91.9	91.9	91.8	92.0	91.7	91.8	91.8	91.7	91.8	91.7	91.3	91.8	**0.7**
MSB-2	80.0	81.1	81.3	81.5	81.5	81.6	81.6	81.6	81.8	81.8	81.9	81.9	81.9	81.9	**0.8**
MSB-3	85.0	83.0	83.0	82.7	82.3	82.1	81.4	81.6	81.4	80.8	dead	dead	dead	dead	**2.2**
MSB-8	93.0	92.9	92.7	92.8	92.7	92.7	92.7	92.6	92.7	92.8	92.9	92.8	92.8	92.8	**0.3**
MSB-10	94.0	92.7	92.7	92.7	92.7	92.8	92.7	92.7	92.8	92.7	92.8	92.8	93.0	92.8	**0.3**
MSB-11	82.0	82.4	82.7	82.3	82.4	82.4	82.3	82.4	82.4	82.4	82.5	82.1	82.4	82.5	**0.6**
MSB-13	75.0	85.0	84.1	83.7	83.4	83.3	83.2	83.4	83.6	83.3	83.5	83.1	83.1	83.2	**1.9**
Minimum	**75.0**	**81.1**	**81.3**	**81.5**	**81.5**	**81.6**	**81.4**	**81.6**	**81.4**	**80.8**	**81.9**	**81.9**	**81.9**	**81.9**	**0.3**
Maximum	**94.0**	**92.9**	**92.7**	**92.8**	**92.7**	**92.8**	**92.7**	**92.7**	**92.8**	**92.8**	**92.9**	**92.8**	**93.0**	**92.8**	**2.2**
Average	**86.0**	**87.0**	**86.9**	**86.8**	**86.7**	**86.7**	**86.5**	**86.6**	**86.6**	**86.5**	**87.6**	**87.4**	**87.4**	**87.5**	**1.0**
Median	**85.0**	**85.0**	**84.1**	**83.7**	**83.4**	**83.3**	**83.2**	**83.4**	**83.6**	**83.3**	**87.7**	**87.4**	**87.2**	**87.5**	**0.7**
Std. Dev.	**6.9**	**4.9**	**4.9**	**4.9**	**5.0**	**5.1**	**5.1**	**5.0**	**5.1**	**5.2**	**5.0**	**5.1**	**5.0**	**5.0**	**0.7**

Table D-10 shows the CRI of directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Correlated Color Temperature

The baseline average CCT of all directional LED medium screw-base products tested was 2,739 Kelvin (K). For the average baseline product, CCT ranged from a low of 2,641 K to a high of 3,011 K.

Table D-11: Correlated Color Temperature of Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT
MSB-1	2,700	2,682	2,704	2,698	2,707	2,687	2,698	2,695	2,695	2,698	2,692	2,707	2,753	2,701	71.0
MSB-2	2,700	2,679	2,709	2,695	2,694	2,693	2,688	2,708	2,722	2,724	2,721	2,735	2,734	2,733	56.0
MSB-3	2,700	2,646	2,632	2,651	2,642	2,621	2,393	2,593	2,582	2,562	dead	dead	dead	dead	258.0
MSB-8	2,700	2,751	2,724	2,722	2,723	2,716	2,706	2,702	2,701	2,692	2,692	2,711	2,706	2,715	59.0
MSB-10	3,000	2,631	2,639	2,651	2,649	2,634	2,626	2,652	2,644	2,639	2,654	2,671	2,663	2,671	45.0
MSB-11	2,700	2,665	2,653	2,689	2,678	2,688	2,659	2,674	2,675	2,679	2,681	2,693	2,701	2,692	48.0
MSB-13	2,700	2,969	2,939	2,918	2,958	2,911	2,894	2,916	2,927	2,949	2,951	3,005	3,018	3,008	124.0
Minimum	**2,700**	**2,631**	**2,632**	**2,651**	**2,642**	**2,621**	**2,393**	**2,593**	**2,582**	**2,562**	**2,654**	**2,671**	**2,663**	**2,671**	**45**
Maximum	**3,000**	**2,969**	**2,939**	**2,918**	**2,958**	**2,911**	**2,894**	**2,916**	**2,927**	**2,949**	**2,951**	**3,005**	**3,018**	**3,008**	**258**
Average	**2,743**	**2,718**	**2,714**	**2,718**	**2,722**	**2,707**	**2,666**	**2,706**	**2,707**	**2,706**	**2,732**	**2,754**	**2,763**	**2,753**	**94**
Median	**2,700**	**2,679**	**2,704**	**2,695**	**2,694**	**2,688**	**2,688**	**2,695**	**2,695**	**2,692**	**2,692**	**2,709**	**2,720**	**2,708**	**59**
Std. Dev.	**105**	**109**	**98**	**85**	**100**	**89**	**137**	**93**	**100**	**111**	**100**	**114**	**118**	**115**	**71**

Table D-11 shows the CCT of directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-12: Correlated Color Temperature of Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**
MSB-1	2,699	2,699	2,719	2,715	2,723	2,692	2,712	2,704	2,707	2,710	2,706	2,717	2,771	2,716	79.0
MSB-2	2,699	2,699	2,723	2,712	2,712	2,717	2,712	2,716	2,725	2,727	2,726	2,739	2,740	2,738	41.0
MSB-3	2,687	2,687	2,674	2,680	2,657	2,646	2,588	2,606	2,593	2,562	dead	dead	dead	dead	125.0
MSB-8	2,757	2,757	2,736	2,725	2,727	2,720	2,711	2,706	2,706	2,700	2,699	2,717	2,710	2,719	58.0
MSB-10	2,641	2,641	2,654	2,664	2,665	2,641	2,648	2,665	2,655	2,664	2,671	2,683	2,684	2,687	45.7
MSB-11	2,678	2,678	2,672	2,709	2,700	2,705	2,685	2,695	2,700	2,696	2,700	2,713	2,728	2,723	56.3
MSB-13	3,011	3,011	2,999	2,979	2,972	2,945	2,934	2,940	2,956	2,992	2,986	3,020	3,035	3,024	100.5
Minimum	**2,641**	**2,641**	**2,654**	**2,664**	**2,657**	**2,641**	**2,588**	**2,606**	**2,593**	**2,562**	**2,671**	**2,683**	**2,684**	**2,687**	**41**
Maximum	**3,011**	**3,011**	**2,999**	**2,979**	**2,972**	**2,945**	**2,934**	**2,940**	**2,956**	**2,992**	**2,986**	**3,020**	**3,035**	**3,024**	**125**
Average	**2,739**	**2,739**	**2,740**	**2,741**	**2,737**	**2,724**	**2,713**	**2,719**	**2,720**	**2,722**	**2,748**	**2,765**	**2,778**	**2,768**	**72**
Median	**2,699**	**2,699**	**2,719**	**2,712**	**2,712**	**2,705**	**2,711**	**2,704**	**2,706**	**2,700**	**2,703**	**2,717**	**2,734**	**2,721**	**58**
Std. Dev.	**116**	**116**	**110**	**99**	**99**	**95**	**100**	**97**	**105**	**121**	**108**	**115**	**118**	**115**	**29**

Table D-12 shows the CCT of directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

D_{UV}

The baseline average D_{UV} of all directional LED medium screw-base products tested was -0.000522. For the average product, D_{UV} ranged from a low of -0.002571 to a high of 0.001091 for baseline measurement.

Table D-13: D_{UV} of Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**
MSB-1	N/A	−0.002078	−0.002142	−0.001991	−0.001997	−0.002040	−0.001841	−0.001907	−0.001875	−0.001751	−0.001724	−0.001555	−0.001224	−0.001575	0.000918
MSB-2	N/A	0.000164	0.000152	0.000241	0.000155	0.000186	0.000156	0.000189	0.000366	0.000386	0.000362	0.000306	0.000369	0.000351	0.000234
MSB-3	N/A	0.000326	0.000164	0.000177	0.000573	0.000533	0.000876	0.001131	0.001623	0.002101	dead	dead	dead	dead	0.001937
MSB-8	N/A	0.000710	0.000772	0.000896	0.001058	0.001056	0.001072	0.001125	0.001019	0.000701	0.000701	0.000745	0.000819	0.000817	0.000424
MSB-10	N/A	−0.003117	−0.003141	−0.003044	−0.002615	−0.003187	−0.003120	−0.003218	−0.003213	−0.003147	−0.003106	−0.003030	−0.003030	−0.003156	0.000603
MSB-11	N/A	0.000593	0.000546	0.000805	0.000669	0.000674	0.000611	0.000693	0.000723	0.000731	0.000587	0.000727	0.000922	0.000766	0.000376
MSB-13	N/A	−0.002591	−0.002100	−0.001657	−0.001400	−0.001974	−0.002266	−0.002166	−0.002413	−0.002111	−0.001983	0.000421	0.000154	0.000188	0.003012
Minimum	**N/A**	**−0.003117**	**−0.003141**	**−0.003044**	**−0.002615**	**−0.003187**	**−0.003120**	**−0.003218**	**−0.003213**	**−0.003147**	**−0.003106**	**−0.003030**	**−0.003030**	**−0.003156**	**0.000234**
Maximum	**N/A**	**0.000710**	**0.000772**	**0.000896**	**0.001058**	**0.001056**	**0.001072**	**0.001131**	**0.001623**	**0.002101**	**0.000701**	**0.000745**	**0.000922**	**0.000817**	**0.003012**
Average	**N/A**	**−0.000856**	**−0.000821**	**−0.000653**	**−0.000508**	**−0.000679**	**−0.000645**	**−0.000593**	**−0.000539**	**−0.000441**	**−0.000861**	**−0.000398**	**−0.000332**	**−0.000435**	**0.001072**
Median	**N/A**	**0.000164**	**0.000152**	**0.000177**	**0.000155**	**0.000186**	**0.000156**	**0.000189**	**0.000366**	**0.000386**	**−0.000681**	**0.000364**	**0.000262**	**0.000270**	**0.000603**
Std. Dev.	**N/A**	**0.001540**	**0.001468**	**0.001441**	**0.001357**	**0.001553**	**0.001589**	**0.001660**	**0.001771**	**0.001759**	**0.001476**	**0.001414**	**0.001396**	**0.001456**	**0.000953**

Table D-13 shows the D_{uv} of directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-14: D_{UV} of Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**
MSB-1	N/A	–0.001751	–0.001898	–0.001765	–0.001739	–0.001805	–0.001581	–0.001622	–0.001554	–0.001409	–0.001456	–0.001205	–0.000841	–0.001251	0.001057
MSB-2	N/A	0.000452	0.000279	0.000363	0.000341	0.000292	0.000290	0.000322	0.000414	0.000389	0.000378	0.000422	0.000402	0.000416	0.000173
MSB-3	N/A	0.000511	0.000362	0.000449	0.000766	0.000850	0.001230	0.001366	0.001704	0.002101	dead	dead	dead	dead	0.001740
MSB-8	N/A	0.001091	0.001181	0.001257	0.001422	0.001489	0.001460	0.001488	0.001393	0.001168	0.001087	0.001101	0.001135	0.001202	0.000401
MSB-10	N/A	–0.002571	–0.002579	–0.002510	–0.002354	–0.002667	–0.002587	–0.002585	–0.002618	–0.002563	–0.002525	–0.002454	–0.002457	–0.002628	0.000313
MSB-11	N/A	0.000971	0.000978	0.001216	0.001096	0.001105	0.001037	0.001091	0.001112	0.001139	0.001043	0.001168	0.001317	0.001145	0.000346
MSB-13	N/A	–0.002358	–0.001760	–0.001396	–0.001082	–0.001330	–0.001734	–0.001913	–0.001893	–0.001171	–0.001043	0.000478	0.000494	0.000550	0.002908
Minimum	**N/A**	**–0.002571**	**–0.002579**	**–0.002510**	**–0.002354**	**–0.002667**	**–0.002587**	**–0.002585**	**–0.002618**	**–0.002563**	**–0.002525**	**–0.002454**	**–0.002457**	**–0.002628**	**0.000173**
Maximum	**N/A**	**0.001091**	**0.001181**	**0.001257**	**0.001422**	**0.001489**	**0.001460**	**0.001488**	**0.001704**	**0.002101**	**0.001087**	**0.001168**	**0.001317**	**0.001202**	**0.002908**
Average	**N/A**	**–0.000522**	**–0.000491**	**–0.000341**	**–0.000221**	**–0.000295**	**–0.000269**	**–0.000265**	**–0.000206**	**–0.000049**	**–0.000419**	**–0.000082**	**0.000008**	**–0.000094**	**0.000991**
Median	**N/A**	**0.000452**	**0.000279**	**0.000363**	**0.000341**	**0.000292**	**0.000290**	**0.000322**	**0.000414**	**0.000389**	**–0.000333**	**0.000450**	**0.000448**	**0.000483**	**0.000401**
Std. Dev.	**N/A**	**0.001508**	**0.001425**	**0.001411**	**0.001379**	**0.001501**	**0.001535**	**0.001597**	**0.001639**	**0.001564**	**0.001350**	**0.001317**	**0.001302**	**0.001393**	**0.000936**

Table D-14 shows the D_{uv} of directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Flicker

The baseline average percent flicker of all directional LED medium screw-base products tested was 13.9 percent. For the average product, percent flicker ranged from a low of 6.3 percent to a high of 20.1 percent for baseline measurements.

Table D-15: Percent Flicker of Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**
MSB-1	N/A	10.17	10.24	10.30	10.23	10.26	10.03	10.02	10.03	10.34	10.45	10.28	10.18	10.17	0.4
MSB-2	N/A	10.38	10.90	10.49	10.38	10.16	11.77	11.25	24.12	N/A	N/A	22.85	24.08	24.06	14.0
MSB-3	N/A	12.60	11.95	11.66	11.23	9.93	8.78	10.66	14.81	23.17	dead	dead	dead	dead	14.4
MSB-8	N/A	6.19	6.17	5.89	5.83	5.63	5.55	5.53	5.50	N/A	N/A	6.23	5.39	5.33	0.9
MSB-10	N/A	12.87	13.34	13.20	13.20	12.53	12.49	12.49	12.44	13.25	12.99	12.22	12.74	12.76	1.1
MSB-11	N/A	19.54	19.98	19.97	20.23	20.02	20.09	20.15	20.16	20.51	20.63	19.62	20.51	20.48	1.1
MSB-13	N/A	11.01	11.67	11.69	11.36	11.32	11.41	11.50	11.46	12.19	12.43	12.82	12.48	12.48	1.8
Minimum	**N/A**	**6.19**	**6.17**	**5.89**	**5.83**	**5.63**	**5.55**	**5.53**	**5.50**	**10.34**	**10.45**	**6.23**	**5.39**	**5.33**	**0.43**
Maximum	**N/A**	**19.54**	**19.98**	**19.97**	**20.23**	**20.02**	**20.09**	**20.15**	**24.12**	**23.17**	**20.63**	**22.85**	**24.08**	**24.06**	**14.39**
Average	**N/A**	**11.82**	**12.04**	**11.89**	**11.78**	**11.41**	**11.45**	**11.66**	**14.07**	**15.89**	**14.13**	**14.00**	**14.23**	**14.21**	**4.81**
Median	**N/A**	**11.01**	**11.67**	**11.66**	**11.23**	**10.26**	**11.41**	**11.25**	**12.44**	**13.25**	**12.71**	**12.52**	**12.61**	**12.62**	**1.12**
Std. Dev.	**N/A**	**3.75**	**3.85**	**3.92**	**4.03**	**4.03**	**4.14**	**4.04**	**5.83**	**5.02**	**3.87**	**5.61**	**6.28**	**6.28**	**5.93**

Table D-15 shows the percent flicker of directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-16: Percent Flicker of Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**
MSB-1	N/A	10.67	10.76	10.76	10.66	10.69	10.47	10.44	10.44	10.78	10.85	10.80	10.59	10.63	0.4
MSB-2	N/A	15.81	16.28	16.06	16.00	16.82	23.40	20.29	24.71	N/A	N/A	23.46	24.46	24.44	8.9
MSB-3	N/A	19.35	19.55	19.31	19.84	17.95	17.49	18.03	19.79	23.17	dead	dead	dead	dead	5.7
MSB-8	N/A	6.31	6.35	6.01	5.92	5.78	5.65	5.62	5.58	N/A	N/A	6.33	5.46	5.41	0.9
MSB-10	N/A	13.64	15.14	13.96	14.04	13.34	13.30	13.33	13.28	16.71	14.06	13.24	13.65	13.65	3.5
MSB-11	N/A	20.12	20.55	21.96	20.77	20.63	21.90	20.71	20.77	21.02	21.19	20.21	21.04	21.08	1.8
MSB-13	N/A	11.36	11.98	11.91	11.75	11.69	11.72	11.69	11.73	12.59	12.86	14.82	12.74	13.23	3.5
Minimum	**N/A**	**6.31**	**6.35**	**6.01**	**5.92**	**5.78**	**5.65**	**5.62**	**5.58**	**10.78**	**10.85**	**6.33**	**5.46**	**5.41**	**0.41**
Maximum	**N/A**	**20.12**	**20.55**	**21.96**	**20.77**	**20.63**	**23.40**	**20.71**	**24.71**	**23.17**	**21.19**	**23.46**	**24.46**	**24.44**	**8.90**
Average	**N/A**	**13.90**	**14.37**	**14.28**	**14.14**	**13.84**	**14.85**	**14.30**	**15.18**	**16.85**	**14.74**	**14.81**	**14.66**	**14.74**	**3.53**
Median	**N/A**	**13.64**	**15.14**	**13.96**	**14.04**	**13.34**	**13.30**	**13.33**	**13.28**	**16.71**	**13.46**	**14.03**	**13.20**	**13.44**	**3.45**
Std. Dev.	**N/A**	**4.58**	**4.66**	**4.98**	**4.86**	**4.65**	**5.93**	**5.19**	**6.25**	**4.74**	**3.90**	**5.69**	**6.36**	**6.35**	**2.74**

Table D-16 shows the percent flicker of directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Omni-Directional Medium Screw-Base Products

The research team evaluated seven omni-directional medium screw-base products. At the time of this report, two omni-directional medium screw-base samples of the MSB-12 product failed between baseline and 1,000-hour measurement.

