Measuring Luminaire Luminance Uniformity

January 11, 2022

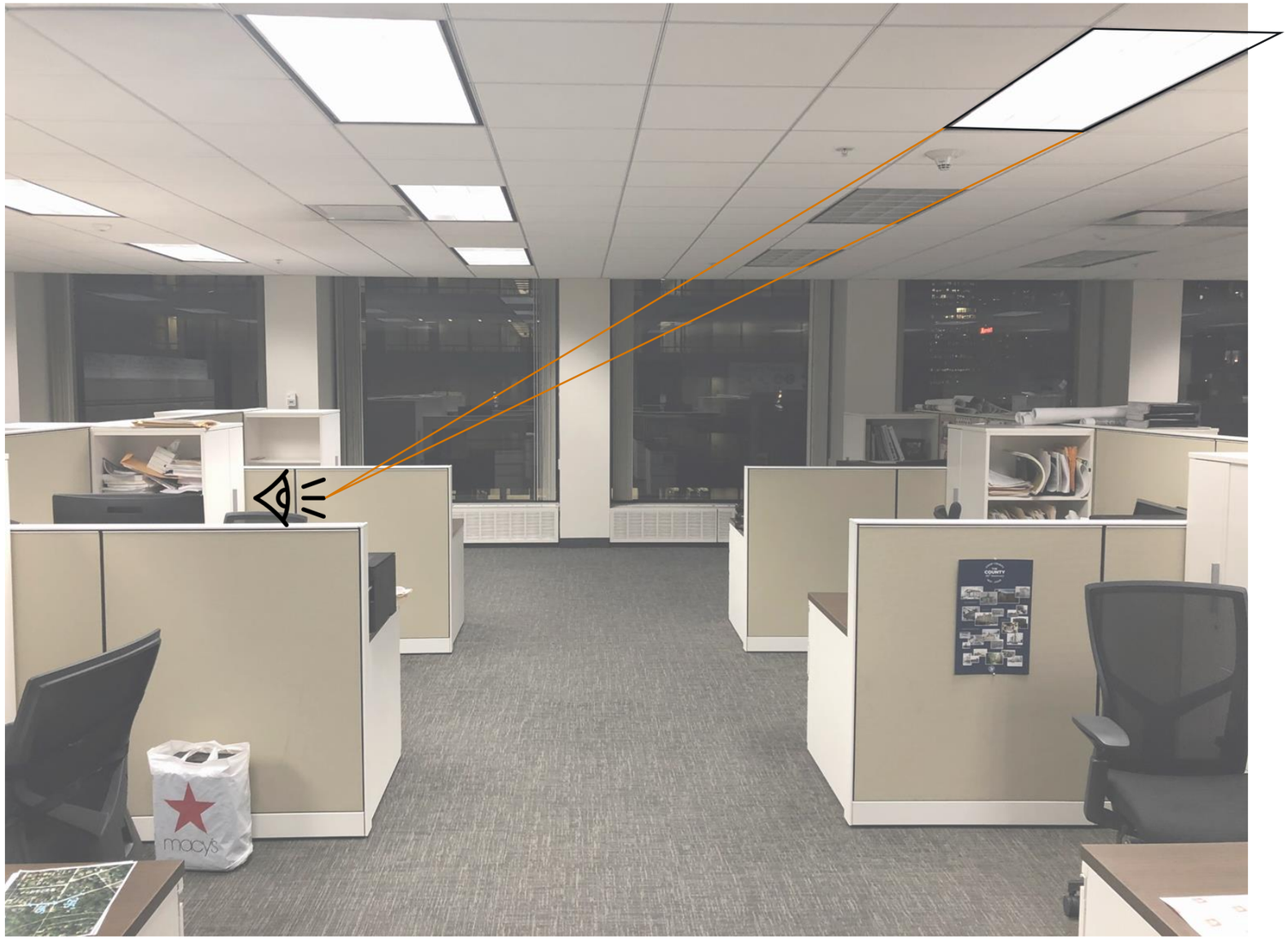
Belal Abboushi

Eduardo Rodriguez-Feo Bermudez

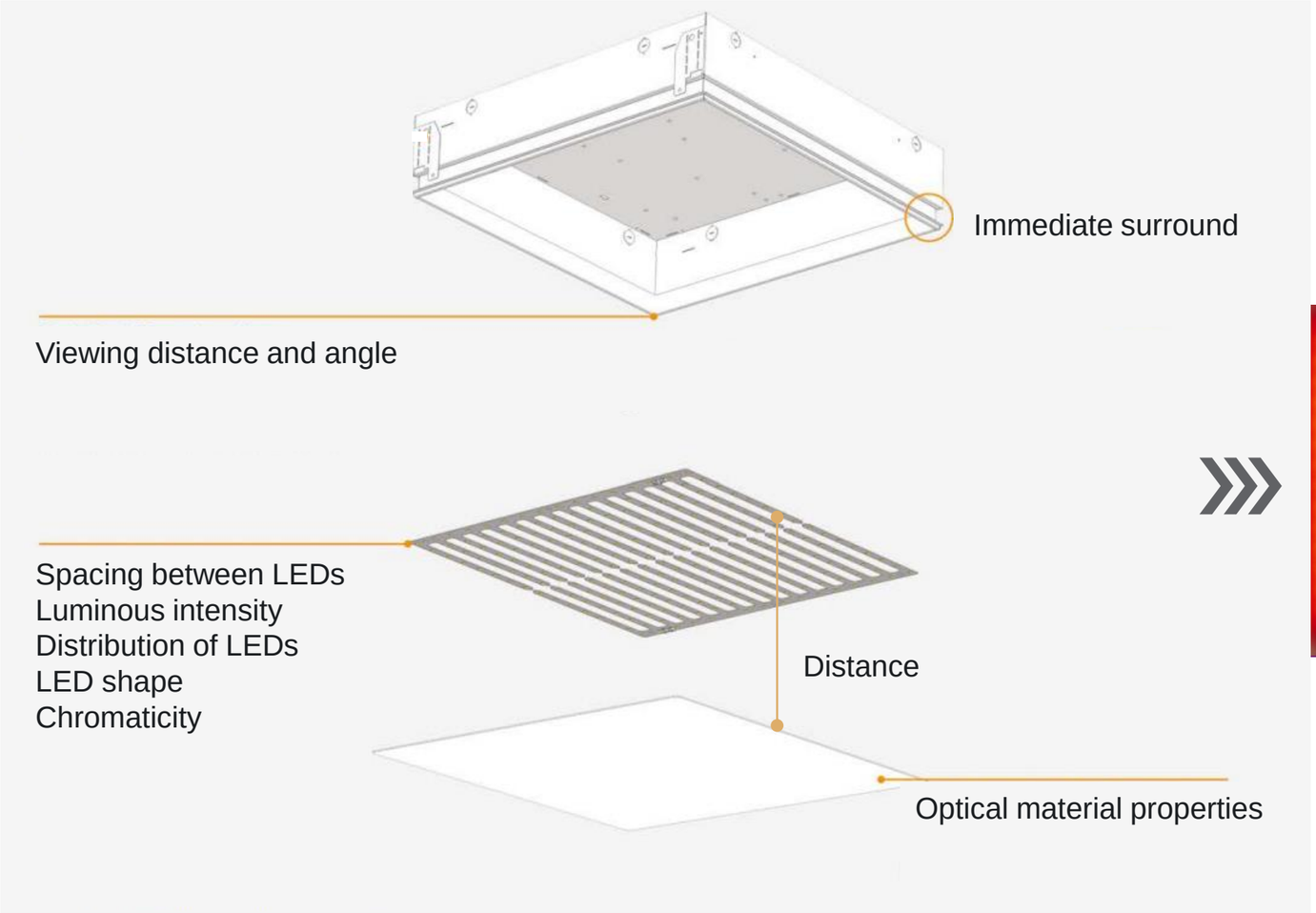
Lia Irvin

PNNL is operated by Battelle for the U.S. Department of Energy

Luminaire Luminance Uniformity



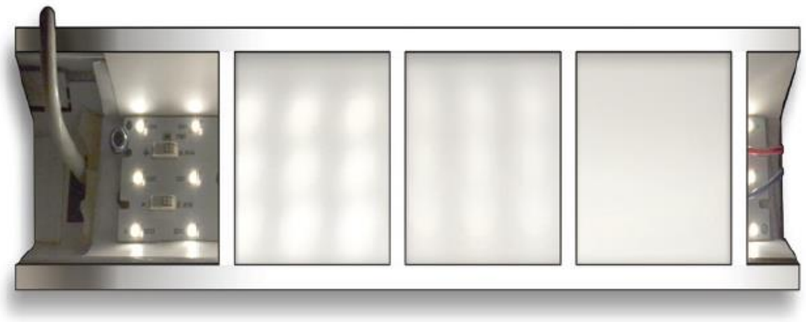
Implications of LLU



Luminaire luminance uniformity

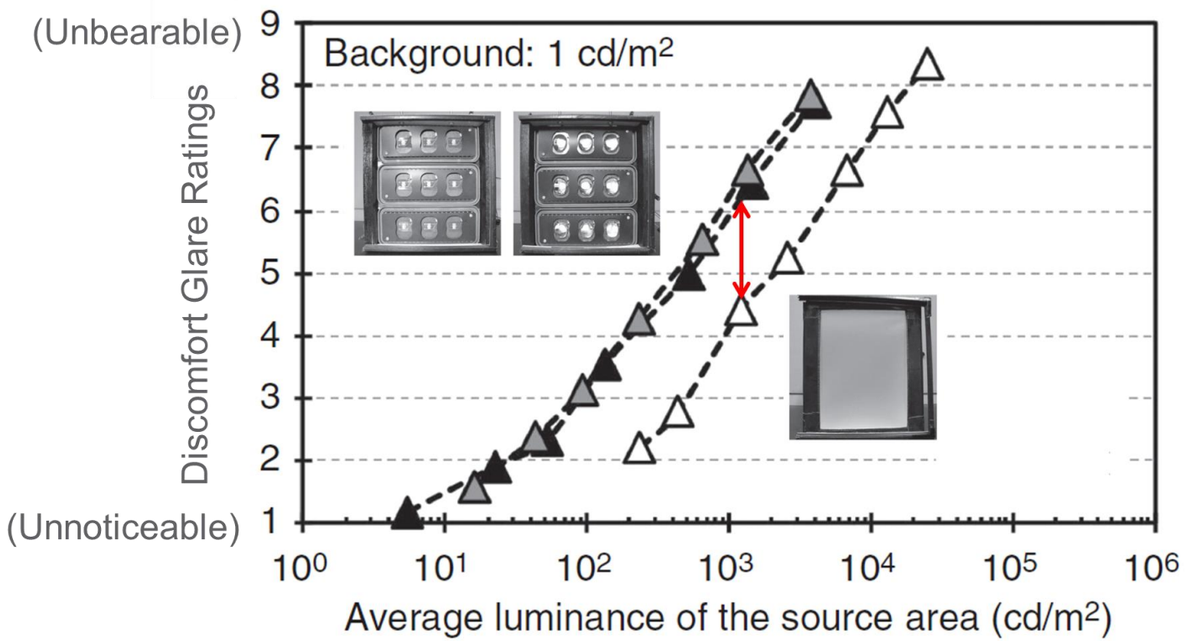
- Luminous efficacy
- Discomfort glare
- Visual appeal

Diagram adapted from FINELITE

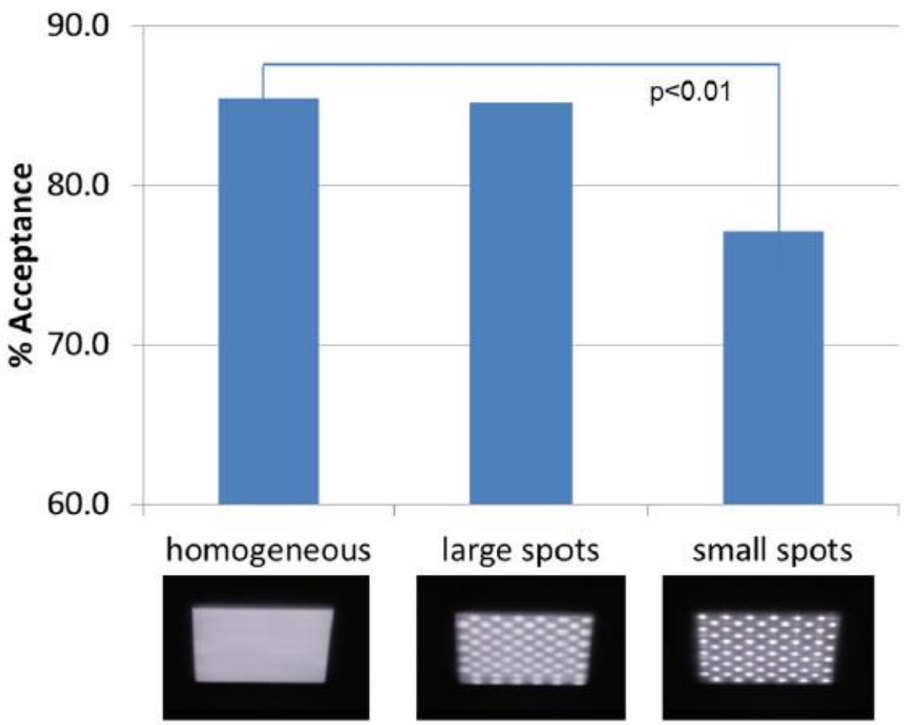


Diffusion angle:	30°	60°	90°
Transmittance*:	89%	73%	64%

Sources: Whiteoptics
* Values from Itioptics library



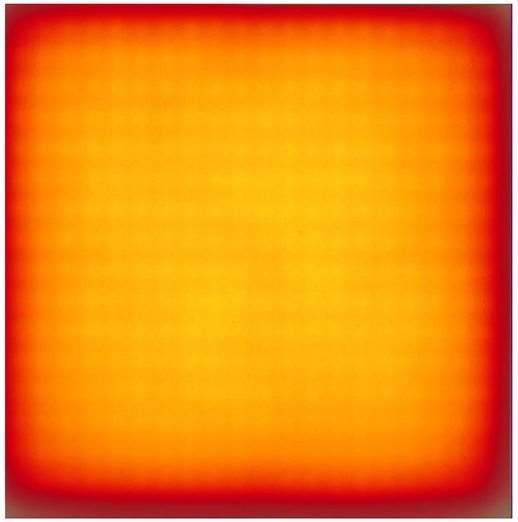
