

Solutions to improve lighting quality, increase consumer acceptance, advance lighting application efficiency, and enhance building occupant wellbeing

Pacific Northwest National Laboratory

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3.2.1.02: PNNL - ET: Optimizing Lighting Systems for Decarbonization, Life Cycle Sustainability, and Occupant Benefits

Project Summary

Objective and outcome

Develop new evidence-based metrics, specifications, and guidance for key lighting quality areas—flicker, glare, spectrum—to improve product performance, increase customer acceptance and adoption of energy efficient lighting technologies, improve lighting application efficiency, reduce energy use intensity, and improve building occupant wellbeing.



Team and Partners

Pacific Northwest National Laboratory:

Michael Royer, Naomi Miller, Belal Abboushi, Lia Irvin, Eduardo Rodriguez-Feo Bermudez, Jianchuan Tan

External Research Partners:

University of British Columbia, National Research Council Canada, Penn State University, Oregon State University, NIST, KU Leuven

Organizations:

IES, CIE, NEMA, IEEE, DLC

Stats

Performance Period: FY23 (Ongoing FY22-24 project)

DOE budget FY23 (new BA): \$810k, Cost Share: \$0k

FY23 Milestone 1: Submit peer-reviewed article on physiological effects of NIR radiation, utilizing data collected in FY22.

FY23 Milestone 2: Submit peer-reviewed article proposing a metric(s) for quantifying the phantom array effect. Complete analysis/development and verification using data collected in FY22.

FY23 Milestone 3: Submit peer-reviewed article based on new experimental evidence of position and spectrum on glare perception. Complete apparatus commissioning, collect psychophysical data, analyze, and report.

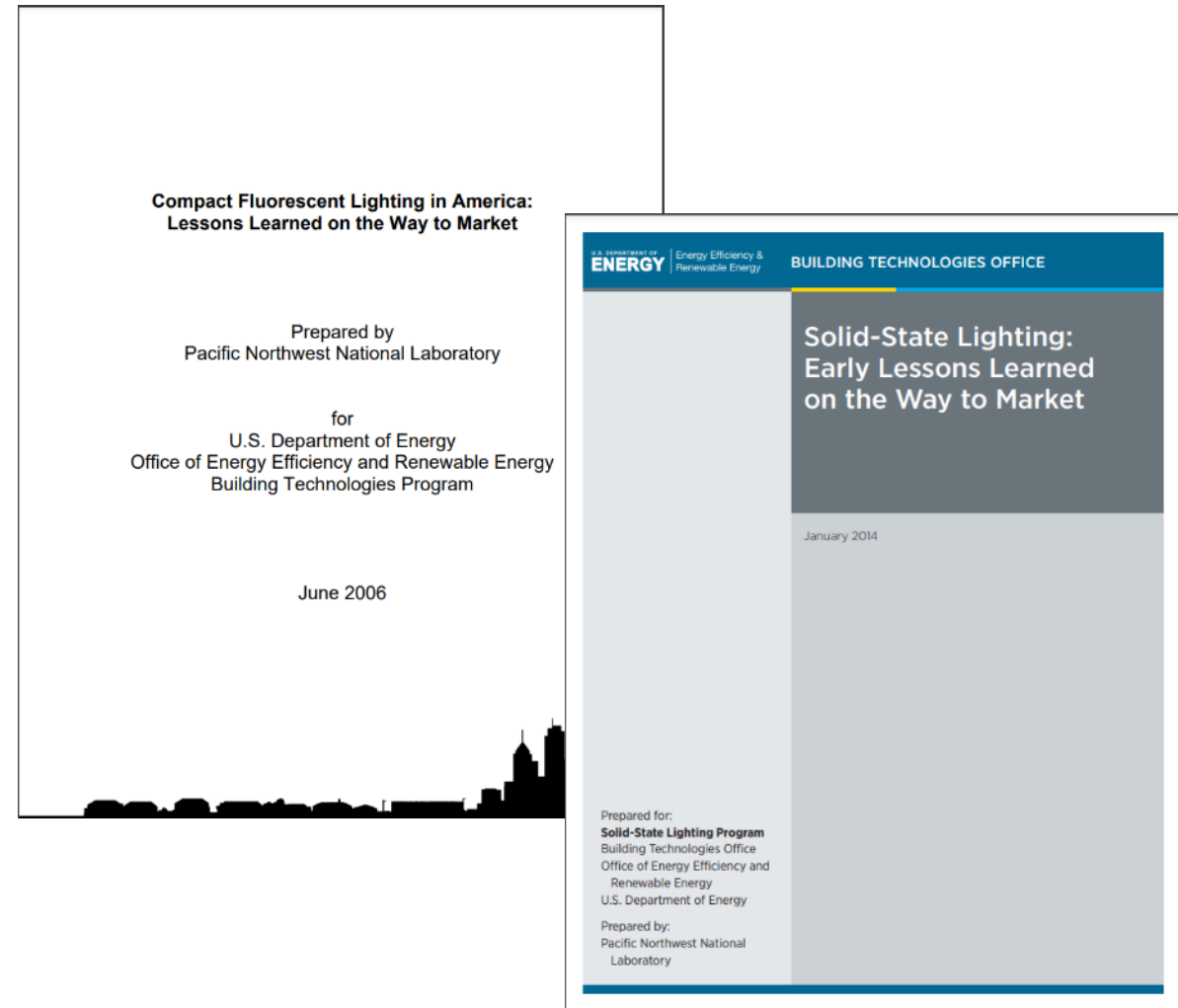
FY23 Milestone 4: Submit peer-reviewed article on spectrum/brightness perception, demonstrating the potential for energy savings through tailoring the spectrum/color rendition. Complete apparatus commissioning, collect psychophysical data, analyze, and report.