Power

The baseline average power of all omni-directional LED medium screw-base products tested was 8.1 Watts (W). For the average product, power ranged from a low of five W to a high of 11 W for baseline measurements.

Table D-17: Power of Omni-Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**
MSB-4	7.0	5.76	5.77	5.78	5.77	5.82	5.81	5.89	dead	dead	dead	dead	dead	dead	0.13
MSB-5	9.8	9.13	9.12	9.10	9.08	9.09	9.10	9.11	9.11	9.10	9.10	9.10	9.13	9.12	0.05
MSB-6	9.0	9.10	8.99	9.08	9.04	9.10	9.07	9.09	9.00	9.06	9.10	9.06	9.09	9.17	0.18
MSB-7	7.0	7.46	7.39	7.38	7.35	7.35	7.35	7.35	7.33	7.32	1.26	1.28	7.42	1.42	6.20
MSB-9	10.5	10.86	10.82	10.82	10.79	10.76	10.73	10.72	10.74	10.61	10.64	10.68	10.59	10.53	0.33
MSB-12	5.0	4.91	4.91	4.90	4.89	4.90	4.91	dead	dead	dead	dead	dead	dead	dead	0.02
MSB-14	8.0	8.53	8.46	8.53	8.51	8.46	8.52	8.53	8.52	8.46	8.51	8.47	8.49	8.53	0.07
Minimum	**5.00**	**4.91**	**4.91**	**4.90**	**4.89**	**4.90**	**4.91**	**5.89**	**7.33**	**7.32**	**1.26**	**1.28**	**7.42**	**1.42**	**0.02**
Maximum	**10.50**	**10.86**	**10.82**	**10.82**	**10.79**	**10.76**	**10.73**	**10.72**	**10.74**	**10.61**	**10.64**	**10.68**	**10.59**	**10.53**	**6.20**
Average	**8.04**	**7.96**	**7.92**	**7.94**	**7.92**	**7.93**	**7.93**	**8.45**	**8.94**	**8.91**	**7.72**	**7.72**	**8.94**	**7.75**	**1.00**
Median	**8.00**	**8.53**	**8.46**	**8.53**	**8.51**	**8.46**	**8.52**	**8.81**	**9.00**	**9.06**	**9.10**	**9.06**	**9.09**	**9.12**	**0.13**
Std. Dev.	**1.75**	**1.92**	**1.90**	**1.91**	**1.90**	**1.89**	**1.88**	**1.51**	**1.10**	**1.07**	**3.31**	**3.30**	**1.03**	**3.23**	**2.13**

Table D-17 shows the power of omni-directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-18: Power of Omni-Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**
MSB-4	7.0	5.87	5.88	5.90	5.91	6.03	6.02	5.92	dead	dead	dead	dead	dead	dead	0.2
MSB-5	9.8	9.35	9.32	9.29	9.26	9.25	9.26	9.27	9.26	9.25	9.26	9.28	9.30	9.30	0.1
MSB-6	9.0	9.28	9.21	9.27	9.24	9.25	9.21	9.25	9.20	9.25	9.27	9.24	9.25	9.34	0.1
MSB-7	7.0	7.51	7.47	7.46	7.43	7.43	7.43	7.44	7.43	7.42	5.86	5.87	7.44	4.76	2.8
MSB-9	10.5	11.00	10.99	10.99	10.94	10.92	10.91	10.93	10.89	10.80	10.80	10.82	10.80	10.74	0.3
MSB-12	5.0	4.98	4.99	4.98	4.97	4.95	4.95	dead	dead	dead	dead	dead	dead	dead	0.0
MSB-14	8.0	8.65	8.63	8.62	8.60	8.59	8.60	8.61	8.61	8.60	8.59	8.59	8.63	8.59	0.1
Minimum	**5.00**	**4.98**	**4.99**	**4.98**	**4.97**	**4.95**	**4.95**	**5.92**	**7.43**	**7.42**	**5.86**	**5.87**	**7.44**	**4.76**	**0.04**
Maximum	**10.50**	**11.00**	**10.99**	**10.99**	**10.94**	**10.92**	**10.91**	**10.93**	**10.89**	**10.80**	**10.80**	**10.82**	**10.80**	**10.74**	**2.75**
Average	**8.04**	**8.09**	**8.07**	**8.07**	**8.05**	**8.06**	**8.05**	**8.57**	**9.08**	**9.06**	**8.76**	**8.76**	**9.08**	**8.55**	**0.50**
Median	**8.00**	**8.65**	**8.63**	**8.62**	**8.60**	**8.59**	**8.60**	**8.93**	**9.20**	**9.25**	**9.26**	**9.24**	**9.25**	**9.30**	**0.14**
Std. Dev.	**1.75**	**1.95**	**1.94**	**1.94**	**1.93**	**1.91**	**1.91**	**1.57**	**1.12**	**1.10**	**1.62**	**1.62**	**1.09**	**2.02**	**0.92**

Table D-18 shows the power of omni-directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Luminous Output

The baseline average luminous output of all omni-directional LED medium screw-base products tested was 730 lumens. For the average product, luminous output ranged from a low of 501 lumens to a high of 855 lumens for baseline measurements.

Table D-19: Luminous Output of Omni-Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**
MSB-4	800	771	747	679	579	424	290	339	dead	dead	dead	dead	dead	dead	481
MSB-5	800	763	756	759	730	725	698	697	679	661	666	666	653	610	153
MSB-6	800	836	816	835	826	836	818	817	797	783	787	815	774	784	62
MSB-7	450	500	487	501	494	492	454	441	419	406	68	70	86	85	433
MSB-9	800	819	784	804	798	795	767	759	743	736	742	754	747	717	103
MSB-12	500	495	475	465	422	4,022	353	dead	dead	dead	dead	dead	dead	dead	3,669
MSB-14	800	844	845	853	849	860	835	829	821	814	830	843	847	822	46
Minimum	**450**	**495**	**475**	**465**	**422**	**424**	**290**	**339**	**419**	**406**	**68**	**70**	**86**	**85**	**46**
Maximum	**800**	**844**	**845**	**853**	**849**	**4,022**	**835**	**829**	**821**	**814**	**830**	**843**	**847**	**822**	**3,669**
Average	**707**	**718**	**701**	**699**	**671**	**1,165**	**602**	**647**	**692**	**680**	**619**	**630**	**621**	**603**	**707**
Median	**800**	**771**	**756**	**759**	**730**	**795**	**698**	**728**	**743**	**736**	**742**	**754**	**747**	**717**	**153**
Std. Dev.	**147**	**142**	**143**	**147**	**159**	**1,177**	**213**	**189**	**145**	**146**	**281**	**286**	**275**	**269**	**1,220**

Table D-19 shows the luminous output of omni-directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-20: Luminous Output of Omni-Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**
MSB-4	800	788	748	705	626	492	404	349	dead	dead	dead	dead	dead	dead	439.0
MSB-5	800	782	761	765	744	740	713	713	694	677	679	676	669	640	141.9
MSB-6	800	847	826	851	838	843	831	822	811	795	800	823	793	799	58.4
MSB-7	450	511	499	513	500	497	468	457	437	420	321	318	287	272	241.1
MSB-9	800	825	802	821	814	813	788	783	766	758	766	779	774	745	79.7
MSB-12	500	501	487	474	437	411	361	dead	dead	dead	dead	dead	dead	dead	140.0
MSB-14	800	855	857	862	859	868	844	838	831	826	839	855	858	831	42.0
Minimum	**450**	**501**	**487**	**474**	**437**	**411**	**361**	**349**	**437**	**420**	**321**	**318**	**287**	**272**	**42**
Maximum	**800**	**855**	**857**	**862**	**859**	**868**	**844**	**838**	**831**	**826**	**839**	**855**	**858**	**831**	**439**
Average	**707**	**730**	**711**	**713**	**688**	**666**	**630**	**660**	**708**	**695**	**681**	**690**	**676**	**657**	**163**
Median	**800**	**788**	**761**	**765**	**744**	**740**	**713**	**748**	**766**	**758**	**766**	**779**	**774**	**745**	**140**
Std. Dev.	**147**	**144**	**142**	**148**	**157**	**179**	**196**	**189**	**143**	**146**	**188**	**196**	**204**	**203**	**129**

Table D-20 shows the luminous output of omni-directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Efficacy

The baseline average efficacy of all omni-directional LED medium screw-base products tested was 93.1 lumens per watt (lm/W). For the average product, efficacy ranged from a low of 68.1 lm/W to a high of 134.4 lm/W for baseline measurements.

Table D-21: Efficacy of Omni-Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**
MSB-4	114.29	131.66	123.10	113.42	95.39	67.89	44.26	57.59	dead	dead	dead	dead	dead	dead	87.4
MSB-5	81.63	82.20	80.21	80.91	78.70	78.51	75.82	75.53	73.65	71.77	71.41	69.91	68.97	65.83	16.4
MSB-6	88.89	89.14	87.67	89.12	88.76	89.27	88.34	87.06	86.10	83.79	84.42	88.19	83.77	84.79	5.5
MSB-7	64.29	66.37	64.89	66.82	66.44	65.73	60.63	59.00	56.05	54.44	53.31	52.69	50.74	47.34	19.5
MSB-9	76.19	74.57	72.50	74.34	73.89	73.66	71.43	70.64	69.18	69.36	69.77	70.59	70.01	67.84	6.7
MSB-12	100.00	99.29	96.63	92.59	83.54	82.12	71.81	dead	dead	dead	dead	dead	dead	dead	27.5
MSB-14	100.00	98.03	98.15	99.18	99.21	100.47	97.55	96.67	95.79	95.14	96.78	98.49	98.10	96.03	5.3
Minimum	**64.29**	**66.37**	**64.89**	**66.82**	**66.44**	**65.73**	**44.26**	**57.59**	**56.05**	**54.44**	**53.31**	**53**	**51**	**47**	**5.33**
Maximum	**114.29**	**131.66**	**123.10**	**113.42**	**99.21**	**100.47**	**97.55**	**96.67**	**95.79**	**95.14**	**96.78**	**98**	**98**	**96**	**87.40**
Average	**89.33**	**91.61**	**89.02**	**88.05**	**83.70**	**79.66**	**72.83**	**74.42**	**76.15**	**74.90**	**75.14**	**76**	**74**	**72**	**24.04**
Median	**88.89**	**89.14**	**87.67**	**89.12**	**83.54**	**78.51**	**71.81**	**73.09**	**73.65**	**71.77**	**71.41**	**71**	**70**	**68**	**16.37**
Std. Dev.	**15.63**	**19.73**	**17.88**	**14.54**	**10.84**	**11.35**	**16.16**	**14.09**	**13.74**	**13.77**	**14.65**	**16**	**16**	**17**	**26.99**

Table D-21 shows the efficacy of omni-directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-22: Efficacy of Omni-Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**
MSB-4	114.29	134.37	125.37	119.55	106.07	82.01	67.85	58.95	dead	dead	dead	dead	dead	dead	75.4
MSB-5	81.63	83.59	81.76	82.38	80.33	80.02	77.05	77.05	74.95	73.17	73.31	72.89	71.98	68.89	14.7
MSB-6	88.89	91.22	89.67	91.87	90.70	91.18	90.25	88.92	88.10	85.98	86.31	89.17	85.73	86.45	6.1
MSB-7	64.29	68.09	66.80	68.77	67.43	66.91	62.93	61.51	58.82	56.58	54.54	54.33	52.21	52.70	16.6
MSB-9	76.19	75.06	73.04	74.78	74.45	74.47	72.21	71.60	70.33	70.15	70.89	72.00	71.68	69.42	5.6
MSB-12	100.00	100.74	97.56	95.18	88.03	83.03	73.00	dead	dead	dead	dead	dead	dead	dead	27.7
MSB-14	100.00	98.88	99.35	99.99	99.84	101.12	98.10	97.36	96.56	96.03	97.66	99.55	99.36	96.79	5.1
Minimum	**64.29**	**68.09**	**66.80**	**68.77**	**67.43**	**66.91**	**62.93**	**58.95**	**58.82**	**56.58**	**54.54**	**54**	**52**	**53**	**5.09**
Maximum	**114.29**	**134.37**	**125.37**	**119.55**	**106.07**	**101.12**	**98.10**	**97.36**	**96.56**	**96.03**	**97.66**	**100**	**99**	**97**	**75.42**
Average	**89.33**	**93.14**	**90.51**	**90.36**	**86.69**	**82.68**	**77.34**	**75.90**	**77.75**	**76.38**	**76.54**	**78**	**76**	**75**	**21.61**
Median	**88.89**	**91.22**	**89.67**	**91.87**	**88.03**	**82.01**	**73.00**	**74.33**	**74.95**	**73.17**	**73.31**	**73**	**72**	**69**	**14.70**
Std. Dev.	**15.63**	**20.14**	**18.08**	**15.78**	**12.69**	**10.25**	**11.59**	**13.81**	**13.28**	**13.56**	**14.61**	**16**	**16**	**15**	**23.22**

Table D-22 shows the efficacy of omni-directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Power Factor

The baseline average power factor of all omni-directional LED medium screw-base products tested was 0.87. For the average product, power factor ranged from a low of 0.60 to a high of 0.98 for baseline measurements.

Table D-23: Power Factor of Omni-Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**
MSB-4	N/A	0.60	0.60	0.60	0.60	0.60	0.60	0.60	dead	dead	dead	dead	dead	dead	0.00
MSB-5	N/A	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.00
MSB-6	N/A	0.98	0.98	0.98	0.91	0.98	0.88	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.11
MSB-7	N/A	0.84	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.86	0.65	0.64	0.86	0.65	0.22
MSB-9	N/A	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.00
MSB-12	0.90	0.90	0.90	0.90	0.90	0.90	0.90	dead	dead	dead	dead	dead	dead	dead	0.00
MSB-14	N/A	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.00
Minimum	**0.90**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.85**	**0.86**	**0.65**	**0.64**	**0.86**	**0.65**	**0.00**
Maximum	**0.90**	**0.98**	**0.98**	**0.98**	**0.97**	**0.98**	**0.97**	**0.98**	**0.98**	**0.98**	**0.98**	**0.99**	**0.99**	**0.99**	**0.22**
Average	**0.90**	**0.87**	**0.87**	**0.87**	**0.86**	**0.87**	**0.86**	**0.87**	**0.92**	**0.92**	**0.88**	**0.88**	**0.93**	**0.88**	**0.05**
Median	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**	**0.91**	**0.91**	**0.91**	**0.91**	**0.91**	**0.91**	**0.91**	**0.00**
Std. Dev.	**0.00**	**0.12**	**0.12**	**0.12**	**0.11**	**0.12**	**0.11**	**0.13**	**0.05**	**0.04**	**0.12**	**0.12**	**0.05**	**0.12**	**0.08**

Table D-23 shows the power factor of omni-directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-24: Power Factor of Omni-Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**
MSB-4	N/A	0.60	0.60	0.60	0.60	0.60	0.60	dead	dead	dead	dead	dead	dead	dead	0.0
MSB-5	N/A	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.0
MSB-6	N/A	0.98	0.98	0.98	0.97	0.98	0.96	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.0
MSB-7	N/A	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.86	0.88	0.81	0.80	0.86	0.79	0.1
MSB-9	N/A	0.90	0.90	0.90	0.90	0.90	0.90	0.91	0.91	0.91	0.90	0.90	0.90	0.90	0.0
MSB-12	0.90	0.90	0.90	0.90	0.90	0.90	dead	dead	dead	dead	dead	dead	dead	dead	0.0
MSB-14	N/A	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.0
Minimu m	**0.90**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.85**	**0.86**	**0.88**	**0.81**	**0.80**	**0.86**	**0.79**	**0.00**
Maximum	**0.90**	**0.98**	**0.98**	**0.98**	**0.97**	**0.98**	**0.97**	**0.98**	**0.98**	**0.98**	**0.98**	**0.99**	**0.99**	**0.99**	**0.09**
Average	**0.90**	**0.87**	**0.87**	**0.87**	**0.87**	**0.87**	**0.87**	**0.92**	**0.93**	**0.93**	**0.91**	**0.92**	**0.93**	**0.91**	**0.02**
Median	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**	**0.91**	**0.91**	**0.91**	**0.91**	**0.91**	**0.91**	**0.91**	**0.91**	**0.00**
Std. Dev.	**0.00**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**0.13**	**0.05**	**0.04**	**0.04**	**0.06**	**0.07**	**0.05**	**0.07**	**0.03**

Table D-24 shows the power factor of omni-directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Color Rendering Index

The baseline average CRI of all omni-directional LED medium screw-base products tested was 86.0. For the average product, CRI ranged from a low of 81.0 to a high of 92.4 for baseline measurements.