Source: Tashiro, T., S. Kawanobe, T. Kimura-Minoda, S. Kohko, T. Ishikawa, and M. Ayama. "Discomfort Glare for White LED Light Sources with Different Spatial Arrangements." Lighting Research and Technology



Geerdinck et al. 2014. Discomfort glare perception of non-uniform light sources in an office Setting. Journal of Environmental Psychology.

Uniformity Metrics

- Max:Min
- Avg:Min
- Coefficient of variation (CV)
- Entropy Uniformity (EU)

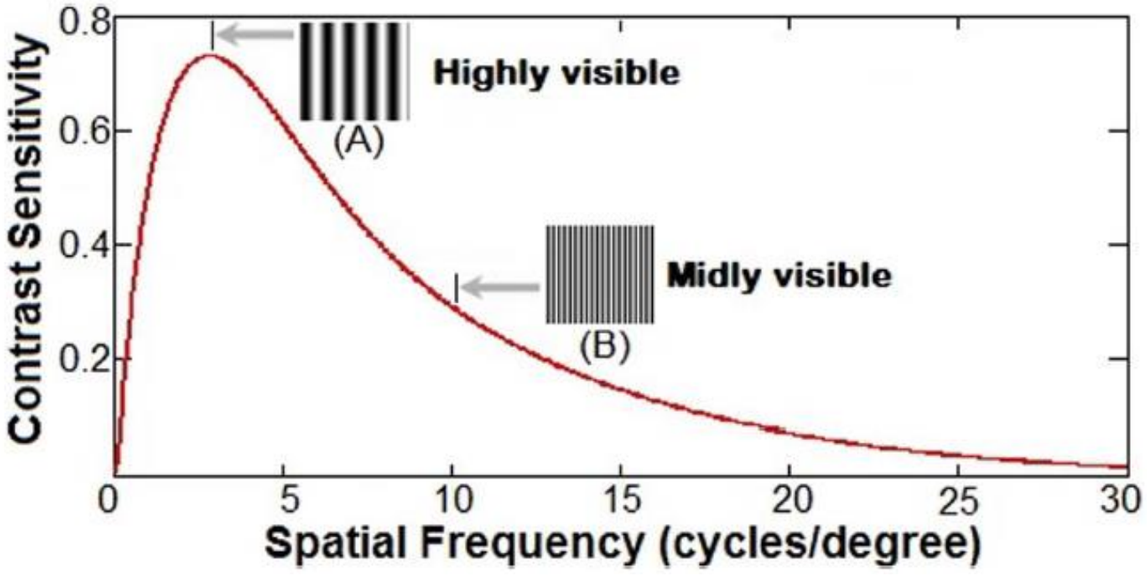


$$P_i = \frac{L_i}{\sum_{i=1}^{n} L_i}$$

$$EU = 1/n \cdot \exp(-\sum p_i \ln(p_i)).$$

Yao, Qi, Botao Zhong, Yue Shi, and Jiaqi Ju. “Evaluation of Several Different Types of Uniformity Metrics and Their Correlation with Subjective Perceptions Evaluation of Several Different Types of Uniformity Metrics and Their Correlation with Subjective Perceptions.” Leukos 13, no. August (2017): 33–45.