Problem

Lessons learned from CFLs and early LED adoption point to quality issues as preventing maximum energy savings.

- LEDs have reintroduced temporal light modulation (i.e., “**flicker**”) into electric lighting, which can cause visual fatigue, distraction, discomfort, migraines, and even severe neurological problems in some sensitive individuals.
- LEDs are high-intensity point sources, and goals of maximizing efficiency often mean high levels of **glare**.
- Like fluorescent, the emitted **spectrum** of LED products has been tuned to optimize old metrics, leading to dissatisfaction.

Many metrics, specifications, and guidance documents from past eras have not been updated. Effective metrics lead to more effective optimizations, which can improve occupant comfort and deliver maximum benefit per joule.



Alignment and Impact

PNNL & PARTNERS

Conduct human factors experiments and analyses to develop new lighting performance metrics and associated specifications and guidance

Work with voluntary standards organizations (e.g., IES, CIE) to formalize recommendations

Work with industry to increase adoption and optimize performance

INDUSTRY

Uses PNNL work to:

- Improve existing products and develop new products that are higher quality and use energy more effectively
- Provide greater variety of products or increased product flexibility
- Identify and specify products using new tools and workflows

COUNTRY AND USERS

Are impacted through:

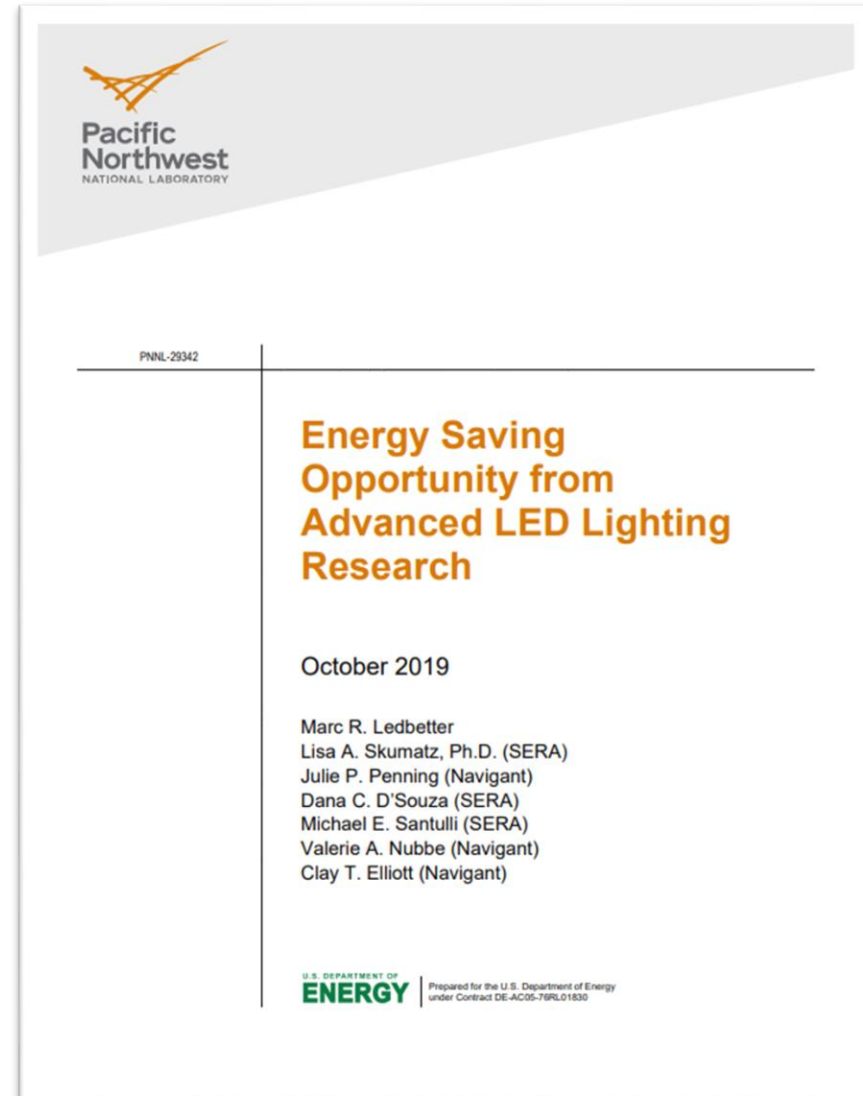
- Increased lighting application efficiency
- Reduced energy use intensity
- Improved occupant wellbeing
- Protection of sensitive populations

Alignment and Impact

2019 valuation study documents energy saving potential from improved lighting quality: **334 TBtu in 2035 (= 10% lighting energy reduction)** [4.5% reduction by 2030]

<https://www.energy.gov/eere/ssl/energy-saving-opportunity-advanced-led-lighting-research>

<https://www.ledsmagazine.com/manufacturing-services-testing/article/14201337/doe-projects-energy-savings-related-to-expected-ssl-quality-improvements>



Alignment and Impact

Increase customer acceptance to increase adoption.

Enable color-mixed LED future.