Table D-25: CRI of Omni-Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**
MSB-4	80.0	81.1	80.9	81.0	81.3	82.0	82.0	83.0	dead	dead	dead	dead	dead	dead	2.1
MSB-5	90.0	92.3	92.0	91.9	91.8	91.8	91.8	91.7	91.6	91.6	91.6	91.4	91.3	91.3	1.0
MSB-6	92.0	91.5	91.3	91.1	91.0	90.9	90.8	90.9	90.7	90.6	90.7	90.9	90.4	90.8	1.0
MSB-7	80.0	81.2	80.7	80.9	80.6	80.6	80.5	80.5	80.6	80.6	81.1	81.1	80.9	80.9	0.7
MSB-9	90.0	91.5	91.5	91.5	91.4	91.4	91.5	91.4	91.5	91.5	91.5	91.6	91.5	91.5	0.2
MSB-12	80.0	83.0	83.8	83.8	83.9	84.0	84.2	dead	dead	dead	dead	dead	dead	dead	1.2
MSB-14	80.0	80.9	81.7	81.6	81.6	81.6	81.5	81.4	81.5	81.6	81.5	81.5	81.5	81.5	0.8
Minimum	**80.00**	**80.89**	**80.74**	**80.90**	**80.60**	**80.60**	**80.50**	**80.50**	**80.60**	**80.60**	**81.10**	**81**	**81**	**81**	**0.16**
Maximum	**92.00**	**92.25**	**91.97**	**91.90**	**91.80**	**91.80**	**91.80**	**91.70**	**91.60**	**91.60**	**91.60**	**92**	**92**	**92**	**2.08**
Average	**84.57**	**85.91**	**85.98**	**85.97**	**85.94**	**86.04**	**86.04**	**86.48**	**87.18**	**87.18**	**87.28**	**87**	**87**	**87**	**1.01**
Median	**80.00**	**82.96**	**83.78**	**83.80**	**83.90**	**84.00**	**84.20**	**86.95**	**90.70**	**90.60**	**90.70**	**91**	**90**	**91**	**0.99**
Std. Dev.	**5.31**	**5.08**	**4.94**	**4.87**	**4.82**	**4.71**	**4.73**	**4.91**	**5.02**	**4.99**	**4.89**	**5**	**5**	**5**	**0.54**

Table D-25 shows the CRI of omni-directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-26: CRI of Omni-Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**
MSB-4	80.0	81.2	81.0	81.2	81.5	82.3	82.6	83.1	dead	dead	dead	dead	dead	dead	2.1
MSB-5	90.0	92.4	92.1	92.0	91.9	92.0	91.9	91.9	91.8	91.7	91.7	91.6	91.5	91.4	0.9
MSB-6	92.0	91.6	91.4	91.1	91.1	91.0	91.0	91.0	91.0	90.8	91.0	91.0	90.6	90.9	1.0
MSB-7	80.0	81.4	81.1	81.1	80.9	80.8	80.8	80.8	80.9	80.9	81.3	81.3	81.3	81.3	0.6
MSB-9	90.0	91.6	91.6	91.6	91.5	91.6	91.6	91.5	91.5	91.6	91.6	91.6	91.6	91.6	0.1
MSB-12	80.0	83.1	83.8	83.9	83.9	84.0	84.2	dead	dead	dead	dead	dead	dead	dead	1.1
MSB-14	80.0	81.0	81.8	81.7	81.6	81.7	81.6	81.5	81.7	81.6	81.6	81.7	81.7	81.6	0.8
Minimum	**80.00**	**80.98**	**81.00**	**81.10**	**80.90**	**80.80**	**80.80**	**80.80**	**80.90**	**80.90**	**81.30**	**81**	**81**	**81**	**0.15**
Maximum	**92.00**	**92.38**	**92.09**	**92.00**	**91.90**	**92.00**	**91.90**	**91.90**	**91.80**	**91.70**	**91.70**	**92**	**92**	**92**	**2.10**
Average	**84.57**	**86.03**	**86.11**	**86.09**	**86.06**	**86.20**	**86.24**	**86.63**	**87.38**	**87.32**	**87.44**	**87**	**87**	**87**	**0.95**
Median	**80.00**	**83.08**	**83.84**	**83.90**	**83.90**	**84.00**	**84.20**	**87.05**	**91.00**	**90.80**	**91.00**	**91**	**91**	**91**	**0.95**
Std. Dev.	**5.31**	**5.08**	**4.92**	**4.83**	**4.80**	**4.71**	**84.20**	**4.89**	**4.98**	**4.97**	**4.90**	**5**	**5**	**5**	**0.55**

Table D-26 shows the CRI of omni-directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Correlated Color Temperature

The baseline average correlated color temperature (CCT) of all omni-directional LED medium screw-base products tested was 2,699 Kelvin. For the average product, CCT ranged from a low of 2,626 Kelvin to a high of 2,760 Kelvin for baseline measurements.

Table D-27: Correlated Color Temperature of Omni-Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**
MSB-4	2,700	2,676	2,739	2,712	2,739	2,813	2,874	2,935	dead	dead	dead	dead	dead	dead	259
MSB-5	2,700	2,653	2,642	2,659	2,669	2,672	2,672	2,667	2,669	2,659	2,658	2,662	2,662	2,651	30
MSB-6	2,700	2,619	2,621	2,639	2,641	2,631	2,632	2,618	2,637	2,642	2,636	2,685	2,701	2,703	85
MSB-7	2,700	2,721	2,715	2,717	2,713	2,699	2,692	2,695	2,698	2,701	2,647	2,663	2,669	2,675	74
MSB-9	2,700	2,673	2,686	2,706	2,711	2,711	2,715	2,718	2,724	2,731	2,733	2,759	2,766	2,762	93
MSB-12	2,700	2,720	2,712	2,723	2,736	2,751	2,765	dead	dead	dead	dead	dead	dead	dead	53
MSB-14	2,700	2,750	2,728	2,742	2,747	2,745	2,745	2,743	2,749	2,748	2,754	2,771	2,768	2,762	43
Minimum	**2,700**	**2,619**	**2,621**	**2,639**	**2,641**	**2,631**	**2,632**	**2,618**	**2,637**	**2,642**	**2,636**	**2,662**	**2,662**	**2,651**	**30**
Maximum	**2,700**	**2,750**	**2,739**	**2,742**	**2,747**	**2,813**	**2,874**	**2,935**	**2,749**	**2,748**	**2,754**	**2,771**	**2,768**	**2,762**	**259**
Average	**2,700**	**2,687**	**2,692**	**2,700**	**2,708**	**2,717**	**2,728**	**2,729**	**2,695**	**2,696**	**2,686**	**2,708**	**2,713**	**2,711**	**91**
Median	**2,700**	**2,676**	**2,712**	**2,712**	**2,713**	**2,711**	**2,715**	**2,707**	**2,698**	**2,701**	**2,658**	**2,685**	**2,701**	**2,703**	**74**
Std. Dev.	**0**	**42**	**41**	**34**	**36**	**55**	**72**	**100**	**40**	**41**	**48**	**47**	**46**	**45**	**72**

Table D-27 shows the CCT of omni-directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-28: Correlated Color Temperature of Omni-Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**
MSB-4	2,700	2,683	2,742	2,748	2,788	2,853	2,942	2,966	dead	dead	dead	dead	dead	dead	283.0
MSB-5	2,700	2,666	2,656	2,671	2,680	2,684	2,686	2,684	2,686	2,680	2,682	2,686	2,683	2,671	30.3
MSB-6	2,700	2,626	2,628	2,649	2,652	2,651	2,653	2,648	2,670	2,676	2,677	2,692	2,736	2,715	109.6
MSB-7	2,700	2,748	2,743	2,739	2,734	2,726	2,709	2,704	2,711	2,722	2,722	2,738	2,737	2,742	44.0
MSB-9	2,700	2,676	2,695	2,713	2,725	2,723	2,726	2,729	2,737	2,744	2,744	2,768	2,774	2,769	98.0
MSB-12	2,700	2,735	2,721	2,735	2,748	2,759	2,773	dead	dead	dead	dead	dead	dead	dead	52.0
MSB-14	2,700	2,760	2,743	2,751	2,757	2,755	2,755	2,754	2,760	2,759	2,764	2,780	2,780	2,778	37.3
Minimum	**2,700**	**2,626**	**2,628**	**2,649**	**2,652**	**2,651**	**2,653**	**2,648**	**2,670**	**2,676**	**2,677**	**2,686**	**2,683**	**2,671**	**30**
Maximum	**2,700**	**2,760**	**2,743**	**2,751**	**2,788**	**2,853**	**2,942**	**2,966**	**2,760**	**2,759**	**2,764**	**2,780**	**2,780**	**2,778**	**283**
Average	**2,700**	**2,699**	**2,704**	**2,715**	**2,726**	**2,736**	**2,749**	**2,748**	**2,713**	**2,716**	**2,718**	**2,733**	**2,742**	**2,735**	**93**
Median	**2,700**	**2,683**	**2,721**	**2,735**	**2,734**	**2,726**	**2,726**	**2,717**	**2,711**	**2,722**	**2,722**	**2,738**	**2,737**	**2,742**	**52**
Std. Dev.	**0**	**46**	**43**	**37**	**43**	**59**	**87**	**103**	**33**	**33**	**34**	**38**	**35**	**39**	**82**

Table D-28 shows the CCT of omni-directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

D_{UV}

The baseline average D_{UV} of all omni-directional LED medium screw-base products tested was 0.000608. For the average product, D_{UV} ranged from a low of -0.002648 to a high of 0.002002 for baseline measurements.

Table D-29: D_{UV} of Omni-Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**
MSB-4	N/A	0.001779	0.001697	0.001050	0.000260	–0.001279	–0.003244	–0.001856	dead	dead	dead	dead	dead	dead	0.005023
MSB-5	N/A	0.000952	0.001453	0.001628	0.001781	0.001849	0.001941	0.002110	0.002232	0.002344	0.002591	0.002828	0.003135	0.003262	0.002310
MSB-6	N/A	0.000179	0.000185	0.000212	0.000200	0.000286	0.000286	0.000457	0.000545	0.000684	0.000787	0.000913	0.001312	0.001113	0.001133
MSB-7	N/A	–0.000895	0.000234	0.000237	0.000803	0.001013	0.001024	0.001082	0.001232	0.001888	0.002245	0.002558	0.002883	0.003205	0.004100
MSB-9	N/A	–0.002895	–0.002993	–0.002988	–0.002859	–0.002789	–0.002814	–0.002798	–0.002716	–0.002549	–0.002739	–0.002752	–0.002689	–0.002592	0.000444
MSB-12	N/A	0.001100	–0.001884	–0.002134	–0.002347	–0.002073	–0.002415	dead	dead	dead	dead	dead	dead	dead	0.003515
MSB-14	N/A	0.000600	0.000399	0.000515	0.000708	0.000911	0.000933	0.001113	0.001138	0.001300	0.001324	0.001433	0.001567	0.001735	0.001336
Minimum	**N/A**	**–0.002895**	**–0.002993**	**–0.002988**	**–0.002859**	**–0.002789**	**–0.003244**	**–0.002798**	**–0.002716**	**–0.002549**	**–0.002739**	**–0.002752**	**–0.002689**	**–0.002592**	**0.000444**
Maximum	**N/A**	**0.001779**	**0.001697**	**0.001628**	**0.001781**	**0.001849**	**0.001941**	**0.002110**	**0.002232**	**0.002344**	**0.002591**	**0.002828**	**0.003135**	**0.003262**	**0.005023**
Average	**N/A**	**0.000117**	**–0.000130**	**–0.000211**	**–0.000208**	**–0.000297**	**–0.000613**	**0.000018**	**0.000486**	**0.000733**	**0.000842**	**0.000996**	**0.001242**	**0.001345**	**0.002552**
Median	**N/A**	**0.000600**	**0.000234**	**0.000237**	**0.000260**	**0.000286**	**0.000286**	**0.000770**	**0.001138**	**0.001300**	**0.001324**	**0.001433**	**0.001567**	**0.001735**	**0.002310**
Std. Dev.	**N/A**	**0.001452**	**0.001587**	**0.001572**	**0.001595**	**0.001623**	**0.001979**	**0.001748**	**0.001690**	**0.001733**	**0.001902**	**0.002002**	**0.002090**	**0.002137**	**0.001578**

Table D-29 shows the D_{uv} of omni-directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-30: D_{UV} of Omni-Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv
MSB-4	N/A	0.002002	0.001731	0.001584	0.000956	–0.000261	–0.001157	–0.001568	dead	dead	dead	dead	dead	dead	0.003570
MSB-5	N/A	0.001364	0.001869	0.001990	0.002186	0.002272	0.002380	0.002558	0.002705	0.002781	0.002984	0.003209	0.003484	0.003600	0.002236
MSB-6	N/A	0.000275	0.000286	0.000374	0.000411	0.000548	0.000572	0.000720	0.000878	0.001058	0.001063	0.001170	0.001562	0.001404	0.001288
MSB-7	N/A	0.000180	0.000285	0.000525	0.001118	0.001498	0.001566	0.001641	0.001660	0.002060	0.002645	0.002976	0.003241	0.003549	0.003369
MSB-9	N/A	–0.002648	–0.002655	–0.002637	–0.002530	–0.002451	–0.002483	–0.002402	–0.002335	–0.002278	–0.002308	–0.002298	–0.002214	–0.002062	0.000593
MSB-12	N/A	0.001400	–0.001565	–0.001613	–0.001700	–0.001870	–0.002187	dead	dead	dead	dead	dead	dead	dead	0.003587
MSB-14	N/A	0.001683	0.001486	0.001818	0.001801	0.001974	0.001983	0.002188	0.002208	0.002335	0.002409	0.002481	0.002385	0.002827	0.001341
Minimum	**N/A**	**–0.002648**	**–0.002655**	**–0.002637**	**–0.002530**	**–0.002451**	**–0.002483**	**–0.002402**	**–0.002335**	**–0.002278**	**–0.002308**	**–0.002298**	**–0.002214**	**–0.002062**	**0.000593**
Maximum	**N/A**	**0.002002**	**0.001869**	**0.001990**	**0.002186**	**0.002272**	**0.002380**	**0.002558**	**0.002705**	**0.002781**	**0.002984**	**0.003209**	**0.003484**	**0.003600**	**0.003587**
Average	**N/A**	**0.000608**	**0.000205**	**0.000291**	**0.000320**	**0.000244**	**0.000096**	**0.000523**	**0.001023**	**0.001191**	**0.001359**	**0.001508**	**0.001692**	**0.001863**	**0.002283**
Median	**N/A**	**0.001364**	**0.000286**	**0.000525**	**0.000956**	**0.000548**	**0.000572**	**0.001181**	**0.001660**	**0.002060**	**0.002409**	**0.002481**	**0.002385**	**0.002827**	**0.002236**
Std. Dev.	**N/A**	**0.001473**	**0.001606**	**0.001654**	**0.001644**	**0.001722**	**0.001874**	**0.001877**	**0.001785**	**0.001824**	**0.001946**	**0.002030**	**0.002067**	**0.002117**	**0.001151**

Table D-30 shows the D_{uv} of omni-directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Flicker

The baseline average percent flicker of all omni-directional LED medium screw-base products tested was 23.6 percent. For the average product, percent flicker ranged from a low of 0.39 percent to a high of 52.4 percent for baseline measurements. Some data omitted due to operator error during test.