Uniformity based on the Human Visual System (UHVS)



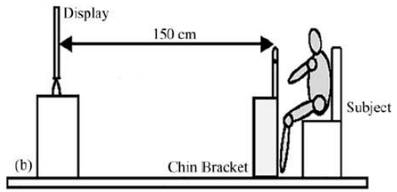
$$U_{HVS} = \frac{1}{1 + k \cdot CV^{\alpha} \cdot NU_{HVS}^{\beta}}$$

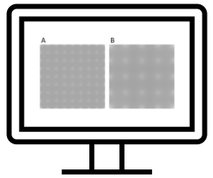
- U_{HVS} ranges from 0 to 1
- Higher is more uniform

- Accounts for:
  - CSF of pattern
  - Adaptation luminance (cd/m^2)
  - Viewing distance (m)
  - Pattern area (squared degrees)
  - Viewing angle (degrees)

Source: Moreno, Ivan. "Illumination Uniformity Assessment Based on Human Vision." Optics Letters, 2010.

Performance of Metrics





Metric	Adjusted R^2 (Yao et al. 2017)	R^2 (Abboushi et al. 2020)
Max:Min	-	0.88
Avg:Min	0.71	0.50
Coefficient of variation (CV)	0.85	0.57
Entropy Uniformity (EU)	0.95	0.37
U_{HVS}	0.96	0.94

Yao, Qi, Botao Zhong, Yue Shi, and Jiaqi Ju. “Evaluation of Several Different Types of Uniformity Metrics and Their Correlation with Subjective Perceptions Evaluation of Several Different Types of Uniformity Metrics and Their Correlation with Subjective Perceptions.” Leukos 13, no. August (2017): 33–45.

Abboushi, B., Bermudez, E. R.-F., Irvin, L., Feagin, B., Royer, M., and Davis, R. (2021). Examining perceptual luminance uniformity of simulated luminaire patterns. in Light-Emitting Devices, Materials, and Applications XXV, eds. J. K. Kim, M. R. Krames, and M. Strassburg (SPIE), 115–124. doi:10.1117/12.2577901.

Procedure: Luminance Measurements using High Dynamic Range Images

Eduardo Rodriguez-Feo Bermudez

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Measuring Uniformity Using the LLUA

- Headless Raspberry Pi
- Debian/Linux
- Python 3
- Main Packages
  - Gtk3+
  - gphoto2
  - libusb
  - pyenttec
  - Phidget22

Luminaire Luminance Uniformity Apparatus (LLUA) Components

Image and information retrieved from :
*Feagin Jr. B., A.C. Irvin, E. Rodriguez-Feo Bermudez, and M.P. Royer. 2020. "**Apparatus for Studying Human Perception of Luminaire Luminance Uniformity**" In IES Annual Conference 2020 Proceedings*

Phase 1 – Set up

- Set up the experimental space
  - Darken the experimental space (i.e., turn off lights, close windows, etc.)
  - Set the temperature to stable value

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  - Add the high-definition camera
  - Add the luminance meter
  - Place the optical material to be tested in the slot the optical material slot

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  - Add the high-definition camera
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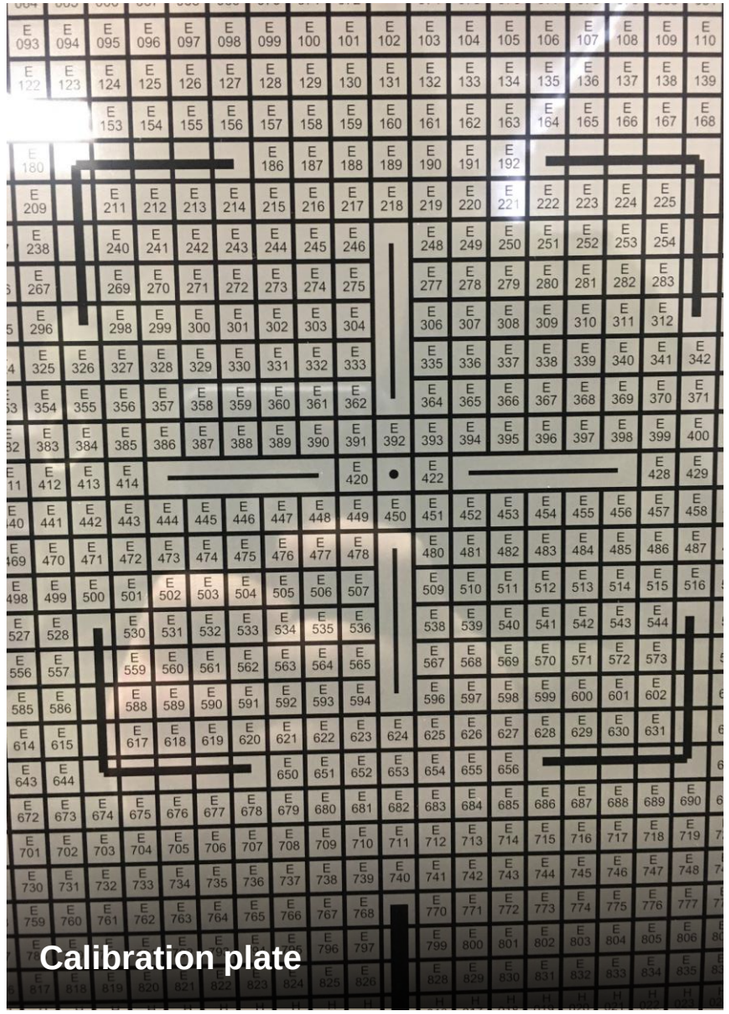
  - Place the optical material to be tested in the slot the optical material slot
- Turn on the LED array at 100%
  - Measure the intensity output of the LED array every 5 minutes
  - Continue this process until the LED have reached stable conditions

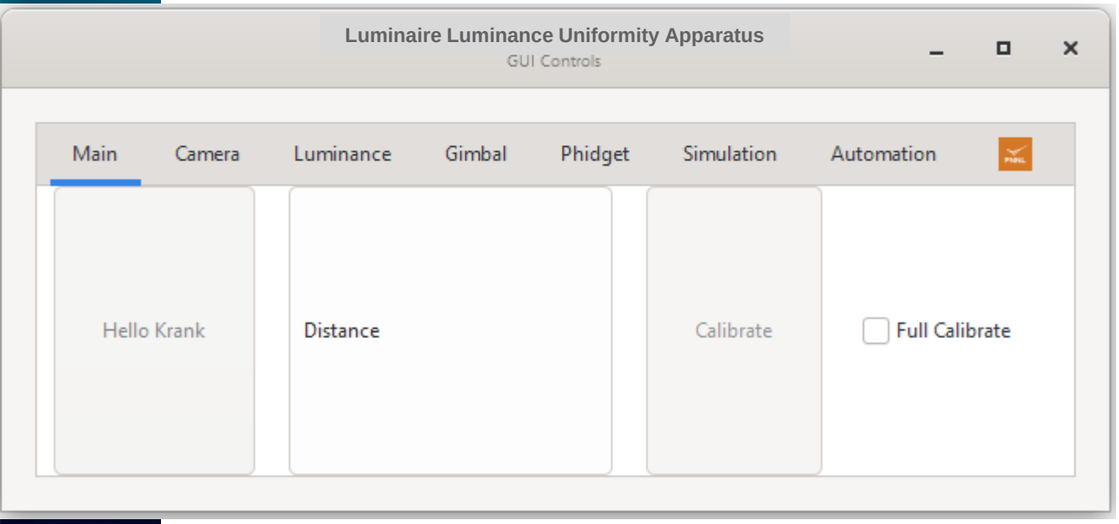
Camera and luminance meter on the gimbal system