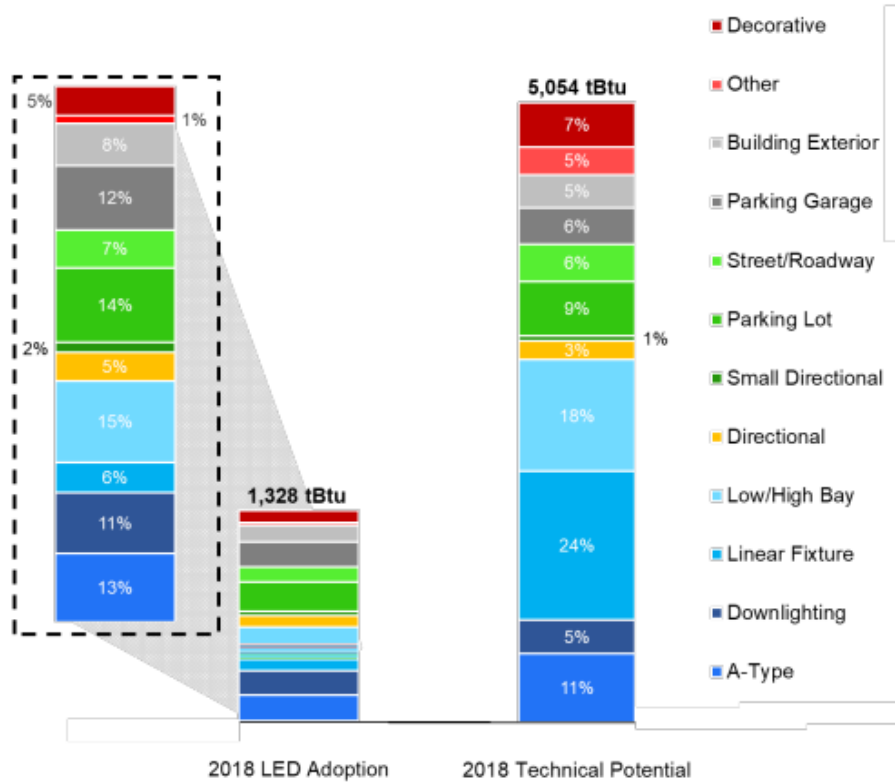


Figure ES.1 Comparison of 2018 Adoption and Technical Potential from LED Lighting. In 2018, LED and connected lighting contributed 1,328 tBtu in source energy savings, but if all lighting installations were converted to top tier LED products (100% LED penetration, 95th percentile efficacy) with connected lighting controls, LED savings could reach 5,054 tBtu.

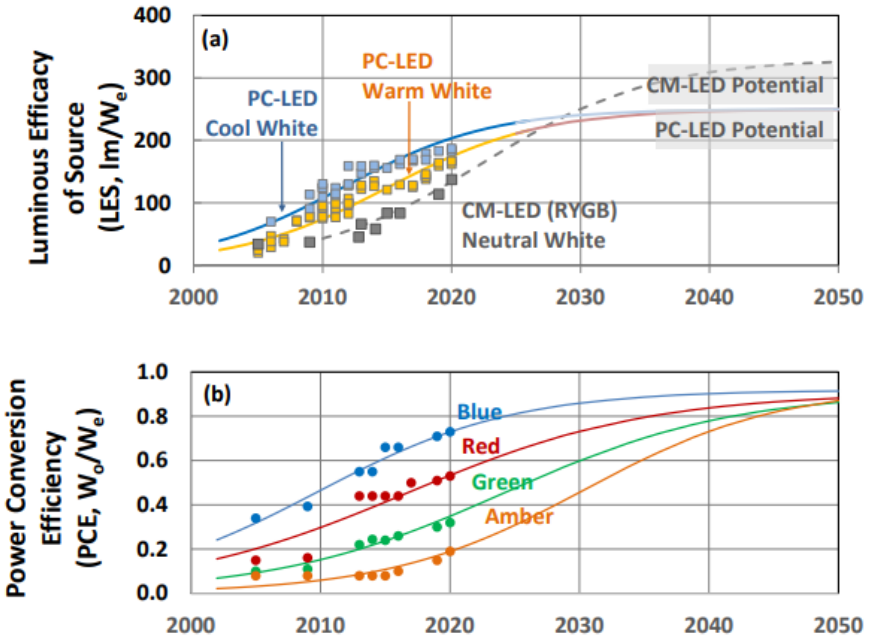


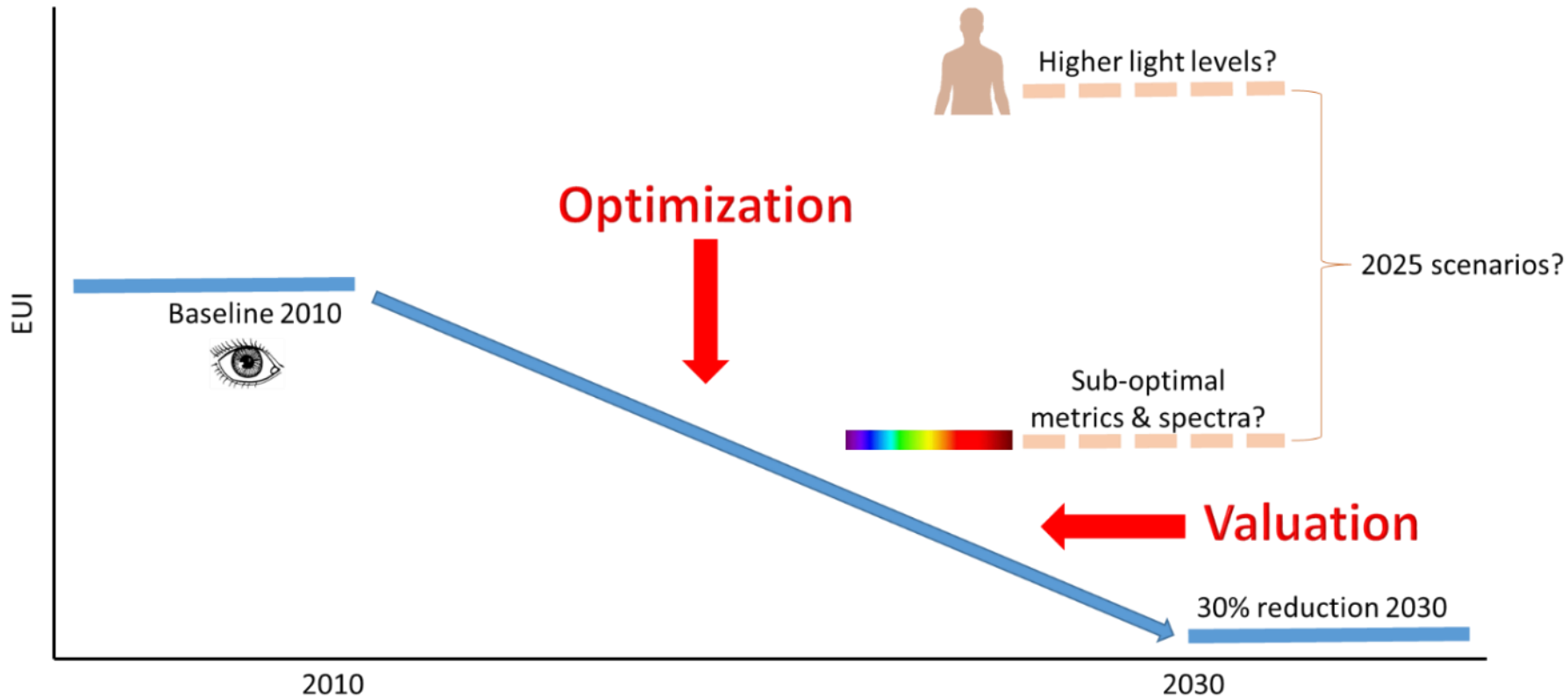
Figure 2.5 Efficacies and efficiencies over time for white and colored commercial LED packages measured at 25 °C and 35 A/cm² input current density. All curves are logistic fits using various assumptions for long-term future performance, and historical experimental data. The data are from qualified products at the representative operating conditions of 25 °C and 35 A/cm² input current density.