Table D-31: Percent Flicker of Omni-Directional LED Medium Screw-Base Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	Flicker	Flicker	Flicker	Flicker	Flicker	Flicker	Flicker	Flicker	Flicker	Flicker	Flicker	Flicker	Flicker	Flicker	Flicker
MSB-4	N/A	0.33	0.58	0.53	0.61	0.61	0.39	0.47	dead	dead	dead	dead	dead	dead	0.3
MSB-5	N/A	10.40	10.81	10.84	10.77	10.63	10.43	10.32	10.14	N/A	N/A	9.86	9.73	9.65	1.2
MSB-6	N/A	29.19	30.04	30.18	29.65	30.08	17.28	29.53	29.43	30.09	30.01	30.13	30.12	30.90	13.6
MSB-7	N/A	17.86	18.46	18.22	18.39	22.37	14.50	26.65	28.01	N/A	N/A	13.25	35.63	28.49	22.4
MSB-9	N/A	13.51	27.93	27.87	27.93	27.62	27.59	27.56	27.68	N/A	N/A	27.76	27.36	27.33	14.4
MSB-12	N/A	49.27	49.49	49.35	48.62	51.75	50.72	dead	dead	dead	dead	dead	dead	dead	3.1
MSB-14	N/A	27.25	27.20	27.10	26.84	26.59	26.83	26.10	26.37	N/A	N/A	22.52	25.45	25.97	4.7
Minimum	**N/A**	**0.33**	**0.58**	**0.53**	**0.61**	**0.61**	**0.39**	**0.47**	**10.14**	**30.09**	**30.01**	**10**	**10**	**10**	**0.28**
Maximum	**N/A**	**49.27**	**49.49**	**49.35**	**48.62**	**51.75**	**50.72**	**29.53**	**29.43**	**30.09**	**30.01**	**30**	**36**	**31**	**22.38**
Average	**N/A**	**21.12**	**23.50**	**23.44**	**23.26**	**24.24**	**21.11**	**20.11**	**24.33**	**30.09**	**30.01**	**21**	**26**	**24**	**8.54**
Median	**N/A**	**17.86**	**27.20**	**27.10**	**26.84**	**26.59**	**17.28**	**26.38**	**27.68**	**30.09**	**30.01**	**23**	**27**	**27**	**4.73**
Std. Dev.	**N/A**	**14.69**	**14.46**	**14.45**	**14.20**	**14.90**	**14.90**	**10.84**	**7.16**	**0.00**	**0.00**	**8**	**9**	**8**	**7.73**

Table D-31 shows the percent flicker of omni-directional LED medium screw-base products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-32: Percent Flicker of Omni-Directional LED Medium Screw-Base Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**
MSB-4	N/A	0.39	0.68	4.06	0.73	0.68	0.48	0.47	dead	dead	dead	dead	dead	dead	3.7
MSB-5	N/A	10.53	10.93	10.97	10.92	10.80	10.54	10.42	10.28	N/A	N/A	9.97	9.94	9.81	1.2
MSB-6	N/A	30.49	31.40	31.10	30.98	31.27	29.36	31.26	30.70	31.56	31.31	30.70	31.04	31.37	2.2
MSB-7	N/A	18.21	18.77	18.59	19.90	23.69	24.97	27.49	28.90	N/A	N/A	38.48	37.80	35.97	20.3
MSB-9	N/A	25.66	28.39	28.61	28.35	28.16	28.29	28.12	28.10	N/A	N/A	28.44	27.97	27.85	3.0
MSB-12	N/A	52.43	51.17	51.03	50.57	51.84	50.75	dead	dead	dead	dead	dead	dead	dead	1.9
MSB-14	N/A	27.62	27.56	27.33	27.23	27.09	27.08	26.86	26.86	N/A	N/A	25.44	26.35	26.61	2.2
Minimum	**N/A**	**0.39**	**0.68**	**4.06**	**0.73**	**0.68**	**0.48**	**0.47**	**10.28**	**31.56**	**31.31**	**9.97**	**9.94**	**9.81**	**1.15**
Maximum	**N/A**	**52.43**	**51.17**	**51.03**	**50.57**	**51.84**	**50.75**	**31.26**	**30.70**	**31.56**	**31.31**	**38.48**	**37.80**	**35.97**	**20.27**
Average	**N/A**	**23.62**	**24.13**	**24.53**	**24.10**	**24.79**	**24.49**	**20.77**	**24.97**	**31.56**	**31.31**	**26.61**	**26.62**	**26.32**	**4.90**
Median	**N/A**	**25.66**	**27.56**	**27.33**	**27.23**	**27.09**	**27.08**	**27.17**	**28.10**	**31.56**	**31.31**	**28.44**	**27.97**	**27.85**	**2.20**
Std. Dev.	**N/A**	**15.30**	**14.96**	**14.18**	**14.70**	**14.97**	**14.67**	**11.30**	**7.45**	**0.00**	**0.00**	**9.37**	**9.22**	**8.87**	**6.32**

Table D-32 shows the percent flicker of omni-directional LED medium screw-base products for the average sample of each product measured.

Source: California Lighting Technology Center

Linear LED Replacement Products

The research team evaluated seven linear LED replacement products. Three products are marketed as UL Type A, one product is marketed as UL Type A/B, two products are marketed as UL Type B, and one product is marketed as UL Type C. Six samples of each product were tested. One sample of TLED-5 failed before it reached 2,000 hours of runtime due to operator error during photometric characterization.

The electrical and photometric performance of the UL Type A/B product was captured for the baseline performance in both UL Type A and UL Type B configurations. The UL Type A/B product was evaluated in the UL Type A configuration for the duration of testing as the more common retrofit scenario encountered in the field.

Power

The baseline average power of all linear LED replacement products tested was 24.1 Watts (W). For the average product, power ranged from a low of 15.5 W to a high of 44.8 W for baseline measurements.

Table D-33: Power of Linear LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**
TLED 1 (2-Lamp Configu-ration)	22.0	44.46	44.59	44.83	45.05	45.64	24.78	dead	dead	dead	dead	dead	dead	dead	20.9
TLED 2	22.0	16.37	16.40	10.38	10.39	10.38	10.42	10.45	10.44	10.29	10.34	10.32	10.31	10.32	6.1
TLED 3	15.0	15.42	15.40	15.43	15.43	15.42	15.44	15.36	15.44	15.42	15.44	15.44	15.43	15.44	0.1
TLED 4	18.0	17.77	17.78	17.74	17.76	17.76	17.78	17.77	17.77	17.78	17.78	17.74	17.76	17.75	0.0
TLED 5	15.0	25.25	25.15	25.22	25.30	25.40	25.37	25.55	24.95	25.37	25.26	25.50	25.04	25.49	0.6
TLED 6	14.0	26.66	26.66	26.67	26.62	26.51	26.83	26.89	26.27	26.55	26.48	26.67	26.39	26.84	0.6
TLED 7	15.0	21.25	21.44	16.28	15.68	14.67	14.51	14.92	4.00	21.41	21.69	21.72	17.68	21.48	17.7
Minimu m	**14.00**	**15.42**	**15.40**	**10.38**	**10.39**	**10.38**	**10.42**	**10.45**	**4.00**	**10.29**	**10.34**	**10.32**	**10.31**	**10.32**	**0.04**
Maximum	**22.00**	**44.46**	**44.59**	**44.83**	**45.05**	**45.64**	**26.83**	**26.89**	**26.27**	**26.55**	**26.48**	**26.67**	**26.39**	**26.84**	**20.86**
Average	**17.29**	**23.88**	**23.92**	**22.36**	**22.32**	**22.25**	**19.30**	**18.49**	**16.48**	**19.47**	**19.50**	**19.57**	**18.77**	**19.55**	**6.58**
Median	**15.00**	**21.25**	**21.44**	**17.74**	**17.76**	**17.76**	**17.78**	**16.57**	**16.61**	**19.60**	**19.74**	**19.73**	**17.72**	**19.62**	**0.62**
Std. Dev.	**3.19**	**9.30**	**9.33**	**10.57**	**10.68**	**10.96**	**5.89**	**5.89**	**7.77**	**5.66**	**5.63**	**5.72**	**5.51**	**5.74**	**8.32**

Table D-33 shows the power of linear LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-34: Power of Linear LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**
TLED 1 (2-Lamp Configu-ration)	22.0	44.77	44.83	45.26	47.68	45.76	24.78	dead	dead	dead	dead	dead	dead	dead	22.9
TLED 2	22.0	16.43	16.50	15.46	15.47	15.67	15.49	15.57	15.52	15.44	15.47	15.47	15.46	15.46	1.1
TLED 3	15.0	15.53	15.53	15.55	15.55	15.53	15.56	15.55	15.56	15.56	15.56	15.56	15.56	15.55	0.0
TLED 4	18.0	17.96	17.97	17.98	17.97	17.97	17.99	18.00	17.99	17.98	17.98	17.98	17.98	17.97	0.0
TLED 5	15.0	25.35	25.21	25.28	25.35	25.67	25.47	25.63	25.48	25.45	25.36	25.62	25.11	25.56	0.6
TLED 6	14.0	26.85	26.91	26.81	26.82	27.16	16.90	27.12	26.86	26.73	26.75	26.88	26.54	27.06	10.3
TLED 7	15.0	21.71	21.73	20.83	19.89	21.68	20.65	20.86	17.68	21.68	21.81	21.89	20.41	21.69	4.2
Minimum	**14.00**	**15.53**	**15.53**	**15.46**	**15.47**	**15.53**	**15.49**	**15.55**	**15.52**	**15.44**	**15.47**	**15.47**	**15.46**	**15.46**	**0.03**
Maximum	**22.00**	**44.77**	**44.83**	**45.26**	**47.68**	**45.76**	**25.47**	**27.12**	**26.86**	**26.73**	**26.75**	**26.88**	**26.54**	**27.06**	**22.90**
Average	**17.29**	**24.09**	**24.10**	**23.88**	**24.10**	**24.21**	**19.55**	**20.46**	**19.85**	**20.47**	**20.49**	**20.56**	**20.17**	**20.55**	**5.58**
Median	**15.00**	**21.71**	**21.73**	**20.83**	**19.89**	**21.68**	**17.99**	**19.43**	**17.84**	**19.83**	**19.90**	**19.93**	**19.19**	**19.83**	**1.06**
Std. Dev.	**3.19**	**9.35**	**9.36**	**9.65**	**10.47**	**9.77**	**3.88**	**4.57**	**4.59**	**4.49**	**4.48**	**4.56**	**4.34**	**4.59**	**7.85**

Table D-34 shows the power of linear LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Luminous Output

The baseline average luminous output of all linear LED replacement products tested was 1,981.4 lumens. For the average product, the luminous output ranged from a low of 1,507 lumens to a high of 2,452 lumens for baseline measurements.

Table D-35: Luminous Output of Linear LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**
TLED 1 (2-Lamp Configu-ration)	2,250	2,092	2,132	2,156	2,136	2,148	2,212	dead	dead	dead	dead	dead	dead	dead	120.0
TLED 2	2,290	1,488	1,506	806	809	824	799	802	796	797	812	827	819	801	710.0
TLED 3	1,800	1,711	1,729	1,753	1,745	1,762	1,713	1,721	1,702	1,705	1,694	1,739	1,751	1,687	75.0
TLED 4	2,200	2,044	2,024	2,050	2,062	2,085	2,046	2,053	2,026	2,018	2,035	2,092	2,079	2,031	74.0
TLED 5	2,000	2,443	2,475	2,521	2,524	2,528	2,481	2,492	2,452	2,471	2,517	2,599	2,530	2,535	156.0
TLED 6	1,800	2,384	2,390	2,437	2,429	2,401	2,340	2,331	2,232	2,199	2,177	2,167	2,153	2,122	315.0
TLED 7	1,600	1,560	1,570	1,244	1,238	1,255	1,226	1,225	47	1,585	1,623	1,650	1,209	1,586	1,603.0
Minimum	**1,600.00**	**1,488.00**	**1,506.00**	**806.00**	**809.00**	**824.00**	**799.00**	**802.00**	**47.00**	**797.00**	**812.00**	**826.60**	**818.50**	**801.00**	**74.00**
Maximum	**2,290.00**	**2,443.00**	**2,475.00**	**2,521.00**	**2,524.00**	**2,528.00**	**2,481.00**	**2,492.00**	**2,452.00**	**2,471.00**	**2,517.00**	**2,599.00**	**2,530.00**	**2,535.00**	**1,603.00**
Average	**1,991.43**	**1,960.29**	**1,975.14**	**1,852.43**	**1,849.00**	**1,857.57**	**1,831.00**	**1,770.67**	**1,542.50**	**1,795.83**	**1,809.67**	**1,845.60**	**1,756.75**	**1,793.67**	**436.14**
Median	**2,000.00**	**2,044.00**	**2,024.00**	**2,050.00**	**2,062.00**	**2,085.00**	**2,046.00**	**1,887.00**	**1,864.00**	**1,861.50**	**1,864.50**	**1,915.50**	**1,915.00**	**1,859.00**	**156.00**
Std. Dev.	**246.72**	**355.03**	**357.33**	**584.93**	**583.77**	**575.87**	**575.44**	**598.96**	**852.02**	**535.12**	**536.90**	**550.70**	**582.97**	**540.62**	**519.78**

Table D-35 shows the luminous output of linear LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-36: Luminous Output of Linear LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**
TLED 1 (2-Lamp Configu-ration)	2,250	2,134	2,162	2,193	2,177	2,189	2,212	dead	dead	dead	dead	dead	dead	dead	78.0
TLED 2	2,290	1,507	1,520	1,411	1,357	1,435	1,396	1,400	1,389	1,385	1,411	1,434	1,420	1,387	163.0
TLED 3	1,800	1,720	1,739	1,761	1,752	1,770	1,723	1,730	1,712	1,714	1,704	1,751	1,760	1,696	73.8
TLED 4	2,200	2,065	2,048	2,078	2,085	2,110	2,063	2,080	2,043	2,033	2,051	2,109	2,095	2,047	77.0
TLED 5	2,000	2,452	2,486	2,551	2,536	2,536	2,492	2,507	2,481	2,483	2,523	2,609	2,542	2,552	157.4
TLED 6	1,800	2,405	2,410	2,458	2,450	2,440	2,379	2,362	2,274	2,233	2,218	2,215	2,185	2,146	311.8
TLED 7	1,600	1,587	1,594	1,564	1,400	1,579	1,547	1,542	1,213	1,605	1,640	1,666	1,498	1,586	453.3
Minimum	**1,600.00**	**1,507.00**	**1,520.00**	**1,411.00**	**1,411.00**	**1,411.00**	**1,411.00**	**1,411.00**	**1,411.00**	**1,411.00**	**1,411.00**	**1,433.93**	**1,419.92**	**1,387.17**	**30**
Maximum	**2,290.00**	**2,452.00**	**2,486.00**	**2,540.00**	**2,540.00**	**2,540.00**	**2,540.00**	**2,540.00**	**2,540.00**	**2,540.00**	**2,540.00**	**2,609.40**	**2,541.80**	**2,551.80**	**109**
Average	**1,991.43**	**1,981.43**	**1,994.14**	**2,000.71**	**2,000.71**	**2,000.71**	**2,000.71**	**2,000.71**	**2,000.71**	**2,000.71**	**2,000.71**	**1,964.19**	**1,916.31**	**1,902.44**	**58.57**
Median	**2,000.00**	**2,065.00**	**2,048.00**	**2,078.00**	**2,078.00**	**2,078.00**	**2,078.00**	**2,078.00**	**2,078.00**	**2,078.00**	**2,078.00**	**1,930.08**	**1,927.00**	**1,871.75**	**53**
Std. Dev.	**246.72**	**354.59**	**357.76**	**403.35**	**403.35**	**403.35**	**403.35**	**403.35**	**403.35**	**403.35**	**403.35**	**390.64**	**396.06**	**389.50**	**27.73**

Table D-36 shows the luminous output of linear LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Efficacy

The baseline average efficacy of all linear LED replacement products tested was 96.1 lumens per watt. For the average product, the efficacy ranged from a low of 73.1 lumens per watt to a high of 114.7 lumens per watt for baseline measurements.