LED Array



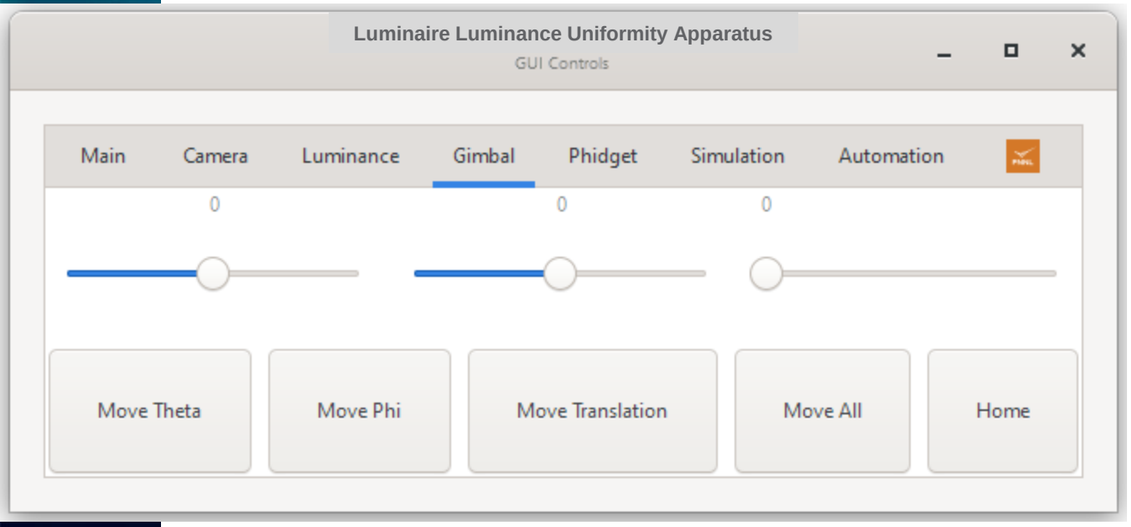
Calibration plate

Phase 2 – Calibration



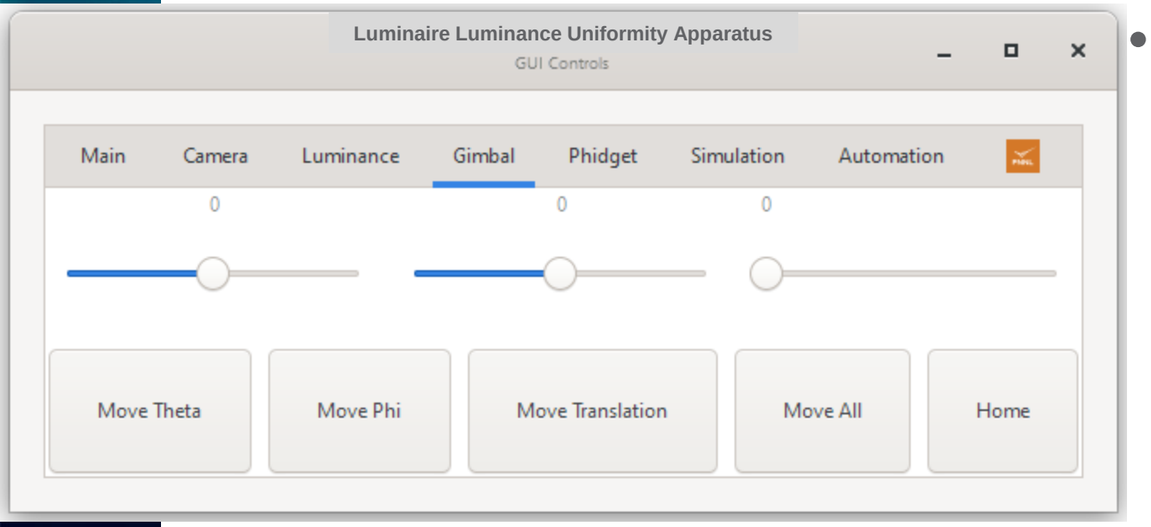
- Adjust distance
  - Set the distance between the optical material and the LED array
  - Set the distance between the two halves of the LLUA

Phase 2 – Calibration



- Adjust distance
  - Set the distance between the optical material and the LED array
  - Set the distance between the two halves of the LLUA
- Center the high-definition camera
  - Place the calibration in from of the optical material
  - Zoom and focus on the calibration plate until the numbers and scares are clearly define

Phase 2 – Calibration



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- Center gimbal to the luminance meter
  - Take note of the spot measurement location on the optical material
  - Take luminance measurement value

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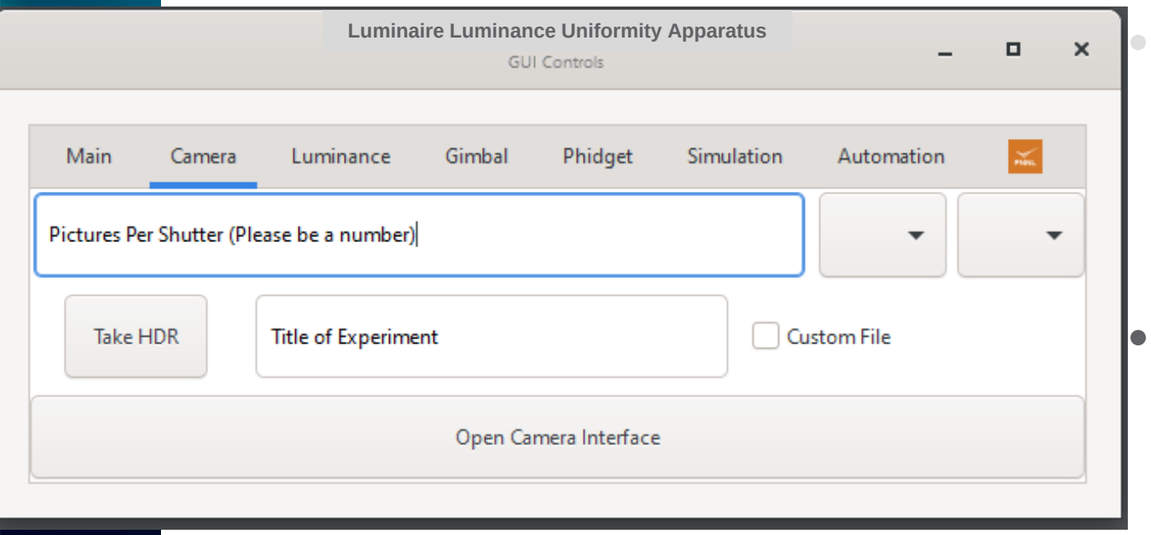

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- Center gimbal to the luminance meter
  - Take note of the spot measurement location on the optical material
  - Take luminance measurement value
- Center the high-definition camera
  - Place the calibration in and
  - Capture pictures of the optical material at varying shutter speeds

Phase 3 – Automated Measurements

- Center the high-definition camera
  - Capture HDR of the optical material by taking pictures at varying shutter speeds from 6 seconds to 1/1600 seconds