Upper panel (a) are the luminous efficacies and conversion efficiencies of warm-white (3000-3500 K) and cool-white (5700 K) PC-LEDs and hypothetical CM-LEDs.

Lower panel (b) are the power-conversion efficiencies of direct-emitting LEDs at the various colors (blue, green, amber, near-red) necessary for CM-LED white light of highest luminous efficacy of source and high color rendering quality. Approximate long-term-future potential power-conversion efficiencies are depicted as a saturation at 90% for all colors beginning in the years 2040-2045. The historical power conversion efficiencies of these sources were combined and appropriately weighted to give the CM-LED luminous efficacies of source and conversion efficiencies depicted in upper panel (a).

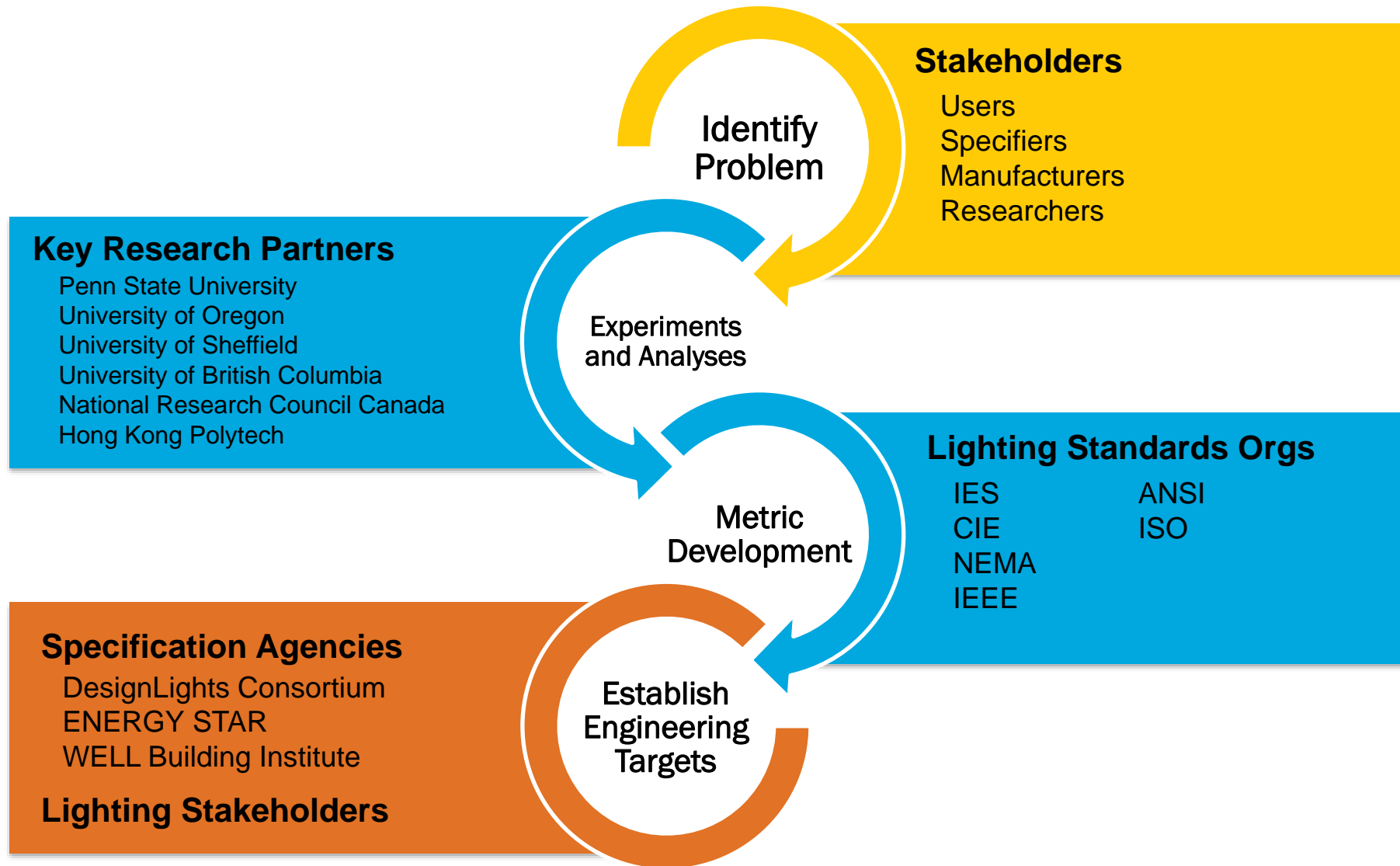
Alignment and Impact

Reduce energy use intensity.