Table D-37: Efficacy (lm/W) of Linear LED Replacement Products – Minimum Sample Measured

	Manufacturer Claimed Performance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**
TLED 1 (2-Lamp Configuration)	102.27	93.57	94.00	94.77	80.85	93.62	178.53	dead	dead	dead	dead	dead	dead	dead	97.7
TLED 2	104.09	90.73	91.10	77.61	77.83	79.41	76.63	76.70	76.25	77.47	78.55	80.10	79.39	77.62	14.9
TLED 3	120.00	109.71	110.91	111.99	111.29	112.95	109.18	109.69	108.48	108.67	107.97	110.83	111.60	107.59	5.4
TLED 4	122.22	113.33	112.56	113.64	114.69	116.16	113.48	114.35	112.49	111.94	112.86	116.23	115.35	113.04	4.3
TLED 5	133.33	95.89	98.29	99.80	99.29	97.39	97.34	97.17	95.51	97.33	99.13	101.44	100.84	99.02	5.9
TLED 6	128.57	88.95	87.29	91.06	90.91	89.22	87.18	85.30	83.64	82.41	81.17	80.59	81.31	78.36	12.7
TLED 7	106.67	72.70	72.84	74.30	73.12	68.48	73.28	70.22	11.75	72.50	73.91	75.15	68.38	73.84	63.4
Minimum	**102.27**	**72.70**	**72.84**	**74.30**	**73.12**	**68.48**	**73.28**	**70.22**	**11.75**	**72.50**	**73.91**	**75.15**	**68.38**	**73.84**	**4.29**
Maximum	**133.33**	**113.33**	**112.56**	**113.64**	**114.69**	**116.16**	**178.53**	**114.35**	**112.49**	**111.94**	**112.86**	**116.23**	**115.35**	**113.04**	**97.68**
Average	**116.74**	**94.98**	**95.28**	**94.74**	**92.57**	**93.89**	**105.09**	**92.24**	**81.35**	**91.72**	**92.27**	**94.06**	**92.81**	**91.58**	**29.17**
Median	**120.00**	**93.57**	**94.00**	**94.77**	**90.91**	**93.62**	**97.34**	**91.24**	**89.58**	**89.87**	**90.15**	**91.02**	**91.08**	**88.69**	**12.70**
Std. Dev.	**11.51**	**12.58**	**12.75**	**14.17**	**15.22**	**15.81**	**33.13**	**16.29**	**33.62**	**15.20**	**15.09**	**16.13**	**17.49**	**15.58**	**33.95**

Table D-37 shows the efficacy of linear LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-38: Efficacy (lm/W) of Linear LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**
TLED 1 (2-Lamp Configu-ration)	102.27	95.32	96.44	96.90	91.84	95.21	178.53	dead	dead	dead	dead	dead	dead	dead	86.7
TLED 2	104.09	91.67	92.14	90.43	89.51	90.82	89.32	89.08	88.68	88.98	90.43	91.94	91.09	88.96	3.5
TLED 3	120.00	110.77	111.99	113.21	112.68	113.99	110.75	111.25	110.01	110.22	109.54	112.56	113.09	109.09	4.9
TLED 4	122.22	115.01	113.96	115.55	116.04	117.44	114.77	115.57	113.58	113.09	114.08	117.32	116.51	113.94	4.3
TLED 5	133.33	96.73	98.62	100.89	100.06	98.80	97.84	97.82	97.78	97.56	99.51	101.87	101.24	99.82	5.1
TLED 6	128.57	89.56	89.55	91.70	91.38	89.84	88.42	87.11	84.65	83.56	82.90	82.42	82.33	79.32	12.4
TLED 7	106.67	73.09	73.33	75.13	77.78	73.67	75.45	74.49	56.96	74.01	75.20	76.14	73.07	73.84	20.8
Minimum	**102.27**	**73.09**	**73.33**	**75.13**	**77.78**	**73.67**	**75.45**	**74.49**	**56.96**	**74.01**	**75.20**	**76.14**	**73.07**	**73.84**	**3.46**
Maximum	**133.33**	**115.01**	**113.96**	**115.55**	**116.04**	**117.44**	**178.53**	**115.57**	**113.58**	**113.09**	**114.08**	**117.32**	**116.51**	**113.94**	**86.69**
Average	**116.74**	**96.02**	**96.58**	**97.69**	**97.04**	**97.11**	**107.87**	**95.89**	**91.94**	**94.57**	**95.28**	**97.04**	**96.22**	**94.16**	**19.68**
Median	**120.00**	**95.32**	**96.44**	**96.90**	**91.84**	**95.21**	**97.84**	**93.45**	**93.23**	**93.27**	**94.97**	**96.90**	**96.16**	**94.39**	**5.14**
Std. Dev.	**11.51**	**12.90**	**12.84**	**12.92**	**12.54**	**13.87**	**31.45**	**14.19**	**18.78**	**13.98**	**13.87**	**15.01**	**15.69**	**14.75**	**27.96**

Table D-38 shows the efficacy of linear LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Power Factor

The baseline average power factor of all linear LED replacement products tested was 0.99. For the average product, the power factor ranged from a low of 0.97 to a high of 0.99 for baseline measurements.

Table D-39: Power Factor of Linear LED Replacement Products – Minimum Sample Measured

	Manufacturer Claimed Performance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**
TLED 1 (2-Lamp Configuration)	0.90	0.99	0.99	0.99	0.99	0.99	0.75	dead	dead	dead	dead	dead	dead	dead	0.2
TLED 2	0.95	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.97	0.97	0.0
TLED 3	N/A	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.0
TLED 4	0.90	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.0
TLED 5	N/A	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.0
TLED 6	N/A	0.99	0.99	0.97	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.0
TLED 7	N/A	0.96	0.99	0.96	0.97	0.96	0.98	0.98	0.94	0.98	0.99	0.99	0.98	0.99	0.1
Minimum	**0.90**	**0.96**	**0.97**	**0.96**	**0.97**	**0.96**	**0.75**	**0.97**	**0.94**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.00**
Maximum	**0.95**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.24**
Average	**0.92**	**0.98**	**0.99**	**0.98**	**0.98**	**0.98**	**0.95**	**0.98**	**0.98**	**0.98**	**0.98**	**0.98**	**0.98**	**0.98**	**0.05**
Median	**0.90**	**0.99**	**0.99**	**0.98**	**0.99**	**0.99**	**0.98**	**0.99**	**0.99**	**0.99**	**0.99**	**0.98**	**0.98**	**0.98**	**0.02**
Std. Dev.	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.08**	**0.01**	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.08**

Table D-39 shows the power factor of linear LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-40: Power Factor of Linear LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**
TLED 1 (2-Lamp Configu-ration)	0.90	0.99	0.99	0.99	0.99	0.99	0.75	dead	dead	dead	dead	dead	dead	dead	0.2
TLED 2	0.95	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.0
TLED 3	N/A	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.0
TLED 4	0.90	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.0
TLED 5	N/A	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.0
TLED 6	N/A	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.0
TLED 7	N/A	0.98	0.99	0.98	0.98	0.98	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.0
Minimum	**0.90**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.75**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.00**
Maximum	**0.95**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.24**
Average	**0.92**	**0.98**	**0.99**	**0.98**	**0.98**	**0.98**	**0.95**	**0.99**	**0.98**	**0.99**	**0.99**	**0.98**	**0.98**	**0.98**	**0.04**
Median	**0.90**	**0.99**	**0.99**	**0.98**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.98**	**0.98**	**0.98**	**0.01**
Std. Dev.	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.08**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.08**

Table D-40 shows the power factor of linear LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Color Rendering Index

The average CRI of all linear LED replacement products tested was initially 83.6. For the average product, the CRI ranged from a low of 81.8 to a high of 85.7 for baseline measurements.

Table D-41: CRI of Linear LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**
TLED 1 (2-Lamp Configu-ration)	80.0	82.4	82.4	82.3	82.3	82.3	83.5	dead	dead	dead	dead	dead	dead	dead	1.2
TLED 2	80.0	85.2	85.2	85.1	85.0	85.0	85.0	85.1	85.0	85.0	85.1	85.0	85.0	85.0	0.3
TLED 3	80.0	81.7	81.6	81.6	81.7	81.6	81.7	81.6	81.8	81.8	81.8	81.8	81.9	82.0	0.4
TLED 4	85.0	84.4	84.2	84.3	84.1	84.2	84.2	84.2	84.2	84.2	84.3	84.4	84.3	84.3	0.3
TLED 5	82.0	82.6	82.7	82.8	82.7	82.7	82.7	82.7	82.7	82.7	82.7	82.6	82.7	82.7	0.2
TLED 6	83.0	85.6	85.5	85.5	85.4	85.4	85.7	85.6	85.7	85.7	85.9	86.0	86.0	86.0	0.6
TLED 7	80.0	81.8	81.7	81.7	81.8	81.7	81.7	81.6	81.8	81.7	81.7	81.7	81.8	81.8	0.2
Minimum	**80.00**	**81.68**	**81.58**	**81.60**	**81.70**	**81.60**	**81.70**	**81.60**	**81.80**	**81.70**	**81.70**	**81.74**	**81.77**	**81.78**	**0.18**
Maximum	**85.00**	**85.60**	**85.46**	**85.50**	**85.40**	**85.40**	**85.70**	**85.60**	**85.70**	**85.70**	**85.90**	**85.98**	**85.97**	**86.04**	**1.20**
Average	**81.43**	**83.39**	**83.30**	**83.33**	**83.29**	**83.27**	**83.50**	**83.47**	**83.53**	**83.52**	**83.58**	**83.59**	**83.60**	**83.64**	**0.45**
Median	**80.00**	**82.62**	**82.66**	**82.80**	**82.70**	**82.70**	**83.50**	**83.45**	**83.45**	**83.45**	**83.50**	**83.50**	**83.48**	**83.53**	**0.27**
Std. Dev.	**1.84**	**1.52**	**1.51**	**1.50**	**1.42**	**1.46**	**1.45**	**1.60**	**1.53**	**1.55**	**1.62**	**1.62**	**1.57**	**1.59**	**0.34**

Table D-41 shows the CRI of linear LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-42: CRI of Linear LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**
TLED 1 (2-Lamp Configu-ration)	80.0	83.1	83.1	83.0	83.1	83.1	83.5	dead	dead	dead	dead	dead	dead	dead	0.5
TLED 2	80.0	85.4	85.4	85.4	85.3	85.3	85.4	85.3	85.4	85.4	85.4	85.4	85.4	85.4	0.1
TLED 3	80.0	81.8	81.6	81.7	81.7	81.7	81.8	81.8	81.8	81.8	81.9	81.9	82.0	82.0	0.4
TLED 4	85.0	84.5	84.4	84.4	84.3	84.4	84.4	84.4	84.4	84.4	84.6	84.6	84.5	84.5	0.3
TLED 5	82.0	82.7	82.8	82.9	82.8	82.8	82.8	82.7	82.8	82.7	82.8	82.7	82.8	82.8	0.2
TLED 6	83.0	85.7	85.5	85.6	85.4	85.5	85.7	85.7	85.8	85.8	86.0	86.1	86.1	86.2	0.8
TLED 7	80.0	81.9	81.7	81.8	81.9	81.8	81.8	81.7	82.1	81.7	81.7	81.8	81.9	81.8	0.4
Minimum	**80.00**	**81.79**	**81.64**	**81.70**	**81.70**	**81.70**	**81.80**	**81.70**	**81.80**	**81.70**	**81.70**	**81.78**	**81.87**	**81.78**	**0.14**
Maximum	**85.00**	**85.66**	**85.50**	**85.60**	**85.40**	**85.50**	**85.70**	**85.70**	**85.80**	**85.80**	**86.00**	**86.12**	**86.11**	**86.17**	**0.77**
Average	**81.43**	**83.58**	**83.50**	**83.54**	**83.50**	**83.51**	**83.63**	**83.60**	**83.72**	**83.63**	**83.73**	**83.76**	**83.78**	**83.79**	**0.39**
Median	**80.00**	**83.08**	**83.08**	**83.00**	**83.10**	**83.10**	**83.50**	**83.55**	**83.60**	**83.55**	**83.70**	**83.66**	**83.62**	**83.67**	**0.40**
Std. Dev.	**1.84**	**1.49**	**1.49**	**1.49**	**1.41**	**1.46**	**1.48**	**1.61**	**1.57**	**1.65**	**1.68**	**1.69**	**1.66**	**1.68**	**0.19**

Table D-42 shows the CRI of linear LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Correlated Color Temperature

The average correlated color temperature (CCT) of all linear LED replacement products tested was initially 3,183 Kelvin. For the average product, the CCT ranged from a low of 2,954 Kelvin to a high of 3,485 Kelvin for baseline measurements.

Table D-43: Correlated Color Temperature of Linear LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT	CCT
TLED 1 (2-Lamp Configu-ration)	3,500.0	3,413	3,421	3,433	3,475	3,496	3,514	dead	dead	dead	dead	dead	dead	dead	101.0
TLED 2	3,000.0	2,999	3,009	3,017	3,031	3,018	3,017	3,017	3,019	3,024	3,022	3,049	3,052	3,044	53.0
TLED 3	3,000.0	2,974	2,976	2,985	2,991	2,991	2,989	2,989	2,995	2,996	2,996	3,017	3,028	3,021	54.0
TLED 4	3,500.0	3,369	3,374	3,381	3,384	3,383	3,381	3,383	3,385	3,385	3,389	3,422	3,424	3,414	55.0
TLED 5	3,000.0	2,999	3,019	3,036	3,029	3,026	3,026	3,027	3,034	3,029	3,029	3,052	3,049	3,047	53.0
TLED 6	3,000.0	3,471	3,481	3,486	3,507	3,505	3,512	3,524	3,538	3,556	3,573	3,622	3,619	3,645	174.0
TLED 7	3,000.0	2,949	2,951	2,857	2,964	2,959	2,955	2,952	2,928	2,955	2,959	2,977	2,977	2,966	120.0
Minimum	**3,000.00**	**2,949.00**	**2,951.00**	**2,857.00**	**2,964.00**	**2,959.00**	**2,955.00**	**2,952.00**	**2,928.00**	**2,955.00**	**2,959.00**	**2,977.00**	**2,977.00**	**2,966.00**	**53.00**
Maximum	**3,500.00**	**3,471.00**	**3,481.00**	**3,486.00**	**3,507.00**	**3,505.00**	**3,514.00**	**3,524.00**	**3,538.00**	**3,556.00**	**3,573.00**	**3,622.00**	**3,619.00**	**3,645.00**	**174.00**
Average	**3,142.86**	**3,167.71**	**3,175.86**	**3,170.71**	**3,197.29**	**3,196.86**	**3,199.14**	**3,148.67**	**3,149.83**	**3,157.50**	**3,161.33**	**3,189.83**	**3,191.50**	**3,189.50**	**87.14**
Median	**3,000.00**	**2,999.00**	**3,019.00**	**3,036.00**	**3,031.00**	**3,026.00**	**3,026.00**	**3,022.00**	**3,026.50**	**3,026.50**	**3,025.50**	**3,050.50**	**3,050.50**	**3,045.50**	**55.00**
Std. Dev.	**225.88**	**218.75**	**218.90**	**235.16**	**227.05**	**232.75**	**238.15**	**220.64**	**227.19**	**228.03**	**233.27**	**243.13**	**241.29**	**250.90**	**43.55**

Table D-43 shows the CCT of linear LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-44: Correlated Color Temperature of Linear LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**
TLED 1 (2-Lamp Configu-ration)	3,500.0	3,444	3,462	3,475	3,496	3,509	3,514	dead	dead	dead	dead	dead	dead	dead	70.0
TLED 2	3,000.0	3,022	3,031	3,037	3,043	3,040	3,039	3,038	3,041	3,044	3,041	3,069	3,071	3,062	49.2
TLED 3	3,000.0	2,983	2,987	2,997	3,004	3,007	3,004	3,005	3,011	3,012	3,012	3,035	3,043	3,038	60.3
TLED 4	3,500.0	3,382	3,387	3,393	3,399	3,397	3,393	3,398	3,401	3,401	3,407	3,438	3,442	3,435	59.5
TLED 5	3,000.0	3,012	3,031	3,039	3,043	3,039	3,037	3,039	3,045	3,042	3,041	3,062	3,064	3,059	51.6
TLED 6	3,000.0	3,485	3,490	3,501	3,511	3,515	3,525	3,544	3,563	3,587	3,606	3,662	3,657	3,680	194.8
TLED 7	3,000.0	2,954	2,954	2,961	2,965	2,962	2,958	2,955	2,954	2,958	2,963	2,980	2,978	2,966	26.3
Minimum	**3,000.00**	**2,954**	**2,954**	**2,961**	**2,965**	**2,962**	**2,958**	**2,955**	**2,954**	**2,958**	**2,963**	**2,980**	**2,978**	**2,966**	**26**
Maximum	**3,500.00**	**3,485**	**3,490**	**3,501**	**3,511**	**3,515**	**3,525**	**3,544**	**3,563**	**3,587**	**3,606**	**3,662**	**3,657**	**3,680**	**195**
Average	**3,142.86**	**3,183**	**3,192**	**3,200**	**3,209**	**3,210**	**3,210**	**3,163**	**3,169**	**3,174**	**3,178**	**3,208**	**3,209**	**3,207**	**73**
Median	**3,000.00**	**3,022**	**3,031**	**3,039**	**3,043**	**3,040**	**3,039**	**3,039**	**3,043**	**3,043**	**3,041**	**3,065**	**3,067**	**3,061**	**60**
Std. Dev.	**225.88**	**222**	**224**	**225**	**229**	**232**	**236**	**223**	**228**	**234**	**240**	**252**	**250**	**260**	**51**

Table D-44 shows the CCT of linear LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

D_{UV}

The average D_{UV} of all linear LED replacement products tested was initially -0.000924. For the average product, the D_{UV} ranged from a low of -0.002095 to a high of 0.000278 for baseline measurements.