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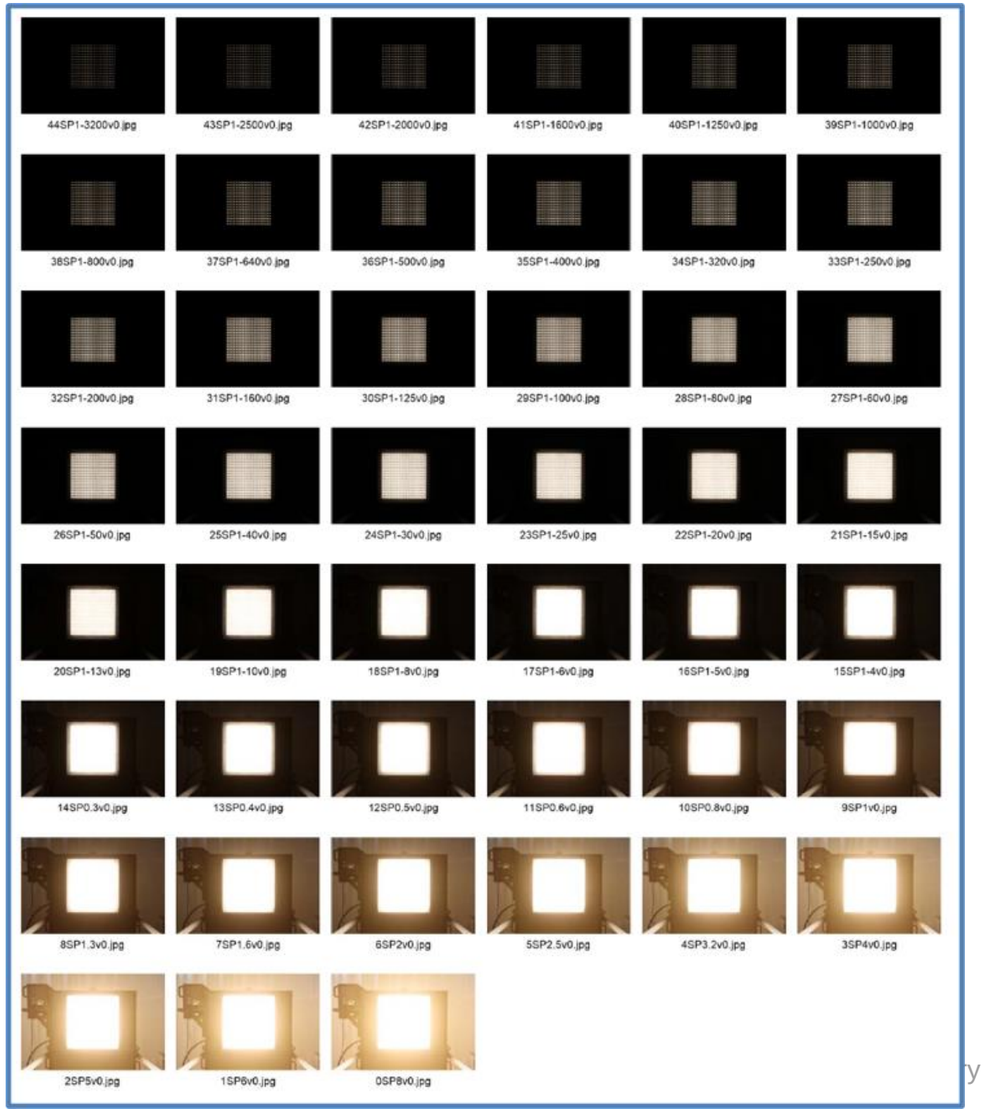
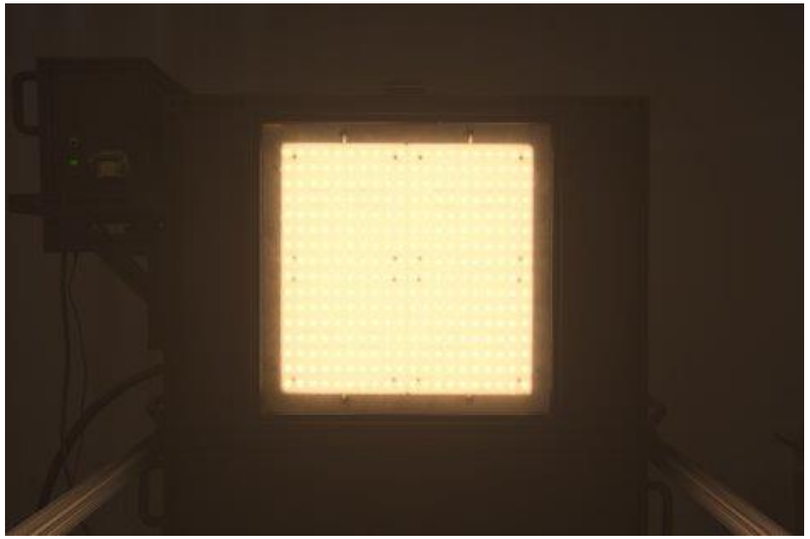
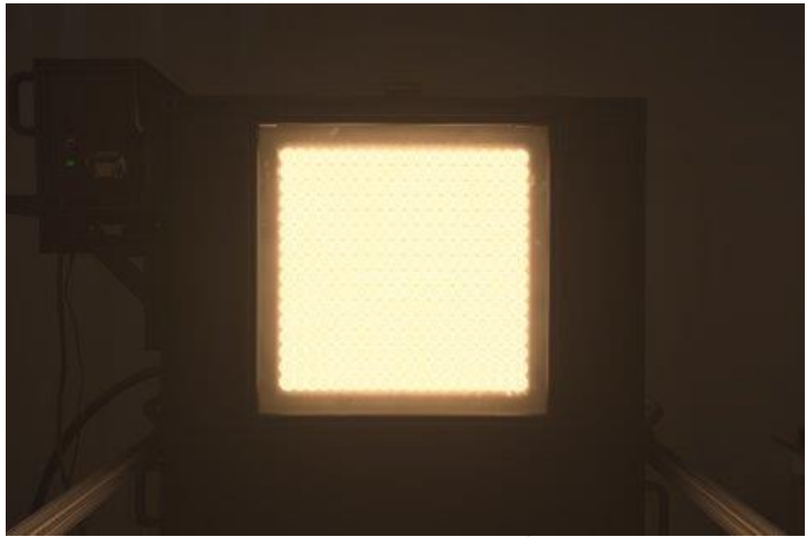
- Center the high-definition camera
  - Capture HDR of the optical material by taking pictures at varying shutter speeds from 8 seconds to 1/3200 seconds