A transition from human visual needs to more holistic goals may mean increased energy use intensity (EUI) due to higher light levels and/or slower EUI reductions due to sub-optimal metrics and technologies. Research that optimizes the metrics and technology, and that increases perceived value of the benefits of future technology improvements, directly supports BTO goals.

Approach



Approach

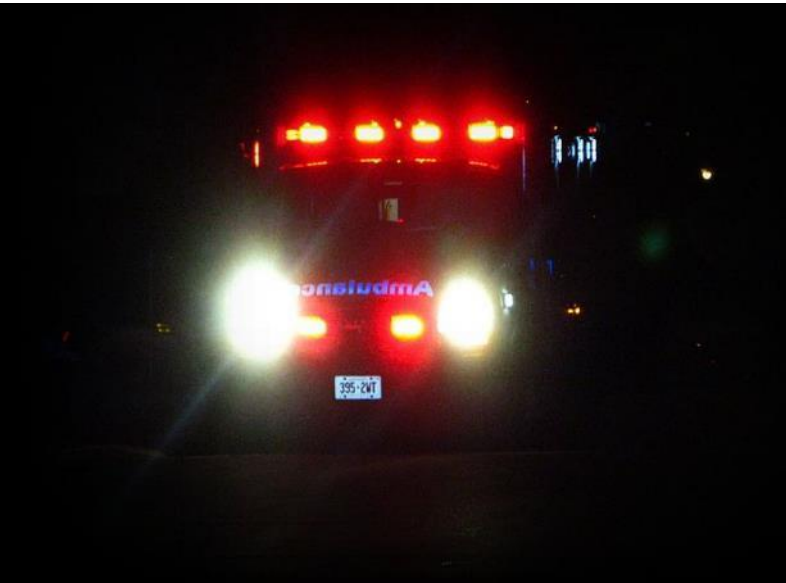
BARRIERS

- Challenging levels of variability in human responses
- Adaptive visual system and wide range of possible stimuli
- Realization of benefits depends on others
- Industry movement to commoditization and reluctance to introduce new performance criteria

- Newly designed apparatuses and new knowledge from methodological studies allow for more useful data collection.
- LED technology is available to improve experimental methods
- Years of working with industry partners has built a strong working relationship
- Extensive involvement in standards organizations can help move research into practice

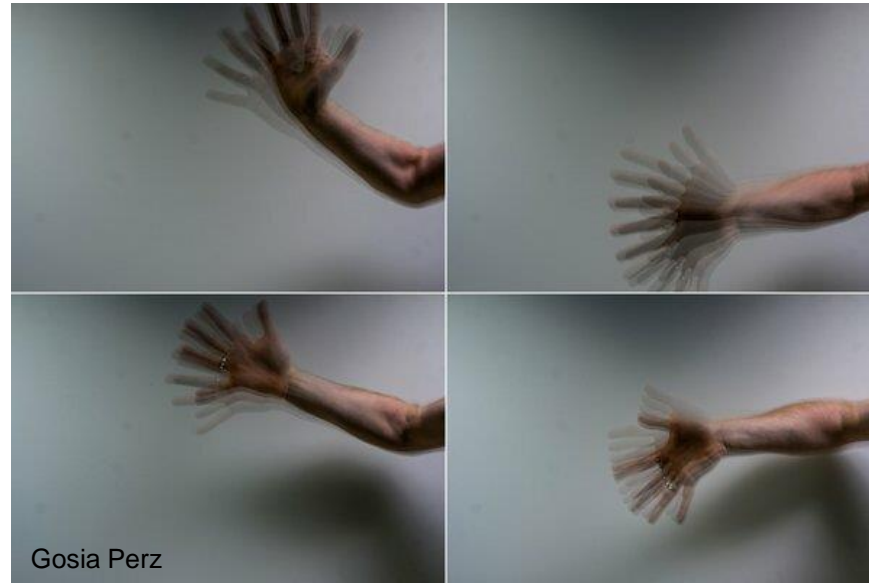
SOLUTIONS

Approach | Flicker



DIRECT FLICKER 3 Hz to 80 Hz

- Minimal problem for electric light sources, with the exception of emergency vehicles
- Established, effective metrics, but limited use



STROBOSCOPIC EFFECT 80 Hz to 1,500 Hz

- Major concern for electric light sources
- Recently established, effective metric, Stroboscopic Visibility Measure (SVM), but limited use
- Using SVM may lead to increased phantom array effect responses
- Work needed to educate and promote use of metric and increase the availability of data



PHANTOM ARRAY EFFECT 80 Hz to 12,000 Hz

- Major concern for electric light sources
- No established metrics
- Highest variability in visibility among different people
- Work needed to collect data, develop metric, promote use, and understand effects for different populations

Progress and Future Work | Flicker

2022 custom built experiment apparatus



2021 Literature review to establish basis for experimental and standards work

Miller N, Leon F, Tan J, Irvin L. Flicker: A review of temporal light modulation stimulus, responses, and measures. *Lighting Research & Technology*. 2023;55(1):5-35. doi:[10.1177/14771535211069482](https://doi.org/10.1177/14771535211069482)

2022 Novel human factors experiment examining both stroboscopic and phantom array, showed key differences in perception

Article submitted and pending publication

Investigation into the stability of existing metrics across with variation in measurement

Tan J, Leon F. Temporal Light Modulation: Data Processing and Metric Calculations. *Lighting Research & Technology*. In Press.