Table D-45: D_{UV} of Linear LED Replacement Products – Minimum Sample Measured

	Manufacturer Claimed Performance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**
TLED 1 (2-Lamp Configu-ration)	N/A	-0.001402	-0.001304	-0.001237	-0.001248	-0.001270	-0.001462	dead	dead	dead	dead	dead	dead	dead	0.000225
TLED 2	N/A	-0.002366	-0.002597	-0.002626	-0.002509	-0.002511	-0.002528	-0.002484	-0.002582	-0.002669	-0.002613	-0.002589	-0.002631	-0.002549	0.000303
TLED 3	N/A	-0.001544	-0.001593	-0.001705	-0.001685	-0.001737	-0.001779	-0.001685	-0.001811	-0.001875	-0.001864	-0.001993	-0.002048	-0.002075	0.000531
TLED 4	N/A	-0.001149	-0.001055	-0.001047	-0.001066	-0.001068	-0.001133	-0.001031	-0.001024	-0.001173	-0.001213	-0.001170	-0.001127	-0.001131	0.000189
TLED 5	N/A	0.000159	0.000176	0.000281	0.000163	0.000191	0.000195	0.000187	0.000197	0.000174	0.000221	0.000193	0.000282	0.000251	0.000123
TLED 6	N/A	-0.001102	-0.000898	-0.000950	-0.000903	-0.000879	-0.001058	-0.001100	-0.001193	-0.001311	-0.001543	-0.001550	-0.001691	-0.001764	0.000885
TLED 7	N/A	-0.000698	-0.000546	-0.000685	-0.000667	-0.000579	-0.000683	-0.000646	-0.001776	-0.000599	-0.000628	-0.000662	-0.000643	0.000438	0.002214
Minimum	**N/A**	**-0.002366**	**-0.002597**	**-0.002626**	**-0.002509**	**-0.002511**	**-0.002528**	**-0.002484**	**-0.002582**	**-0.002669**	**-0.002613**	**0.00**	**0.00**	**0.00**	**0.000123**
Maximum	**N/A**	**0.000159**	**0.000176**	**0.000281**	**0.000163**	**0.000191**	**0.000195**	**0.000187**	**0.000197**	**0.000174**	**0.000221**	**0.00**	**0.00**	**0.00**	**0.002214**
Average	**N/A**	**-0.001157**	**-0.001117**	**-0.001138**	**-0.001131**	**-0.001122**	**-0.001207**	**-0.001127**	**-0.001365**	**-0.001242**	**-0.001273**	**0.00**	**0.00**	**0.00**	**0.000639**
Median	**N/A**	**-0.001149**	**-0.001055**	**-0.001047**	**-0.001066**	**-0.001068**	**-0.001133**	**-0.001066**	**-0.001485**	**-0.001242**	**-0.001378**	**0.00**	**0.00**	**0.00**	**0.000303**
Std. Dev.	**N/A**	**0.000719**	**0.000802**	**0.000829**	**0.000771**	**0.000794**	**0.000793**	**0.000829**	**0.000860**	**0.000900**	**0.000901**	**0.00**	**0.00**	**0.00**	**0.000687**

Table D-45 shows the D_{uv} of linear LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-46: D_{UV} of Linear LED Replacement Products – Average Sample Measured

Product Tested	Manufacturer Claimed Performance	Average Sample Measured: Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	Difference Between Min. and Max. Runtime Data
	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv	Duv
TLED 1 (2-Lamp Configu-ration)	N/A	-0.001108	-0.001028	-0.000998	-0.001046	-0.001109	-0.001462	dead	dead	dead	dead	dead	dead	dead	0.000464
TLED 2	N/A	-0.002095	-0.002305	-0.002232	-0.002127	-0.002137	-0.002136	-0.002081	-0.002144	-0.002260	-0.002187	-0.002151	-0.002207	-0.002140	0.000224
TLED 3	N/A	-0.001276	-0.001351	-0.001430	-0.001462	-0.001513	-0.001536	-0.001473	-0.001544	-0.001618	-0.001607	-0.001758	-0.001811	-0.001899	0.000623
TLED 4	N/A	-0.000954	-0.000812	-0.000774	-0.000789	-0.000773	-0.000776	-0.000793	-0.000782	-0.000887	-0.000925	-0.000840	-0.000812	-0.000855	0.000181
TLED 5	N/A	0.000278	0.000326	0.000368	0.000349	0.000388	0.000362	0.000394	0.000389	0.000345	0.000395	0.000447	0.000506	0.000474	0.000228
TLED 6	N/A	-0.000824	-0.000651	-0.000668	-0.000683	-0.000657	-0.000858	-0.000932	-0.001049	-0.001198	-0.001379	-0.001419	-0.001505	-0.001541	0.000890
TLED 7	N/A	-0.000488	-0.000513	-0.000539	-0.000583	0.000055	-0.000240	-0.000516	-0.000399	-0.000245	-0.000247	-0.000548	-0.000528	0.000438	0.001021
Minimum	**N/A**	**-0.002095**	**-0.002305**	**-0.002232**	**-0.002127**	**-0.002137**	**-0.002136**	**-0.002081**	**-0.002144**	**-0.002260**	**-0.002187**	**-0.002151**	**-0.002207**	**-0.002140**	**0.000181**
Maximum	**N/A**	**0.000278**	**0.000326**	**0.000368**	**0.000349**	**0.000388**	**0.000362**	**0.000394**	**0.000389**	**0.000345**	**0.000395**	**0.000447**	**0.000506**	**0.000474**	**0.001021**
Average	**N/A**	**-0.000924**	**-0.000905**	**-0.000896**	**-0.000906**	**-0.000821**	**-0.000950**	**-0.000900**	**-0.000921**	**-0.000977**	**-0.000992**	**-0.001045**	**-0.001060**	**-0.000920**	**0.000519**
Median	**N/A**	**-0.000954**	**-0.000812**	**-0.000774**	**-0.000789**	**-0.000773**	**-0.000858**	**-0.000863**	**-0.000916**	**-0.001043**	**-0.001152**	**-0.001129**	**-0.001158**	**-0.001198**	**0.000464**
Std. Dev.	**N/A**	**0.000673**	**0.000748**	**0.000744**	**0.000713**	**0.000806**	**0.000782**	**0.000770**	**0.000807**	**0.000856**	**0.000860**	**0.000855**	**0.000901**	**0.001051**	**0.000314**

Table D-46 shows the D_{uv} of linear LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Flicker

The average percent flicker of all linear LED replacement products tested was initially 15.36 percent. For the average product, the percent flicker ranged from a low of 0.15 percent to a high of 33.02 percent for baseline measurements.

Table D-47: Percent Flicker of Linear LED Replacement Products - Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**
TLED 1 (2-Lamp Configu-ration)	N/A	0.14	0.17	0.13	0.12	0.10	0.07	dead	dead	dead	dead	dead	dead	dead	0.1
TLED 2	N/A	0.96	0.83	0.69	0.78	0.66	0.67	0.59	0.60	N/A	N/A	0.95	0.65	0.75	0.4
TLED 3	N/A	19.37	35.25	35.21	35.05	35.01	35.02	35.01	35.02	N/A	N/A	34.95	34.95	34.87	15.9
TLED 4	N/A	29.57	20.14	32.89	34.89	36.47	36.04	35.84	36.92	N/A	N/A	41.39	41.39	41.36	21.3
TLED 5	N/A	5.97	5.38	1.11	5.29	4.92	3.57	4.15	5.40	N/A	N/A	5.71	6.11	5.74	5.0
TLED 6	N/A	16.32	15.28	5.87	15.70	10.22	9.83	9.88	11.39	N/A	N/A	15.47	15.47	16.03	10.5
TLED 7	N/A	17.02	17.46	0.23	0.37	0.19	0.21	0.20	11.09	N/A	N/A	15.17	0.51	16.97	17.3
Minimum	**N/A**	**0.14**	**0.17**	**0.13**	**0.12**	**0.10**	**0.07**	**0.20**	**0.60**	**N/A**	**N/A**	**0.95**	**0.51**	**0.75**	**0.10**
Maximum	**N/A**	**29.57**	**35.25**	**35.21**	**35.05**	**36.47**	**36.04**	**35.84**	**36.92**	**N/A**	**N/A**	**41.39**	**41.39**	**41.36**	**21.25**
Average	**N/A**	**12.76**	**13.50**	**10.88**	**13.17**	**12.51**	**12.20**	**14.28**	**16.74**	**N/A**	**N/A**	**18.94**	**16.51**	**19.29**	**10.05**
Median	**N/A**	**16.32**	**15.28**	**1.11**	**5.29**	**4.92**	**3.57**	**7.02**	**11.24**	**N/A**	**N/A**	**15.32**	**10.79**	**16.50**	**10.45**
Std. Dev.	**N/A**	**10.01**	**11.59**	**14.78**	**14.67**	**15.07**	**15.09**	**15.29**	**14.09**	**N/A**	**N/A**	**14.64**	**16.21**	**14.57**	**7.84**

Table D-47 shows the percent flicker of linear LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-48: Percent Flicker of Linear LED Replacement Products - Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**
TLED 1 (2-Lamp Configu-ration)	N/A	0.15	0.18	0.14	0.14	0.11	0.07	dead	dead	dead	dead	dead	dead	dead	0.1
TLED 2	N/A	0.97	1.00	0.91	0.98	0.87	0.89	0.91	0.86	N/A	N/A	0.69	0.92	0.96	0.3
TLED 3	N/A	33.02	35.97	35.93	35.82	35.76	35.80	35.64	35.75	N/A	N/A	35.72	35.70	35.65	2.9
TLED 4	N/A	32.35	38.82	34.55	36.31	37.70	37.29	37.28	38.35	N/A	N/A	43.36	43.41	43.41	11.1
TLED 5	N/A	6.22	8.94	1.81	5.80	5.24	3.81	4.37	5.76	N/A	N/A	5.98	6.19	5.89	7.1
TLED 6	N/A	17.13	16.44	6.72	16.69	10.50	10.21	11.14	12.64	N/A	N/A	16.78	16.62	16.93	10.4
TLED 7	N/A	17.69	18.13	14.13	12.08	13.95	13.94	14.02	16.23	N/A	N/A	44.11	11.82	17.56	32.3
Minimum	**N/A**	**0.15**	**0.18**	**0.14**	**0.14**	**0.11**	**0.07**	**0.91**	**0.86**	**N/A**	**N/A**	**0.69**	**0.92**	**0.96**	**0.11**
Maximum	**N/A**	**33.02**	**38.82**	**35.93**	**36.31**	**37.70**	**37.29**	**37.28**	**38.35**	**N/A**	**N/A**	**44.11**	**43.41**	**43.41**	**32.29**
Average	**N/A**	**15.36**	**17.07**	**13.46**	**15.40**	**14.87**	**14.57**	**17.23**	**18.26**	**N/A**	**N/A**	**24.44**	**19.11**	**20.06**	**9.18**
Median	**N/A**	**17.13**	**16.44**	**6.72**	**12.08**	**10.50**	**10.21**	**12.58**	**14.43**	**N/A**	**N/A**	**26.25**	**14.22**	**17.25**	**7.13**
Std. Dev.	**N/A**	**12.71**	**14.35**	**14.47**	**14.14**	**14.56**	**14.63**	**14.26**	**14.17**	**N/A**	**N/A**	**17.49**	**15.40**	**15.11**	**10.30**

Table D-48 shows the percent flicker of linear LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

UL Type A/B Results

The research team evaluated one UL Type A/B product, TLED-7. The electrical and photometric performance of TLED-7 was captured for the baseline performance in both UL Type A and UL Type B configurations. Runtime data for TLED-7 after the baseline characterization was evaluated in the UL Type A configuration.

Power

The power of the average TLED-7 product tested in UL Type A configuration was initially 21.7 Watts and 15.4 Watts in the UL Type B configuration. The UL Type B configuration consumes 6.3 Watts less than the UL Type A configuration, or 29 percent less.

Table D-49: Power of TLED-7 in UL Type A and UL Type B Configurations

	Manufacturer Claimed Performance	Minimum Sample Measured Baseline	Average Product Performance over Time
Product Tested	**Power (W)**	**Power (W)**	**Power (W)**
TLED 7 A	15.0	21.3	21.7
TLED 7 B	15.0	15.1	15.4
Minimum	**15.00**	**15.10**	**15.40**
Maximum	**15.00**	**21.30**	**21.70**
Average	**15.00**	**18.20**	**18.55**
Median	**15.00**	**18.20**	**18.55**
Std. Dev.	**0.00**	**3.10**	**3.15**

Table D-49 shows the power of TLED-7 for UL Type A and UL Type B configurations.

Source: California Lighting Technology Center

Luminous Output

The luminous output of the average TLED-7 product tested in UL Type A configuration was initially 1,587 lumens and 1,541 lumens in the UL Type B configuration. The UL Type B configuration produces 46 lumens less than the UL Type A configuration, or 2.8 percent less.

Table D-50: Luminous Output of TLED-7 in UL Type A and UL Type B Configurations

	Manufacturer Claimed Performance	Minimum Sample Measured Baseline	Average Product Performance over Time
Product Tested	**Output (lm)**	**Output (lm)**	**Output (lm)**
TLED 7 A	1,600	1,560.0	1,587
TLED 7 B	1,600	1,525	1,541
Minimum	**1,600**	**1,525**	**1,541**

	Manufacturer Claimed Performance	Minimum Sample Measured Baseline	Average Product Performance over Time
Product Tested	**Output (lm)**	**Output (lm)**	**Output (lm)**
Maximum	**1,600**	**1,560**	**1,587**
Average	**1,600**	**1,543**	**1,564**
Median	**1,600**	**1,543**	**1,564**
Std. Dev.	**0**	**18**	**23**

Table D-50 shows the luminous output of TLED-7 for UL Type A and UL Type B configurations.

Source: California Lighting Technology Center

Efficacy

The efficacy of the average TLED-7 product tested in UL Type A configuration was initially 73.1 lumens per watt and 100.1 lumens per watt in the UL Type B configuration. The UL Type B configuration increases the efficacy by 27 lumens per watt as compared to the UL Type A configuration, or a 37 percent increase. Table D-51 provides the initial minimum and average efficacy per linear LED replacement product UL Type configuration for TLED-7.

Table D-51: Efficacy of TLED-7 in UL Type A and UL Type B Configurations

	Manufacturer Claimed Performance	Minimum Sample Measured Baseline	Average Product Performance over Time
Product Tested	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**
TLED 7 A	106.7	73.2	73.1
TLED 7 B	106.7	101.0	100.1
Minimum	**106.67**	**73.24**	**73.13**
Maximum	**106.70**	**100.99**	**100.06**
Average	**106.68**	**87.12**	**86.60**
Median	**106.68**	**87.12**	**86.60**
Std. Dev.	**0.02**	**13.88**	**13.47**

Table D-51 shows the efficacy of TLED-7 for UL Type A and UL Type B configurations.

Source: California Lighting Technology Center

Power Factor

The power factor of the average TLED-7 product tested in UL Type A configuration was initially 1.0 and 0.95 in the UL Type B configuration. The UL Type B configuration power factor is 0.05 less than the UL Type A configuration, or five percent less.

Table D-52: Power Factor of TLED-7 in UL Type A and UL Type B Configurations

	Manufacturer Claimed Performance	Minimum Sample Measured Baseline	Average Product Performance over Time
Product Tested	**Power Factor**	**Power Factor**	**Power Factor**
TLED 7 A	N/A	1.00	1.00
TLED 7 B	N/A	0.95	0.95
Minimum	**N/A**	**0.95**	**0.95**
Maximum	**N/A**	**1.00**	**1.00**
Average	**N/A**	**0.98**	**0.98**
Median	**N/A**	**0.98**	**0.98**
Std. Dev.	**N/A**	**0.03**	**0.02**

Table D-52 shows the power factor of TLED-7 for UL Type A and UL Type B configurations.