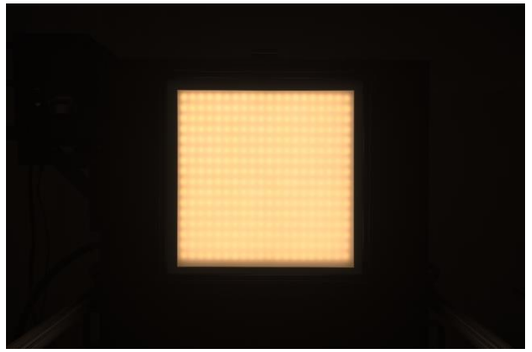
Phase 3 – Automated Measurements

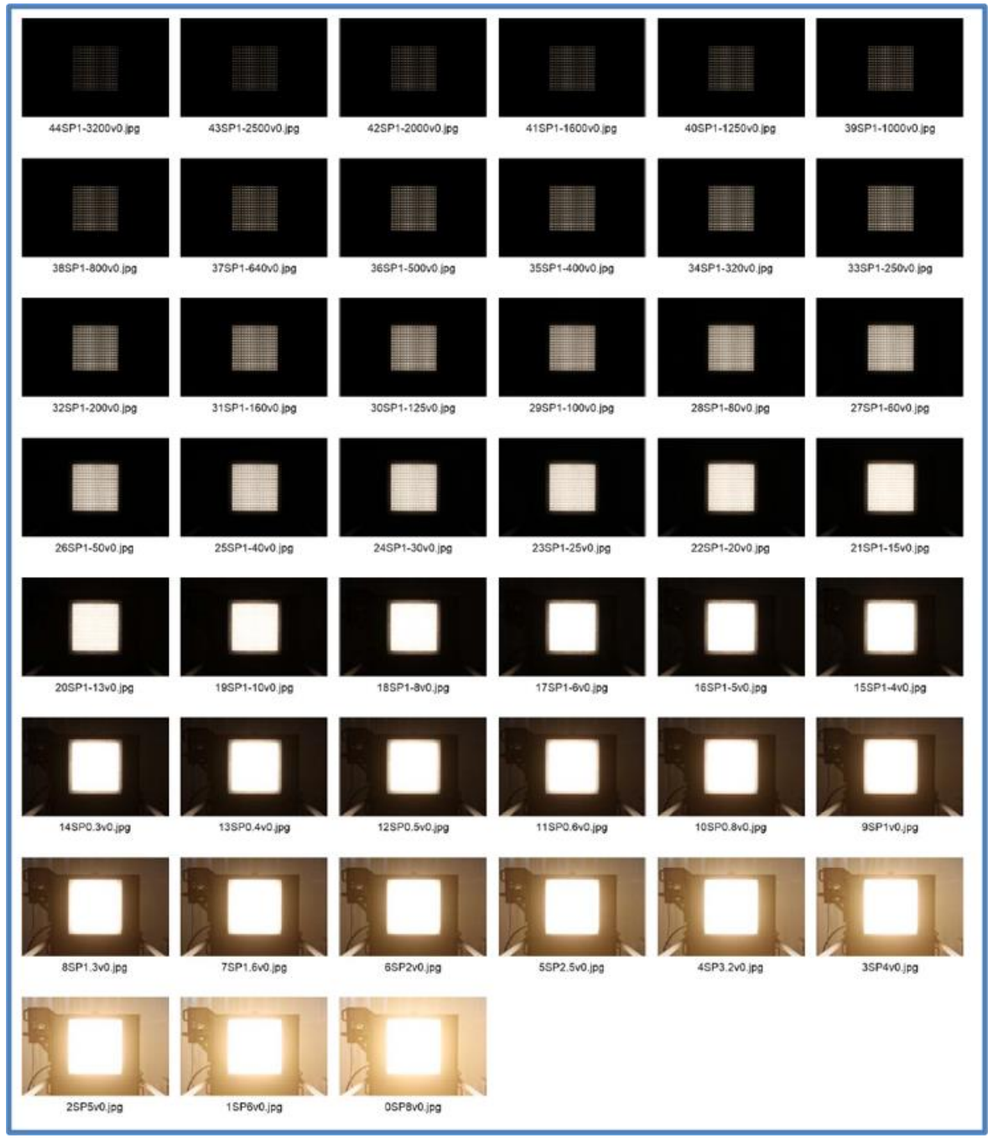
- Move the LED array
  - Motors attached to the LED array move it back by desired increment
  - Capture pictures of the optical material at varying shutter speeds from 8 seconds to 1/3200 seconds
  - Center the luminance meter on the gimbal and take reference luminance spot measurement
  - Move back the LED array by desired increment and take luminance value
  - Center the camera and take HDR
  - Repeat for all desired distance between the LED array and optical





Combine pictures





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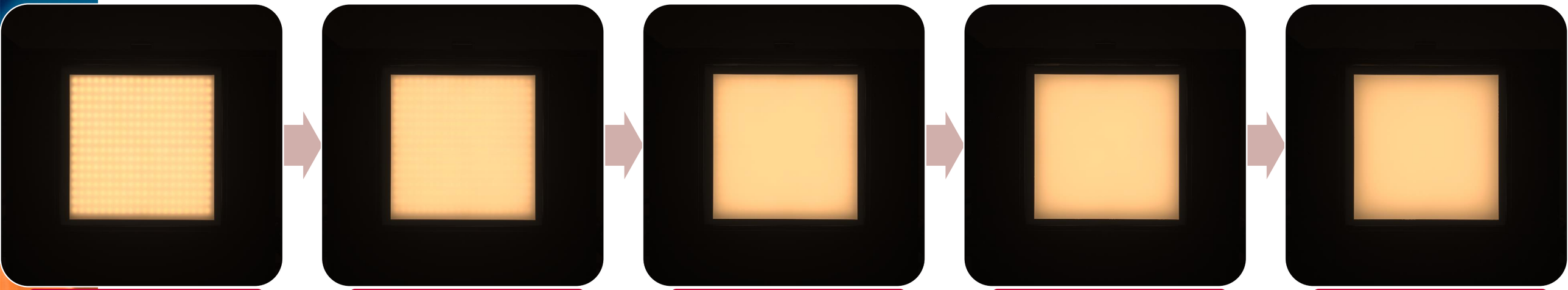
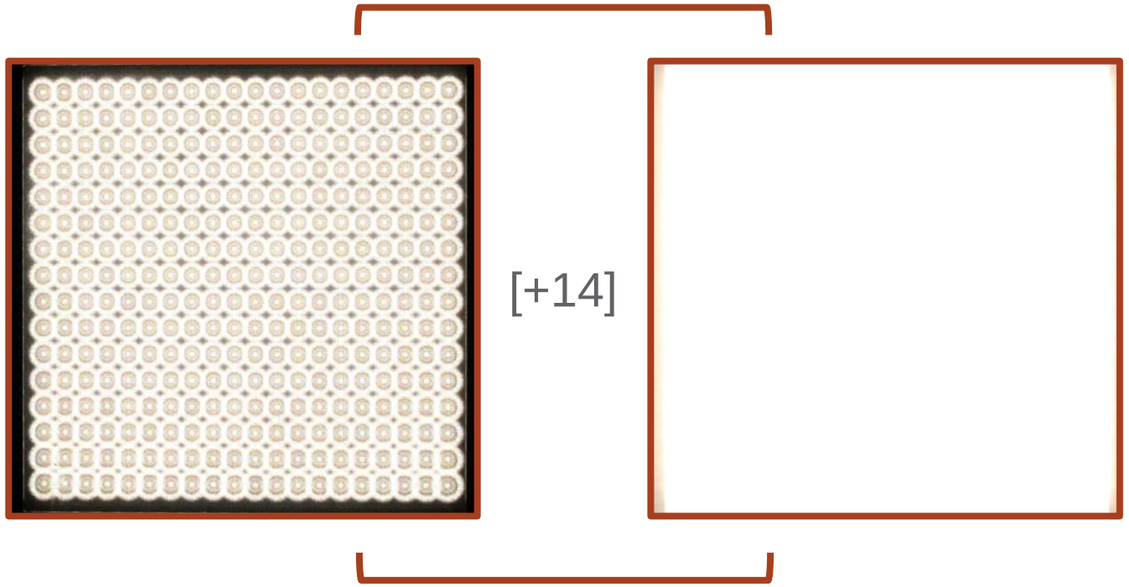


0.5 Inch | 1.0 Inch | 1.5 Inch | 2.0 Inch | 2.5 Inch

Data Analysis and Results

Data Analysis Procedure

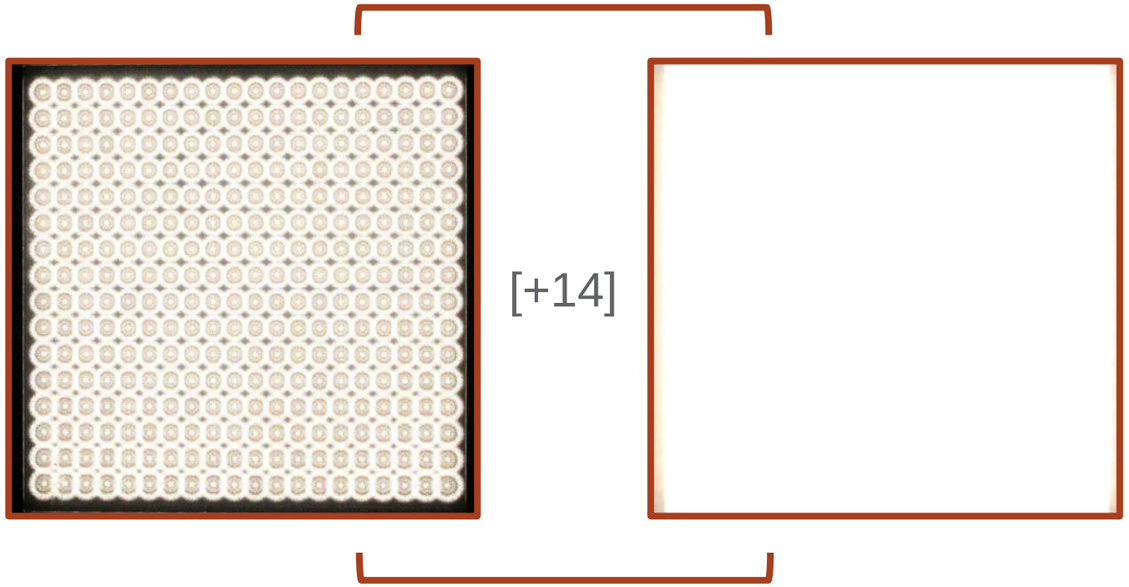
- Combine LDR images using radiance-based software, *raw2hdr*[1]



