Pacific Northwest
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PNNL-38552

The Effect of Luminance Pattern on Nighttime Discomfort Glare Response (CRADA 653) Final Report

September 2025

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U.S. DEPARTMENT OF ENERGY

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Richland, Washington 99354

CRADA FINAL REPORT CERTIFICATION MEMO

Memo Completion Date: 9/19/2025

CRADA number: 653

CRADA Title:

Responsible Technical Contact at DOE Lab (PNNL):

Belal Abboushi

Provide a list of publications, conference papers, or other public releases of results, developed under this CRADA:

This research project resulted in one journal article titled "LED Array Spatial Frequency Impacts Discomfort and Afterimages in a Simulated Nighttime Environment" that is currently under review by Lighting Research and Technology journal (expected publication by end of calendar year). Additionally, the results were presented to Musco Sports Lighting and the McClung foundation on March 24 2025 and to the Next Generation Lighting Industry Alliance (NGLIA) on July 31, 2025. This project helped establish and bolster collaborations with Musco Sports Lighting, FaceX, and the McClung foundation.

Provide a detailed list of all subject inventions, to include patent applications, copyrights, and trademarks:

No inventions were generated under this CRADA.

Executive Summary of CRADA Work

LED luminaires with apertures containing visually resolvable “bright” (i.e., high luminance) spots are commonly used to illuminate outdoor environments. However, the impact of the distance between LEDs, which determines spatial frequency at a given viewing distance, on perceived discomfort caused by these luminaires remains unclear. This study involved 29 participants who were each shown 68 stimuli varying in spatial frequency, intensity, diffusion level, and ambient lighting in a dark laboratory setting. Participants reported their experiences of discomfort from glare, ability to resolve individual LEDs, and afterimages.

The findings revealed that increased spatial frequency heightened both discomfort and the likelihood of experiencing afterimages. It is hypothesized that the point spread function of the eye contributed to these effects, where sources began to be perceived as a single larger source with equal or greater intensity. These results suggest that LED luminaire designs should favor configurations with lower spatial frequencies to minimize discomfort. A simple quantity, direct illuminance at the eye, is recommended for use to predict discomfort from glare because it performed like other more complex models.

Summary of Research Results

LED luminaires with apertures containing visually resolvable “bright” (i.e., high luminance) spots are commonly used to illuminate outdoor environments. However, the impact of the distance between LEDs, which determines spatial frequency (SF) at a given viewing distance, on perceived discomfort caused by these luminaires remains unclear. It is also unclear which of the existing models can be used to predict discomfort.

Following the two gaps outlined above, there were two aims of this study : 1) to investigate the impact of the spatial frequency of LED array on discomfort from glare, visual afterimages, and ability to visually resolve LEDs in outdoor nighttime environments; and2) to evaluate the performance of discomfort-from-glare models focusing on candidate models E_d, Bul08, Bul11, UGRs, Lin15, and the CIE-150:2017 limits on luminous intensity.

We hypothesized that 1) light patterns with higher SF would be associated with a smaller likelihood of discomfort compared to a pattern between 2 and 5 cycles per degree; 2) at the same illuminance at the eye, adding diffusion would reduce the likelihood of discomfort ratings compared to bare LEDs regardless of the SF; 3) afterimages would be associated with the spatial frequency of the source; and 4) two models (Bul08 and E_d) would perform better than other models with diffuse and bare LEDs at different SFs.

Figure 1: The glare apparatus (left), a view from the participant’s position (middle), and an overview showing the ambient lighting source which was hidden from participant’s view.

As SF increased, the likelihood and amount of discomfort from glare significantly increased, the ability to resolve individual LED bright spots significantly decreased, and the likelihood of afterimages significantly increased. We conclude that this is likely due to the projection of point sources on the retina through a point spread function due to aberrations and scattering in the eye. Figure 2 illustrates the perceived image and intensity of the LED patterns.

Given the impact of SF, mediated by the point spread function, on discomfort from glare, it is desirable to reduce the SF of a bare LED array such that the brightness of each LED remains separated and does not become perceptually joined with adjacent LEDs. Another solution is to use diffusion that can mask the SF of the LEDs, which is also useful for reducing the maximum luminance, though this often comes at a reduced luminous efficacy compared to bare LEDs.

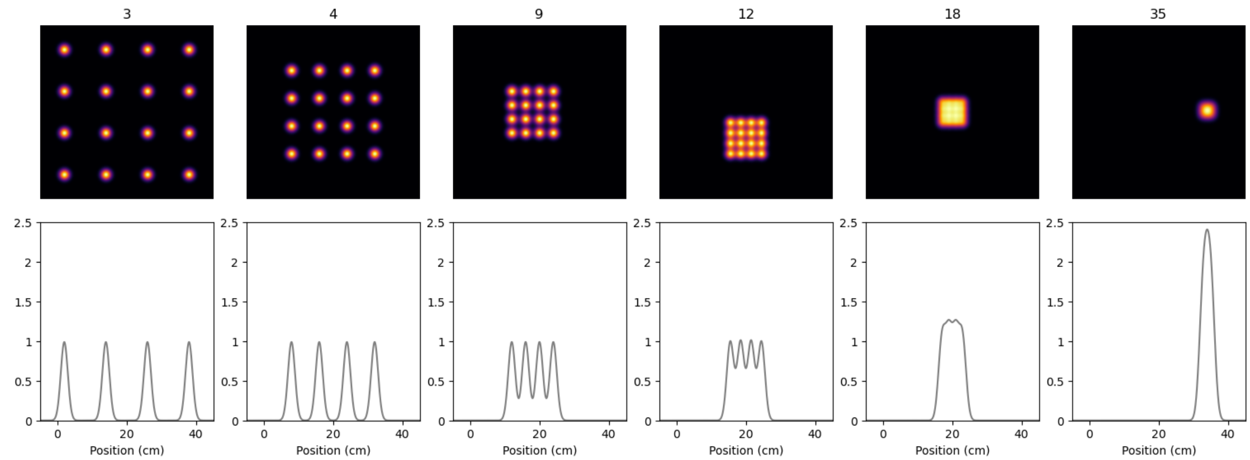

Figure 2: The effect of LED spatial frequency on the perceived image due to the point spread function. At the same maximum luminance (L_{max}), as spatial frequency increases, LEDs are imaged closer to each other on the retina and these images merge to form one larger source at an equal or higher perceived luminance level (top row). The bottom row shows the intensity profile accounting for the point spread function; y axis is the intensity in arbitrary units.

For the range of conditions examined in this experiment, the five models performed similarly for identifying discomfort from non-discomfort conditions. We recommend the use of E_d because of its simplicity and similar diagnostic performance to other more complex models that we tested. The CIE-150:2017 luminous intensity limits —which can be converted to limits on direct illuminance at the eye assuming a point source— appear to be too strict, depending on the selected environmental zone. Further research is needed to determine the ambient illuminance corresponding to each environmental zone, and to test the CIE limits using a wider range of luminous conditions.

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