Source: California Lighting Technology Center

Color Rendering Index

The CRI of the average TLED-7 product tested in UL Type A configuration was initially 81.91 and 81.88 in the UL Type B configuration. The UL Type B configuration CRI is 0.03 less than the UL Type A configuration, or 0.04 percent less. Table D-53 provides the initial minimum and average CRI per linear LED replacement product UL Type configuration for TLED-7.

Table D-53: CRI of TLED-7 in UL Type A and UL Type B Configurations

	Manufacturer Claimed Performance	Minimum Sample Measured Baseline	Average Product Performance over Time
Product Tested	**CRI**	**CRI**	**CRI**
TLED 7 A	80.0	81.8	81.9
TLED 7 B	80.0	81.9	81.9
Minimum	**80.00**	**81.84**	**81.88**
Maximum	**80.00**	**81.85**	**81.91**
Average	**80.00**	**81.85**	**81.90**
Median	**80.00**	**81.85**	**81.90**
Std. Dev.	**0.00**	**0.00**	**0.02**

Table D-53 shows the CRI of TLED-7 for UL Type A and UL Type B configurations.

Source: California Lighting Technology Center

Correlated Color Temperature

The CCT of the average TLED-7 product tested in UL Type A configuration was initially 2,954 Kelvin and 2,950.5 Kelvin in the UL Type B configuration. The UL Type B configuration CCT is

3.5 Kelvin less than the UL Type A configuration, or 0.1 percent less. Table D-54 provides the initial minimum and average CCT per linear LED replacement product UL Type configuration for TLED-7.

Table D-54: Correlated Color Temperature of TLED-7 in UL Type A and UL Type B Configurations

	Manufacturer Claimed Performance	Minimum Sample Measured Baseline	Average Product Performance over Time
Product Tested	**CCT**	**CCT**	**CCT**
TLED 7 A	3,000	2,949.0	2,954.0
TLED 7 B	3,000	2,945.0	2,950.5
Minimum	**3,000**	**2,945.00**	**2,950.50**
Maximum	**3,000**	**2,949.00**	**2,954.00**
Average	**3,000**	**2,947.00**	**2,952.25**
Median	**3,000**	**2,947.00**	**2,952.25**
Std. Dev.	**0**	**2.00**	**1.75**

Table D-54 shows the CCT of TLED-7 for UL Type A and UL Type B configurations.

Source: California Lighting Technology Center

D_{UV}

The D_{UV} of the average TLED-7 product tested in UL Type A configuration was initially -0.000488 and -0.000627 in the UL Type B configuration. The UL Type B configuration D_{UV} is 0.000139 further from the root locus than the UL Type A configuration. Table D-55 provides the initial minimum and average D_{UV} per linear LED replacement product UL Type configuration for TLED-7.

Table D-55: D_{UV} of TLED-7 in UL Type A and UL Type B Configurations

	Manufacturer Claimed Performance	Minimum Sample Measured Baseline	Average Product Performance over Time
Product Tested	**D_{UV}**	**D_{UV}**	**D_{UV}**
TLED 7 A	N/A	–0.000698	–0.000488
TLED 7 B	N/A	–0.000680	–0.000627
Minimum	**N/A**	**–0.000698**	**–0.000627**
Maximum	**N/A**	**–0.000680**	**–0.000488**
Average	**N/A**	**–0.000689**	**–0.000557**
Median	**N/A**	**–0.000689**	**–0.000557**
Std. Dev.	**N/A**	**0.000009**	**0.000070**

Table D-55 shows the D_{uv} of TLED-7 for UL Type A and UL Type B configurations.

Source: California Lighting Technology Center

Flicker

The percent flicker of the average TLED-7 product tested in UL Type A configuration was initially 17 percent and 27.6 percent in the UL Type B configuration. The UL Type B configuration percent flicker is 11 percent greater than the UL Type A configuration. Table D-56 provides the initial minimum and average percent flicker per linear LED replacement product UL Type configuration for TLED-7.

Table D-56: Flicker of TLED-7 in UL Type A and UL Type B Configurations

	Manufacturer Claimed Performance	Minimum Sample Measured Baseline	Average Product Performance over Time
Product Tested	**Flicker (%)**	**Flicker (%)**	**Flicker (%)**
TLED 7 A	N/A	17.0	17.0
TLED 7 B	N/A	26.8	27.6
Minimum	**N/A**	**17.02**	**17.00**
Maximum	**N/A**	**26.76**	**27.59**
Average	**N/A**	**21.89**	**22.30**
Median	**N/A**	**21.89**	**22.30**
Std. Dev.	**N/A**	**4.87**	**5.29**

Table D-56 shows the percent flicker of TLED-7 for UL Type A and UL Type B configurations.

Source: California Lighting Technology Center

Candelabra LED Replacement Products

The research team evaluated two candelabra LED replacement products as described in the methodology section. Performance metrics include power, luminous output, efficacy, power factor, CRI, correlated color temperature, chromaticity, D_{UV}, and flicker. Detailed results for each sample of all products is provided in Appendix 2.

Power

The average power of all candelabra LED replacement products tested was initially 5.6 Watts. For the average product, the power ranged from a low of 5.3 Watts to a high of 5.8 Watts for baseline measurements.

Table D-57: Power of Candelabra LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**
Candle-1	5.0	5.21	5.22	5.23	5.21	5.23	5.22	5.23	5.23	5.22	5.23	3.99	dead	dead	1.24
Candle-2	6.0	5.78	5.80	5.81	5.79	5.78	5.78	5.78	5.78	5.79	5.79	5.79	5.80	5.79	0.03
Minimum	**5.00**	**5.21**	**5.22**	**5.23**	**5.21**	**5.23**	**5.22**	**5.23**	**5.23**	**5.22**	**5.23**	**3.99**	**5.80**	**5.79**	**0.03**
Maximum	**6.00**	**5.78**	**5.80**	**5.81**	**5.79**	**5.78**	**5.78**	**5.78**	**5.78**	**5.79**	**5.79**	**5.79**	**5.80**	**5.79**	**1.24**
Average	**5.50**	**5.50**	**5.51**	**5.52**	**5.50**	**5.51**	**5.50**	**5.51**	**5.51**	**5.51**	**5.51**	**4.89**	**5.80**	**5.79**	**0.64**
Median	**5.50**	**5.50**	**5.51**	**5.52**	**5.50**	**5.51**	**5.50**	**5.51**	**5.51**	**5.51**	**5.51**	**4.89**	**5.80**	**5.79**	**0.64**
Std. Dev.	**0.50**	**0.29**	**0.29**	**0.29**	**0.29**	**0.28**	**0.28**	**0.28**	**0.28**	**0.29**	**0.28**	**0.90**	**0.00**	**0.00**	**0.61**

Table D-57 shows the power of candelabra LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-58: Power of Candelabra LED Replacement Products - Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**	**Power (W)**
Candle-1	5.0	5.28	5.29	5.31	5.29	5.31	5.30	5.31	5.31	5.30	5.33	3.99	dead	dead	1.3
Candle-2	6.0	5.82	5.81	5.84	5.82	5.82	5.81	5.82	5.82	5.82	5.83	5.86	5.83	5.83	0.0
Minimum	**5.00**	**5.28**	**5.29**	**5.31**	**5.29**	**5.31**	**5.30**	**5.31**	**5.31**	**5.30**	**5.33**	**3.99**	**5.83**	**5.83**	**0.05**
Maximum	**6.00**	**5.82**	**5.81**	**5.84**	**5.82**	**5.82**	**5.81**	**5.82**	**5.82**	**5.82**	**5.83**	**5.86**	**5.83**	**5.83**	**1.34**
Average	**5.50**	**5.55**	**5.55**	**5.58**	**5.56**	**5.57**	**5.56**	**5.57**	**5.57**	**5.56**	**5.58**	**4.92**	**5.83**	**5.83**	**0.69**
Median	**5.50**	**5.55**	**5.55**	**5.58**	**5.56**	**5.57**	**5.56**	**5.57**	**5.57**	**5.56**	**5.58**	**4.92**	**5.83**	**5.83**	**0.69**
Std. Dev.	**0.50**	**0.27**	**0.26**	**0.27**	**0.27**	**0.26**	**0.26**	**0.26**	**0.26**	**0.26**	**0.25**	**0.93**	**0.00**	**0.00**	**0.65**

Table D-57 shows the power of candelabra LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Luminous Output

The average luminous output of all candelabra LED replacement products tested was initially 372 lumens. For the average product, the luminous output ranged from a low of 290 lumens to a high of 454 lumens for baseline measurements. Table D-61 and Table D-62 provide the minimum and average luminous output per product for the duration of testing.

Table D-59: Luminous Output of Candelabra LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**
Candle-1	350	270	296	303	241	298	290	292	287	288	247	245	dead	dead	62.00
Candle-2	500	442	458	457	435	418	388	376	355	342	338	339	333	323	135.20
Minimum	**350**	**270**	**296**	**303**	**241**	**298**	**290**	**292**	**287**	**288**	**247**	**245.00**	**333.10**	**322.80**	**62**
Maximum	**500**	**442**	**458**	**457**	**435**	**418**	**388**	**376**	**355**	**342**	**338**	**338.80**	**333.10**	**322.80**	**135**
Average	**425**	**356**	**377**	**380**	**338**	**358**	**339**	**334**	**321**	**315**	**293**	**291.90**	**333.10**	**322.80**	**99**
Median	**425**	**356**	**377**	**380**	**338**	**358**	**339**	**334**	**321**	**315**	**293**	**291.90**	**333.10**	**322.80**	**99**
Std. Dev.	**75**	**86**	**81**	**77**	**97**	**60**	**49**	**42**	**34**	**27**	**46**	**46.90**	**0.00**	**0.00**	**37**

Table D-59 shows the luminous output of candelabra LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-60: Luminous Output of Candelabra LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**	**Output (lm)**
Candle-1	350	290	315	322	300	315	306	309	304	313	287	245	dead	dead	77.0
Candle-2	500	454	465	470	446	432	408	391	378	358	356	349	344	336	134.0
Minimum	**350**	**290**	**315**	**322**	**300**	**315**	**306**	**309**	**304**	**313**	**287**	**245.00**	**343.95**	**336.05**	**77**
Maximum	**500**	**454**	**465**	**470**	**446**	**432**	**408**	**391**	**378**	**358**	**356**	**348.88**	**343.95**	**336.05**	**134**
Average	**425**	**372**	**390**	**396**	**373**	**374**	**357**	**350**	**341**	**336**	**322**	**296.94**	**343.95**	**336.05**	**105**
Median	**425**	**372**	**390**	**396**	**373**	**374**	**357**	**350**	**341**	**336**	**322**	**296.94**	**343.95**	**336.05**	**105**
Std. Dev.	**75**	**82**	**75**	**74**	**73**	**59**	**51**	**41**	**37**	**23**	**35**	**51.94**	**0.00**	**0.00**	**28**

Table D-60 shows the luminous output of candelabra LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Efficacy

The average efficacy (lumens per watt) of all candelabra LED replacement products tested was initially 66.5 lumens per watt. For the average product, the efficacy ranged from a low of 54.7 lumens per watt to a high of 78.3 lumens per watt for baseline measurements. Table D-61 and Table D-61 shows the efficacy of candelabra LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-62 provide the minimum and average efficacy per product for the duration of testing.

Table D-61: Efficacy of Candelabra LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**
Candle-1	70.0	51.15	56.12	57.02	45.35	56.57	54.98	55.37	54.58	55.10	46.21	61.40	dead	dead	16.05
Candle-2	83.3	76.63	78.93	78.67	74.81	72.20	66.15	64.00	60.29	58.18	57.55	57.62	54.71	57.33	24.22
Minimum	**70.00**	**51.15**	**56.12**	**57.02**	**45.35**	**56.57**	**54.98**	**55.37**	**54.58**	**55.10**	**46.21**	**57.62**	**54.71**	**57.33**	**16.05**
Maximum	**83.33**	**76.63**	**78.93**	**78.67**	**74.81**	**72.20**	**66.15**	**64.00**	**60.29**	**58.18**	**57.55**	**61.40**	**54.71**	**57.33**	**24.22**
Average	**76.67**	**63.89**	**67.53**	**67.85**	**60.08**	**64.39**	**60.57**	**59.69**	**57.44**	**56.64**	**51.88**	**59.51**	**54.71**	**57.33**	**20.14**
Median	**76.67**	**63.89**	**67.53**	**67.85**	**60.08**	**64.39**	**60.57**	**59.69**	**57.44**	**56.64**	**51.88**	**59.51**	**54.71**	**57.33**	**20.14**
Std. Dev.	**6.67**	**12.74**	**11.41**	**10.83**	**14.73**	**7.81**	**5.59**	**4.32**	**2.86**	**1.54**	**5.67**	**1.89**	**0.00**	**0.00**	**4.09**

Table D-61 shows the efficacy of candelabra LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-62: Efficacy of Candelabra LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**	**Efficacy (lm/W)**
Candle-1	70.0	54.82	59.55	60.76	56.74	59.36	57.69	58.13	57.18	59.09	53.78	61.40	dead	dead	7.6
Candle-2	83.3	78.09	80.08	80.50	76.59	74.27	70.15	67.27	64.97	61.56	61.14	59.59	58.98	57.66	22.8
Minimum	**70.00**	**54.82**	**59.55**	**60.76**	**56.74**	**59.36**	**57.69**	**58.13**	**57.18**	**59.09**	**53.78**	**59.59**	**58.98**	**57.66**	**7.62**
Maximum	**83.33**	**78.09**	**80.08**	**80.50**	**76.59**	**74.27**	**70.15**	**67.27**	**64.97**	**61.56**	**61.14**	**61.40**	**58.98**	**57.66**	**22.84**
Average	**76.67**	**66.46**	**69.81**	**70.63**	**66.67**	**66.82**	**63.92**	**62.70**	**61.08**	**60.33**	**57.46**	**60.50**	**58.98**	**57.66**	**15.23**
Median	**76.67**	**66.46**	**69.81**	**70.63**	**66.67**	**66.82**	**63.92**	**62.70**	**61.08**	**60.33**	**57.46**	**60.50**	**58.98**	**57.66**	**15.23**
Std. Dev.	**6.67**	**11.64**	**10.27**	**9.87**	**9.92**	**7.45**	**6.23**	**4.57**	**3.90**	**1.24**	**3.68**	**0.90**	**0.00**	**0.00**	**7.61**

Table D-62 shows the efficacy of candelabra LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Power Factor

The average power factor of all candelabra LED replacement products tested was initially 0.81. For the average product, the power factor ranged from a low of 0.67 to a high of 0.94 for baseline measurements. Table D-63 and Table D-64 provide the minimum and average power factor per product for the duration of testing.

Table D-63: Power Factor of Candelabra LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**
Candle-1	N/A	0.94	0.93	0.93	0.93	0.94	0.93	0.93	0.93	0.94	0.94	0.84	dead	dead	0.10
Candle-2	0.7	0.67	0.68	0.67	0.67	0.67	0.67	0.68	0.68	0.68	0.68	0.64	0.68	0.69	0.04
Minimum	**0.70**	**0.67**	**0.68**	**0.67**	**0.67**	**0.67**	**0.67**	**0.68**	**0.68**	**0.68**	**0.68**	**0.64**	**0.68**	**0.69**	**0.04**
Maximum	**0.70**	**0.94**	**0.93**	**0.93**	**0.93**	**0.94**	**0.93**	**0.93**	**0.93**	**0.94**	**0.94**	**0.84**	**0.68**	**0.69**	**0.10**
Average	**0.70**	**0.81**	**0.81**	**0.80**	**0.80**	**0.81**	**0.80**	**0.81**	**0.81**	**0.81**	**0.81**	**0.74**	**0.68**	**0.69**	**0.07**
Median	**0.70**	**0.81**	**0.81**	**0.80**	**0.80**	**0.81**	**0.80**	**0.81**	**0.81**	**0.81**	**0.81**	**0.74**	**0.68**	**0.69**	**0.07**
Std. Dev.	**0.00**	**0.14**	**0.13**	**0.13**	**0.13**	**0.14**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.10**	**0.00**	**0.00**	**0.03**

Table D-63 shows the power factor of candelabra LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-64: Power Factor of Candelabra LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**	**Power Factor**
Candle-1	N/A	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.84	dead	dead	0.1
Candle-2	0.7	0.67	0.68	0.68	0.67	0.68	0.68	0.68	0.68	0.68	0.68	0.67	0.69	0.69	0.0
Minimum	**0.70**	**0.67**	**0.68**	**0.68**	**0.67**	**0.68**	**0.68**	**0.68**	**0.68**	**0.68**	**0.68**	**0.67**	**0.69**	**0.69**	**0.02**
Maximum	**0.70**	**0.94**	**0.94**	**0.94**	**0.94**	**0.94**	**0.94**	**0.94**	**0.94**	**0.94**	**0.94**	**0.84**	**0.69**	**0.69**	**0.10**
Average	**0.70**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.76**	**0.69**	**0.69**	**0.06**
Median	**0.70**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.76**	**0.69**	**0.69**	**0.06**
Std. Dev.	**0.00**	**0.14**	**0.13**	**0.13**	**0.14**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.08**	**0.00**	**0.00**	**0.04**

Table D-64 shows the power factor of candelabra LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Color Rendering Index

The average CRI of all candelabra LED replacement products tested was initially 90.3. For the average product, the CRI ranged from a low of 89.3 to a high of 91.3 for baseline measurements.