1 G. Ward. 2018. http://www.anyhere.com

Data Analysis Procedure

- Combine LDR images using radiance-based software, *raw2hdr*[1]
- Convert RGB values to luminance



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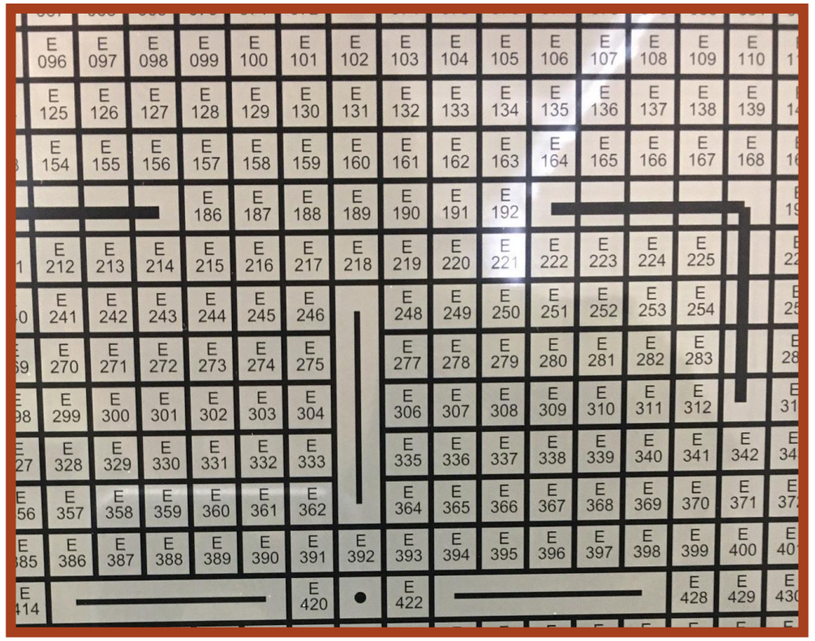
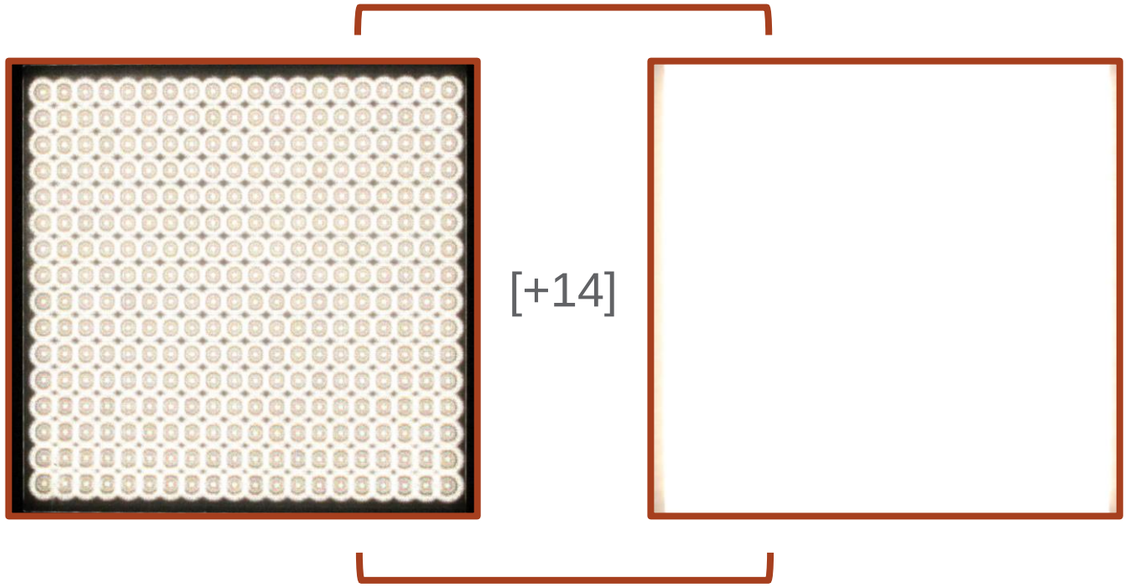
Data Analysis Procedure

- Combine LDR images using radiance-based software, *raw2hdr*[1]
- Convert RGB values to luminance
- Calibrate image using calibration image and spot luminance measurement





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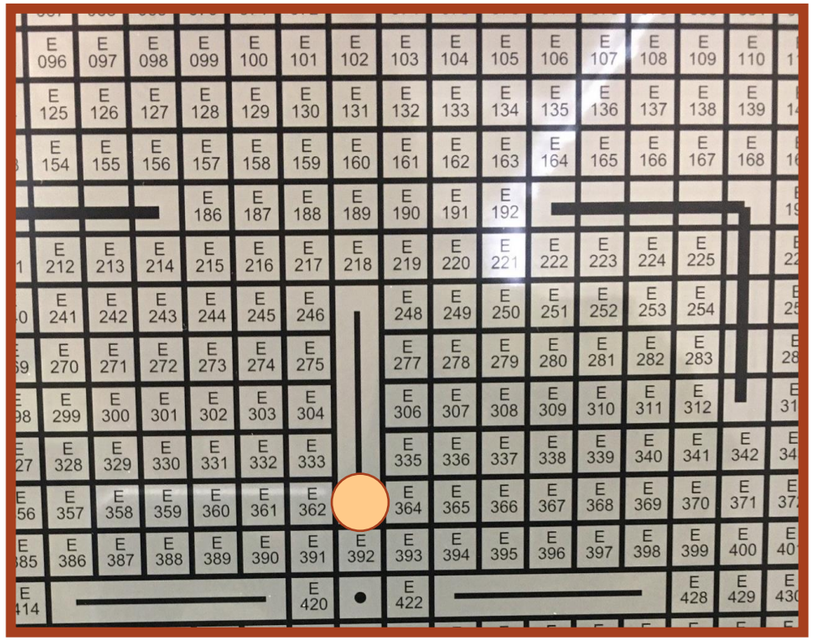