2023 Development of new metric, PAVM, to address phantom array

Article submitted April 2023

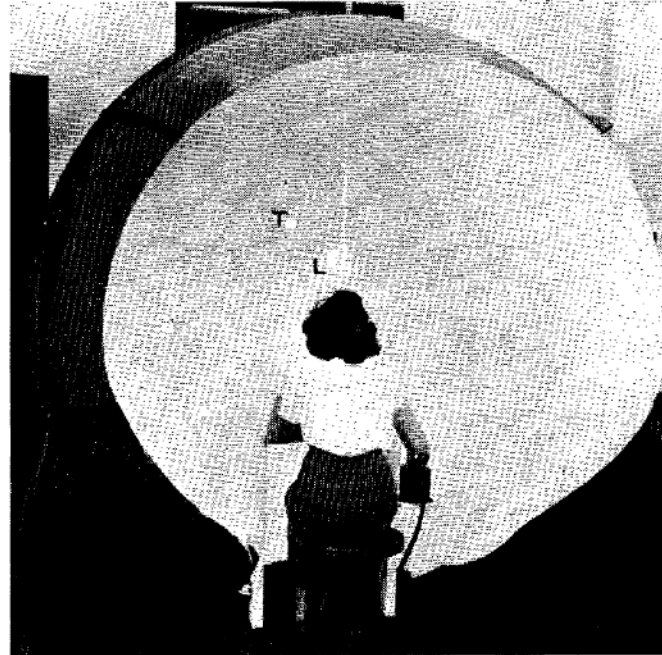
Leadership in development of IES Technical Memorandum on Flicker

Pre-ballot review and coordination with NEMA

2024 Outreach and standardization of metrics and specification guidance

Approach | Glare

- Many glare metrics have been proposed and some see limited use (e.g., UGR, VCP)
- Numerous research studies over many decades have failed to produce universally accepted metrics and established, effective guidance
- New technology, new understanding of research methods enables better results
- Work is needed to collect new data (replicating and extending old work), revise or replace metrics, reach consensus, and assist with the uptake of metrics to develop new products

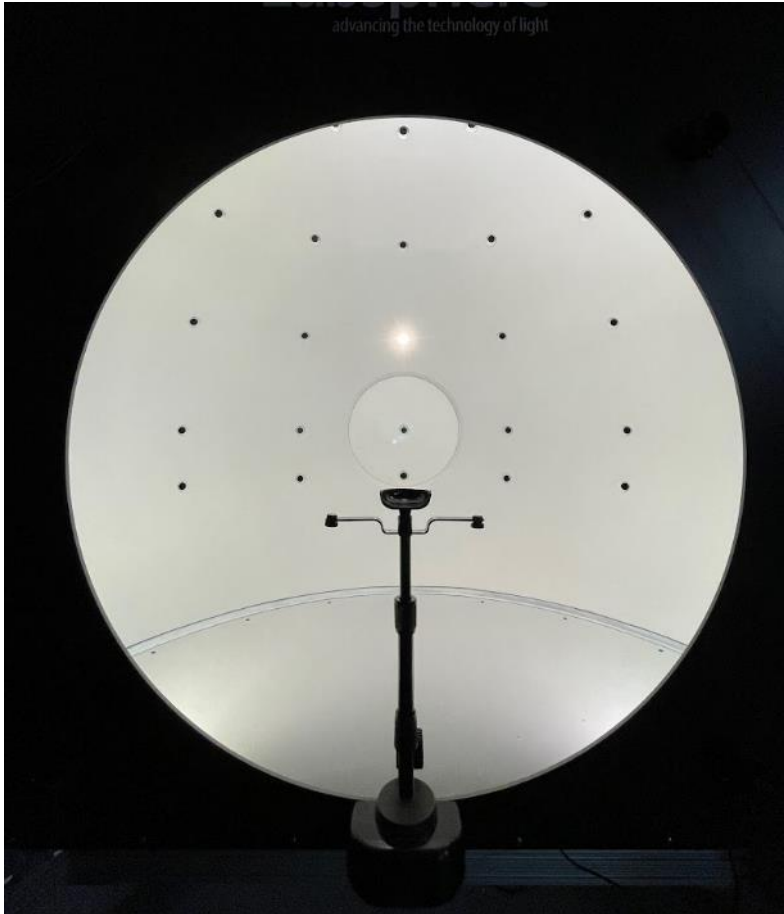


Luckiesh M, Guth SK. Brightnesses in visual field at borderline between comfort and discomfort (BCD). Illuminating Engineering 1949; 44: 650–670.



PNNL 2023

Progress and Future Work | Glare



View of interior of new apparatus for evaluating discomfort glare, used in 2023 experiment

2019 Development of novel apparatus for studying the effect of location in field of view and spectrum of light on discomfort glare
Final commissioning and use of apparatus delayed by Covid-19 protocols

2022 Comparison of existing methods and models for assessing pedestrian discomfort glare

Abboushi B., Miller N. What to measure and report in studies of discomfort from glare for pedestrian applications. *Lighting Research & Technology*. 2022; doi:10.1177/14771535221087133

Abboushi B., Miller N., and Fotios S. 2023. "Models of discomfort from glare for pedestrian-scale lighting: a comparison of tentative models using four independent data sets." *Lighting Research & Technology*. In press.