Table D-65 and Table D-66 provide the minimum and average CRI per product for the duration of testing.

Table D-65: CRI of Candelabra LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**
Candle-1	90.0	90.2	89.0	89.1	89.0	89.1	89.1	89.1	89.1	89.2	89.3	92.6	dead	dead	3.63
Candle-2	90.0	88.9	88.3	88.6	88.7	89.5	90.0	91.4	92.3	92.8	93.4	93.3	93.5	93.4	5.26
Minimum	**90.00**	**88.92**	**88.28**	**88.60**	**88.70**	**89.10**	**89.10**	**89.10**	**89.10**	**89.20**	**89.30**	**92.62**	**93.54**	**93.43**	**3.63**
Maximum	**90.00**	**90.17**	**88.99**	**89.10**	**89.00**	**89.50**	**90.00**	**91.40**	**92.30**	**92.80**	**93.40**	**93.30**	**93.54**	**93.43**	**5.26**
Average	**90.00**	**89.55**	**88.64**	**88.85**	**88.85**	**89.30**	**89.55**	**90.25**	**90.70**	**91.00**	**91.35**	**92.96**	**93.54**	**93.43**	**4.45**
Median	**90.00**	**89.55**	**88.64**	**88.85**	**88.85**	**89.30**	**89.55**	**90.25**	**90.70**	**91.00**	**91.35**	**92.96**	**93.54**	**93.43**	**4.45**
Std. Dev.	**0.00**	**0.63**	**0.35**	**0.25**	**0.15**	**0.20**	**0.45**	**1.15**	**1.60**	**1.80**	**2.05**	**0.34**	**0.00**	**0.00**	**0.81**

Table D-65 shows the CRI of candelabra LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-66: CRI of Candelabra LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**	**CRI**
Candle-1	90.0	91.3	91.3	91.4	91.2	91.4	91.4	91.3	91.4	90.8	90.7	92.6	dead	dead	1.9
Candle-2	90.0	89.3	88.6	88.9	89.0	89.7	90.6	91.8	92.6	93.0	93.8	93.8	94.1	94.2	5.6
Minimum	**90.00**	**89.26**	**88.57**	**88.90**	**89.00**	**89.70**	**90.60**	**91.30**	**91.40**	**90.80**	**90.70**	**92.62**	**94.06**	**94.20**	**1.92**
Maximum	**90.00**	**91.30**	**91.28**	**91.40**	**91.20**	**91.40**	**91.40**	**91.80**	**92.60**	**93.00**	**93.80**	**93.85**	**94.06**	**94.20**	**5.63**
Average	**90.00**	**90.28**	**89.93**	**90.15**	**90.10**	**90.55**	**91.00**	**91.55**	**92.00**	**91.90**	**92.25**	**93.23**	**94.06**	**94.20**	**3.77**
Median	**90.00**	**90.28**	**89.93**	**90.15**	**90.10**	**90.55**	**91.00**	**91.55**	**92.00**	**91.90**	**92.25**	**93.23**	**94.06**	**94.20**	**3.77**
Std. Dev.	**0.00**	**1.02**	**1.36**	**1.25**	**1.10**	**0.85**	**0.40**	**0.25**	**0.60**	**1.10**	**1.55**	**0.61**	**0.00**	**0.00**	**1.85**

Table D-66 shows the CRI of candelabra LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Correlated Color Temperature

The average CCT of all candelabra LED replacement products tested was initially 2,780 Kelvin. For the average product, the CCT ranged from a low of 2,727 Kelvin to a high of 2,833 Kelvin for baseline measurements.

Table D-67 and Table D-70 provide the minimum and average CCT per product for the duration of testing.

Table D-67: Correlated Color Temperature of Candelabra LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**
Candle-1	2,700	2,702	2,646	2,634	2,634	2,632	2,627	2,628	2,629	2,629	2,626	2,757	dead	dead	131.00
Candle-2	2,700	2,805	2,829	2,821	2,843	2,833	2,811	2,791	2,783	2,791	2,755	2,789	2,789	2,786	88.00
Minimum	**2,700**	**2,702.00**	**2,646.00**	**2,634.00**	**2,634.00**	**2,632.00**	**2,627.00**	**2,628.00**	**2,629.00**	**2,629.00**	**2,626.00**	**2,757.00**	**2,789.00**	**2,786.00**	**88.00**
Maximum	**2,700**	**2,805.00**	**2,829.00**	**2,821.00**	**2,843.00**	**2,833.00**	**2,811.00**	**2,791.00**	**2,783.00**	**2,791.00**	**2,755.00**	**2,789.00**	**2,789.00**	**2,786.00**	**131.00**
Average	**2,700**	**2,753.50**	**2,737.50**	**2,727.50**	**2,738.50**	**2,732.50**	**2,719.00**	**2,709.50**	**2,706.00**	**2,710.00**	**2,690.50**	**2,773.00**	**2,789.00**	**2,786.00**	**109.50**
Median	**2,700**	**2,753.50**	**2,737.50**	**2,727.50**	**2,738.50**	**2,732.50**	**2,719.00**	**2,709.50**	**2,706.00**	**2,710.00**	**2,690.50**	**2,773.00**	**2,789.00**	**2,786.00**	**109.50**
Std. Dev.	**0**	**51.50**	**91.50**	**93.50**	**104.50**	**100.50**	**92.00**	**81.50**	**77.00**	**81.00**	**64.50**	**16.00**	**0.00**	**0.00**	**21.50**

Table D-67 shows the CCT of candelabra LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-68: Correlated Color Temperature of Candelabra LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**	**CCT**
Candle-1	2,700	2,727	2,702	2,697	2,700	2,703	2,697	2,699	2,700	2,677	2,684	2,757	dead	dead	80.0
Candle-2	2,700	2,833	2,855	2,843	2,864	2,856	2,832	2,807	2,801	2,807	2,782	2,815	2,816	2,817	82.0
Minimum	**2,700**	**2,727.00**	**2,702.00**	**2,697.00**	**2,700.00**	**2,703.00**	**2,697.00**	**2,699.00**	**2,700.00**	**2,677.00**	**2,684.00**	**2,757.00**	**2,816.00**	**2,817.33**	**80.00**
Maximum	**2,700**	**2,833.00**	**2,855.00**	**2,843.00**	**2,864.00**	**2,856.00**	**2,832.00**	**2,807.00**	**2,801.00**	**2,807.00**	**2,782.00**	**2,814.50**	**2,816.00**	**2,817.33**	**82.00**
Average	**2,700**	**2,780.00**	**2,778.50**	**2,770.00**	**2,782.00**	**2,779.50**	**2,764.50**	**2,753.00**	**2,750.50**	**2,742.00**	**2,733.00**	**2,785.75**	**2,816.00**	**2,817.33**	**81.00**
Median	**2,700**	**2,780.00**	**2,778.50**	**2,770.00**	**2,782.00**	**2,779.50**	**2,764.50**	**2,753.00**	**2,750.50**	**2,742.00**	**2,733.00**	**2,785.75**	**2,816.00**	**2,817.33**	**81.00**
Std. Dev.	**0**	**53.00**	**76.50**	**73.00**	**82.00**	**76.50**	**67.50**	**54.00**	**50.50**	**65.00**	**49.00**	**28.75**	**0.00**	**0.00**	**1.00**

Table D-68 shows the CCT of candelabra LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

D_{UV}

The average D_{UV} of all candelabra LED replacement products tested was initially 0.002759. For the average product, the D_{UV} ranged from a low of 0.001017 to a high of 0.004500 for baseline measurements. Table D-69 and Table 72 provide the minimum and average DUV per product for the duration of testing.

Table D-69: D_{UV} of Candelabra LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**
Candle-1	N/A	0.000000	–0.001271	–0.001032	–0.001142	–0.001249	–0.001378	–0.001299	–0.001353	–0.001478	–0.001766	0.000209	dead	dead	0.001975
Candle-2	N/A	0.004100	0.004836	0.004500	0.004002	0.002875	0.001678	0.000550	0.000239	–0.001002	–0.001799	–0.002029	–0.002082	–0.002166	0.007002
Minimum	**N/A**	**0.000000**	**–0.001271**	**–0.001032**	**–0.001142**	**–0.001249**	**–0.001378**	**–0.001299**	**–0.001353**	**–0.001478**	**–0.001799**	**–0.002029**	**–0.002082**	**–0.002166**	**0.001975**
Maximum	**N/A**	**0.004100**	**0.004836**	**0.004500**	**0.004002**	**0.002875**	**0.001678**	**0.000550**	**0.000239**	**–0.001002**	**–0.001766**	**0.000209**	**–0.002082**	**–0.002166**	**0.007002**
Average	**N/A**	**0.002050**	**0.001783**	**0.001734**	**0.001430**	**0.000813**	**0.000150**	**–0.000375**	**–0.000557**	**–0.001240**	**–0.001783**	**–0.000910**	**–0.002082**	**–0.002166**	**0.004489**
Median	**N/A**	**0.002050**	**0.001783**	**0.001734**	**0.001430**	**0.000813**	**0.000150**	**–0.000375**	**–0.000557**	**–0.001240**	**–0.001783**	**–0.000910**	**–0.002082**	**–0.002166**	**0.004489**
Std. Dev.	**N/A**	**0.002050**	**0.003054**	**0.002766**	**0.002572**	**0.002062**	**0.001528**	**0.000925**	**0.000796**	**0.000238**	**0.000017**	**0.001119**	**0.000000**	**0.000000**	**0.002514**

Table D-69 shows the D_{uv} of candelabra LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-70: D_{UV} of Candelabra LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**	**Duv**
Candle-1	N/A	0.001017	-0.000401	-0.000285	-0.000296	-0.000456	-0.000504	-0.000262	-0.000024	-0.000378	-0.000528	0.000209	dead	dead	0.001545
Candle-2	N/A	0.004500	0.004945	0.004712	0.004434	0.003657	0.002657	0.001435	0.000685	0.000086	-0.001074	-0.001141	-0.001416	-0.001643	0.006587
Minimum	**N/A**	**0.001017**	**-0.000401**	**-0.000285**	**-0.000296**	**-0.000456**	**-0.000504**	**-0.000262**	**-0.000024**	**-0.000378**	**-0.001074**	**-0.001141**	**-0.001416**	**-0.001643**	**0.001545**
Maximum	**N/A**	**0.004500**	**0.004945**	**0.004712**	**0.004434**	**0.003657**	**0.002657**	**0.001435**	**0.000685**	**0.000086**	**-0.000528**	**0.000209**	**-0.001416**	**-0.001643**	**0.006587**
Average	**N/A**	**0.002759**	**0.002272**	**0.002214**	**0.002069**	**0.001600**	**0.001076**	**0.000587**	**0.000331**	**-0.000146**	**-0.000801**	**-0.000466**	**-0.001416**	**-0.001643**	**0.004066**
Median	**N/A**	**0.002759**	**0.002272**	**0.002214**	**0.002069**	**0.001600**	**0.001076**	**0.000587**	**0.000331**	**-0.000146**	**-0.000801**	**-0.000466**	**-0.001416**	**-0.001643**	**0.004066**
Std. Dev.	**N/A**	**0.001742**	**0.002673**	**0.002499**	**0.002365**	**0.002057**	**0.001580**	**0.000848**	**0.000355**	**0.000232**	**0.000273**	**0.000675**	**0.000000**	**0.000000**	**0.002521**

Table D-70 shows the D_{uv} of candelabra LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center

Flicker

The average percent flicker of all candelabra LED replacement products tested was initially 12.2 percent. For the average product, the percent flicker ranged from a low of 3.7 percent to a high of 20.7 percent for baseline measurements.

Table D-71: Percent Flicker of Candelabra LED Replacement Products – Minimum Sample Measured

	Manu-facturer Claimed Perform-ance	Minimum Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**
Candle-1	N/A	17.7	18.6	17.5	13.7	17.3	17.3	17.2	17.2	N/A	N/A	27.0	dead	dead	13.31
Candle-2	N/A	3.5	4.1	3.7	3.6	3.6	3.6	3.7	3.8	4.9	5.3	4.5	4.6	4.6	1.76
Minimum	**N/A**	**3.50**	**4.10**	**3.66**	**3.61**	**3.62**	**3.59**	**3.65**	**3.84**	**4.93**	**5.26**	**4.45**	**4.59**	**4.57**	**1.76**
Maximum	**N/A**	**17.73**	**18.61**	**17.48**	**13.72**	**17.28**	**17.26**	**17.19**	**17.17**	**4.93**	**5.26**	**27.03**	**4.59**	**4.57**	**13.31**
Average	**N/A**	**10.62**	**11.36**	**10.57**	**8.67**	**10.45**	**10.43**	**10.42**	**10.51**	**4.93**	**5.26**	**15.74**	**4.59**	**4.57**	**7.54**
Median	**N/A**	**10.62**	**11.36**	**10.57**	**8.67**	**10.45**	**10.43**	**10.42**	**10.51**	**4.93**	**5.26**	**15.74**	**4.59**	**4.57**	**7.54**
Std. Dev.	**N/A**	**7.12**	**7.26**	**6.91**	**5.06**	**6.83**	**6.84**	**6.77**	**6.67**	**0.00**	**0.00**	**11.29**	**0.00**	**0.00**	**5.78**

Table D-71 shows the percent flicker of candelabra LED replacement products for the minimum sample of each product measured.

Source: California Lighting Technology Center

Table D-72: Percent Flicker of Candelabra LED Replacement Products – Average Sample Measured

	Manu-facturer Claimed Perform-ance	Average Sample Measured													Difference Between Min. and Max. Runtime Data
		Baseline	1,000 Hours of Runtime	2,000 Hours of Runtime	3,000 Hours of Runtime	4,000 Hours of Runtime	5,000 Hours of Runtime	6,000 Hours of Runtime	7,000 Hours of Runtime	8,000 Hours of Runtime	9,000 Hours of Runtime	10,000 Hours of Runtime	11,000 Hours of Runtime	12,000 Hours of Runtime	
Product Tested	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**	**Flicker**
Candle-1	N/A	20.7	22.0	20.8	19.2	20.2	20.1	20.1	20.0	N/A	N/A	27.0	dead	dead	7.8
Candle-2	N/A	3.7	4.3	3.8	3.8	3.8	3.9	6.9	4.0	5.1	5.4	4.8	4.8	4.8	3.2
Minimum	**N/A**	**3.71**	**4.32**	**3.82**	**3.82**	**3.84**	**3.87**	**6.88**	**3.99**	**5.11**	**5.44**	**4.77**	**4.80**	**4.75**	**3.17**
Maximum	**N/A**	**20.71**	**22.01**	**20.85**	**19.19**	**20.17**	**20.12**	**20.05**	**20.00**	**5.11**	**5.44**	**27.03**	**4.80**	**4.75**	**7.84**
Average	**N/A**	**12.21**	**13.17**	**12.33**	**11.50**	**12.00**	**12.00**	**13.46**	**11.99**	**5.11**	**5.44**	**15.90**	**4.80**	**4.75**	**5.51**
Median	**N/A**	**12.21**	**13.17**	**12.33**	**11.50**	**12.00**	**12.00**	**13.46**	**11.99**	**5.11**	**5.44**	**15.90**	**4.80**	**4.75**	**5.51**
Std. Dev.	**N/A**	**8.50**	**8.85**	**8.51**	**7.69**	**8.17**	**8.12**	**6.59**	**8.00**	**0.00**	**0.00**	**11.13**	**0.00**	**0.00**	**2.34**

Table D-72 shows the percent flicker of candelabra LED replacement products for the average sample of each product measured.

Source: California Lighting Technology Center