2023 Completion of new experiment assessing the effect of position and spectrum on perception of discomfort glare, using two different methods

Article to be submitted June 2023

2024 Expected proposal of modifications to existing UGR metric and/or new metric. Collaboration with lighting standards organizations.

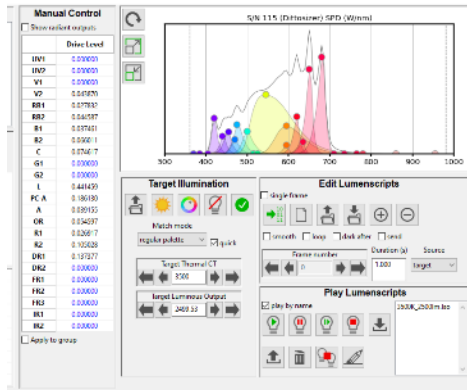
Approach, Progress, and Future Work | Spectrum



FAR-RED & NEAR INFRARED EFFECTS

- LEDs emit little to no far-red (FR) and near infrared (NIR) radiation, but medical research has demonstrated that this energy is photobiologically active, including in the retina.
- The effect of the presence/absence of FR/NIR in ambient interior lighting has not been studied, but new evidence could substantially alter the relationship between humans and electric lighting.
- An experiment studying the effect of FR/NIR on cognition, mood, and cardiovascular physiology was completed in 2022 in partnership with the University of British Columbia, using a novel custom-built room with variable lighting. Reporting is ongoing.
- Follow-up work is contingent on findings.

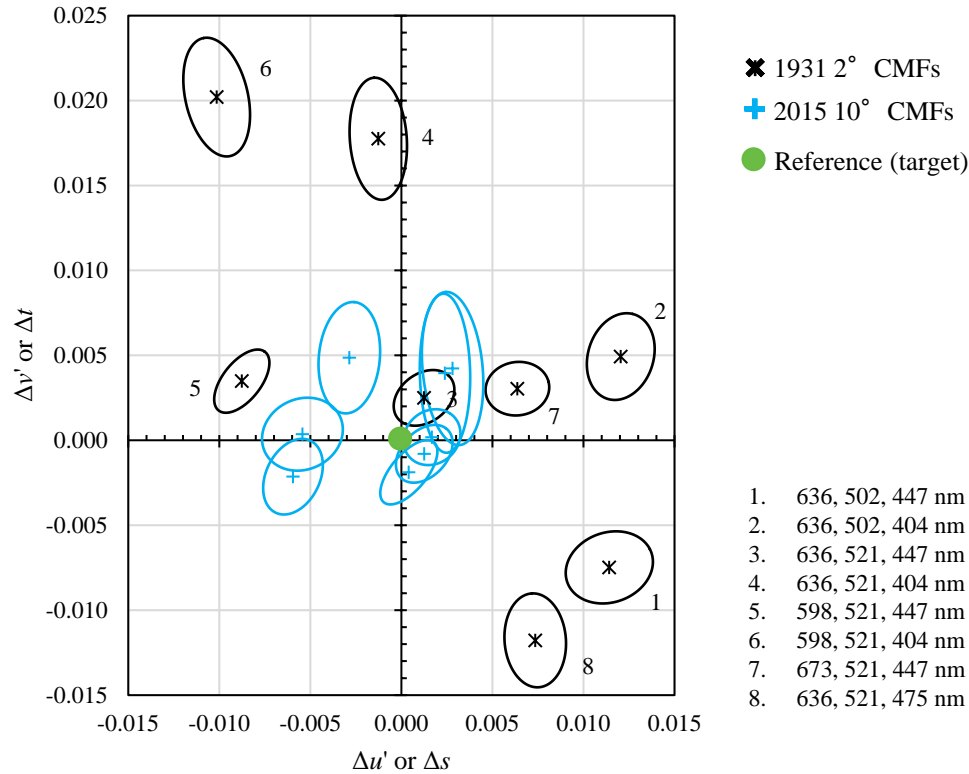
SPATIAL BRIGHTNESS PERCEPTION



- Spectrum has been widely shown to effect spatial brightness perception, but there is no effective model of this relationship, and there are likely multiple components.
- Recent work on color rendition at PNNL resulted in unsolicited reports of the effect of spectrum on brightness perception.
- A new 24-channel tunable lighting system installed in a large room will be used in a summer 2023 experiment to investigate the effect of spectrum, addressing color contrast, melanopic content, etc.
- This work can help to improve models of spatial brightness perception, which could provide the ability to reduce illuminance by 10% or more in some applications, saving substantial energy.
- Follow-up work is contingent on findings.

Approach, Progress, and Future Work | Spectrum

CHROMATICITY & CCT IMPROVEMENTS



Comparison of performance for different CMFs in a recent color matching experiment. Center is average across observers; ellipse shows individual variation.

Recent Publications

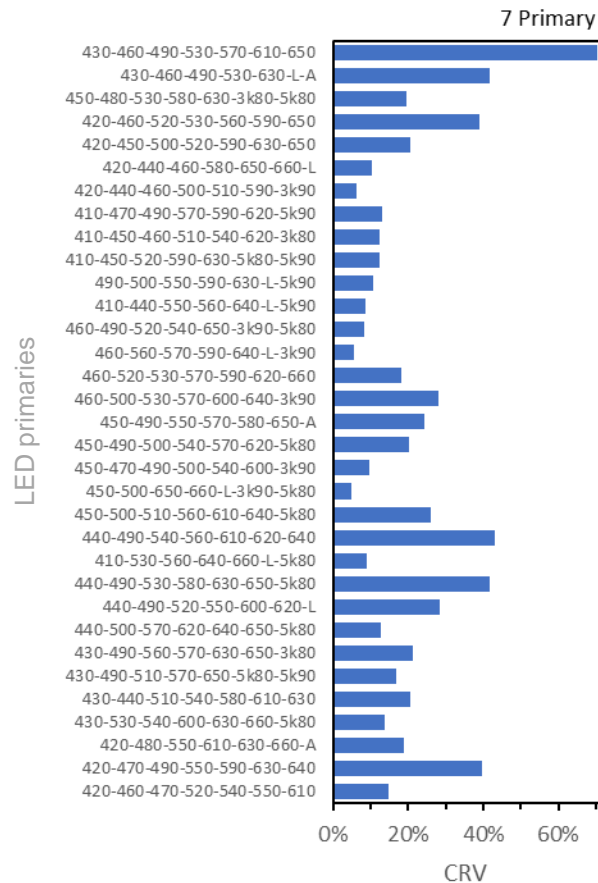
Royer M, Murdoch MJ, Smet K, Whitehead L, David A, Houser K, et al. Improved Method for Evaluating and Specifying the Chromaticity of Light Sources. *Leukos* 2023; 19: 35–52.

Smet KAG, Royer MP, Baxter D, Bretschneider E, Esposito T, Houser K, et al. Recommended method for determining the correlated color temperature and distance from the Planckian locus of a light source. *Leukos*. Submitted.

Royer MP, Smet KAG, Baxter D. Modifications of the Robertson Method for Calculating Correlated Color Temperature to Improve Accuracy and Speed. *Leukos*. In Press.

- The use of outdated color matching functions result in unnecessary mismatch between lighting products.
- Updated CMFs were published by CIE in 2015, but have received little use.
- PNNL led an international group to propose a system (s, t) to enable wider use of these metrics.
- Work in FY23 will focus on having the system recognized by the Illuminating Engineering Society.
- CCT is well-defined, but there is no standard calculation method for this important lighting quantity—it does not have an exact calculation.
- PNNL has led a working group within the IES color committee that in FY23 will publish one article presenting a new, more efficient method for calculating CCT and another article showing the benefits of the method compared to previous proposals.
- Work in FY23 and FY24 will focus on having the system recognized by the Illuminating Engineering Society.
- Refining key lighting metrics that haven't been updated in decades can help ensure effective optimization and higher quality lighting installations.

Approach, Progress, and Future Work | Spectrum



Range in color rendition variation (CRV) for a set of 33 different multi-primary LED systems.

MULTI-PRIMARY LED SYSTEM

- DOE projects multi-primary LED systems to be the most efficacious SSL system by 2030.
- To enable a transition to these system, calculation methods and metrics are needed to characterize and compare performance, enabling system optimization.
- In FY22, PNNL developed a method for calculating large metamer sets that reduces the calculation time by up to ~900 times.
- In FY23, PNNL has proposed a new metric for quantifying color rendition variability that a given multi-primary system can produce, which uses the calculated large metamer sets.
- Work will continue in FY23 to find optimal combinations of LED to use in multi-primary systems, allowing tuning for performance characteristics such as alpha-opic content, color rendition, and luminous flux.
- Better metrics and development targets can accelerate advancement for multi-primary LED systems—achieving energy savings sooner—while simultaneously increasing lighting performance and providing added value for energy efficient lighting.

Recent Publications

Baxter D, Durmus D, Royer MP. Enumeration reduction algorithm for the characterization of multi-primary LED systems. Lighting Research & Technology 2022; Online before print. DOI:10.1177/14771535221111652

Royer MP, Durmus D, Baxter D. A new way to understand the color rendition performance of multi-primary LED lighting systems. Leukos. Submitted.

Summary

FLICKER

Have completed experimental work and are on track for new metric development to move through industry consensus process in 2024. Next steps are to encourage use of metric, leading to product development, data availability, and improved ability to specify lighting products that promote wellbeing—especially for sensitive populations.

GLARE

Experimental work to replicate and extend 1949 experiment that underlies key glare metrics is in progress. Data will be used to evaluate existing glare metrics—specifically the position index and SPD effects—and likely propose modifications to or replacements. These will be proposed to lighting standards organizations to optimize lighting quality, efficiency, and comfort, with the goal of customer acceptance and adoption.

SPECTRUM

Nearing completion of an experiment on effects of near-infrared and far-red radiation on cognition, mood, and cardiovascular physiology. This could provide key new evidence on how an under-studied part of the light spectrum affects building occupants, via architectural lighting systems. There are substantial implications for both wellbeing and energy use.

Have developed new calculation methods and metrics for assessing tunable, color-mixed LED systems. These tools can help advance the development of more efficient LED systems

Have developed new methods for calculating chromaticity and CCT, both of which can now move through the industry consensus standards process. This work will help advance color research and provide for defensible standards.

Thank You

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REFERENCE SLIDES

Project Execution

	FY2022				FY2023				FY2024			
Planned budget												
Spent budget												
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
FY22 Q1: Evaluation of VR tools for assessing lighting quality		◆										
FY22 Q2: flicker literature review article			◆									
FY22 Q3: Glare methods review article				◆								
FY22 Q3: Uniformity perception experiment article				◆								
FY22 Q4: Flicker experiment article				◆								
FY22 Q4: Color rendition variability article				◆								
Current/Future Work												
Q1: FR/NIR experiment article (delayed to validate data)						◆		◆				
Q2: Flicker metric (PAVM) development article							◆					
Q3: Glare experiment article								◆				
Q4: Brightness perception experiment article								◆				

- Go/no-go on 7/31/23 for continue research to support improved glare metrics
- FY23 Q1 deliverable delayed for increased data validation efforts (work is being performed by partners at University of British Columbia)

Team



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