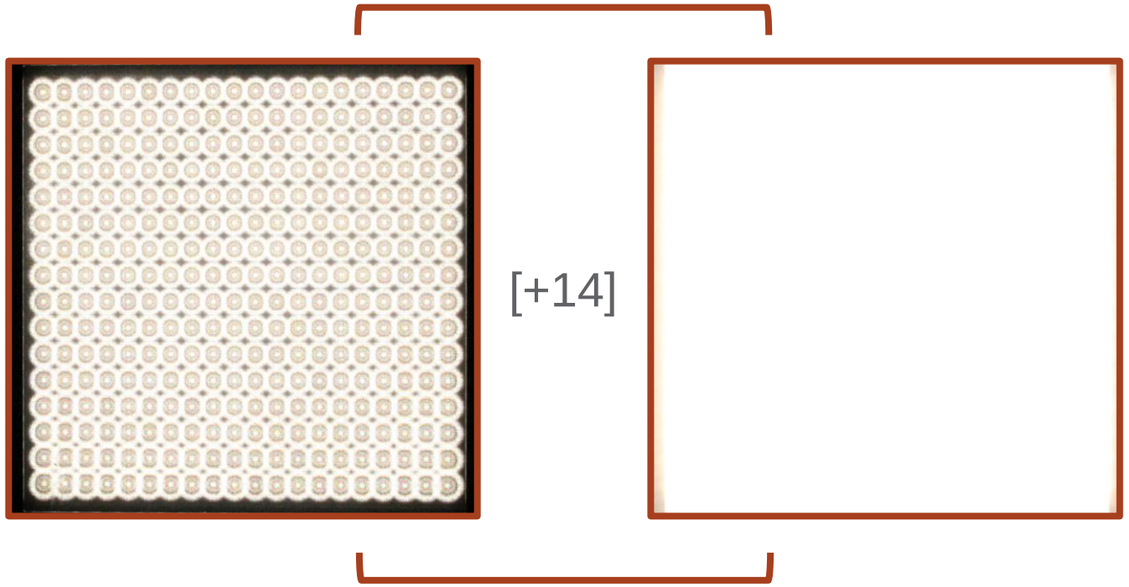

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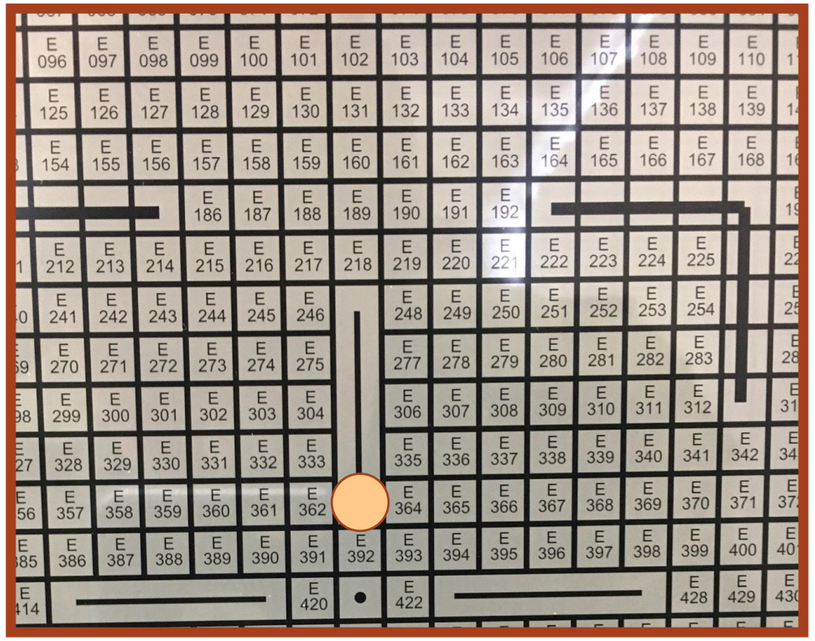
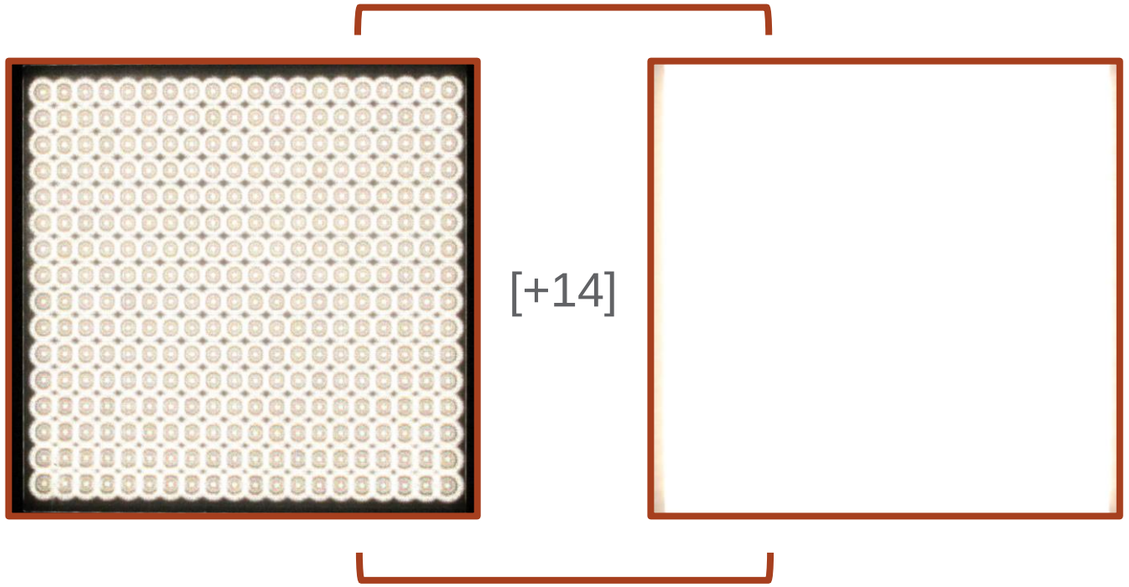
Data Analysis Procedure

- Combine LDR images using radiance-based software, *raw2hdr*[1]
- Convert RGB values to luminance
- Calibrate image using calibration image and spot luminance measurement
- Calculate uniformity metrics





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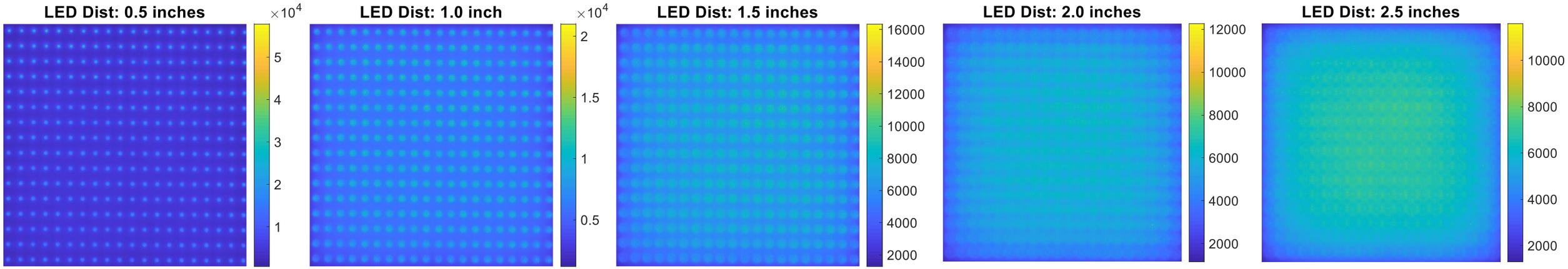
Material 1 Luminance Maps

- Scale: Luminance [cd/m^2]



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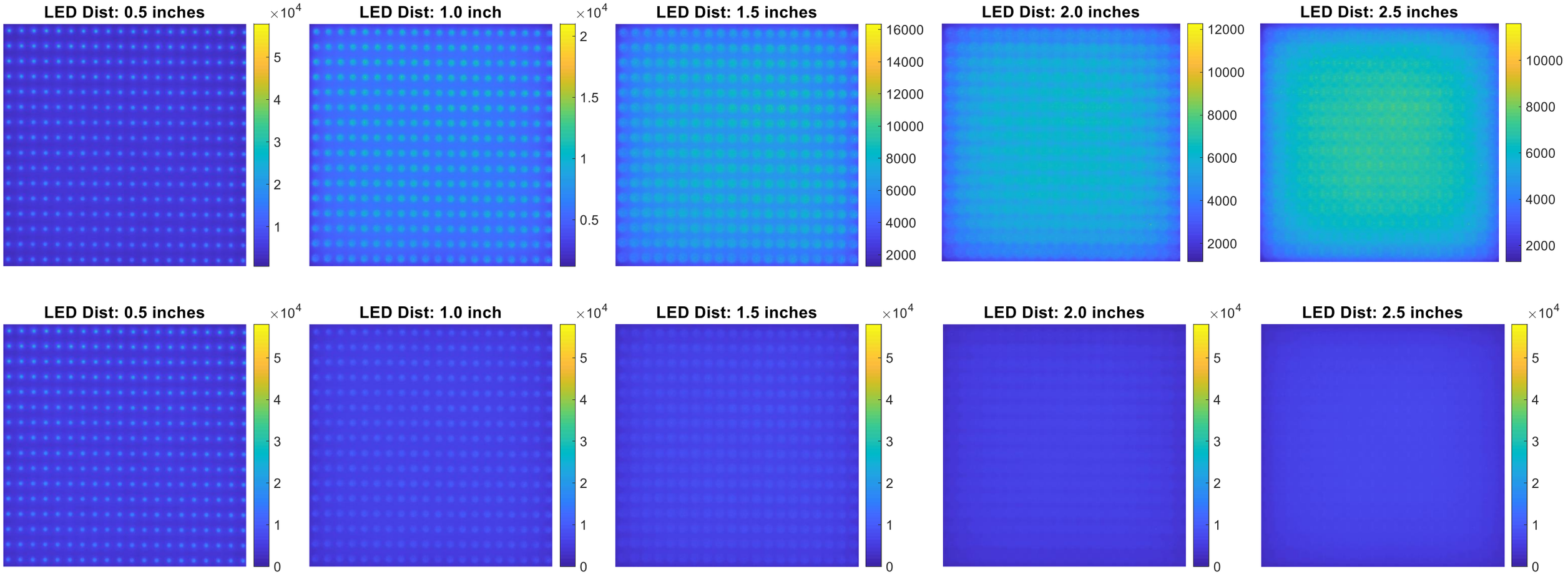
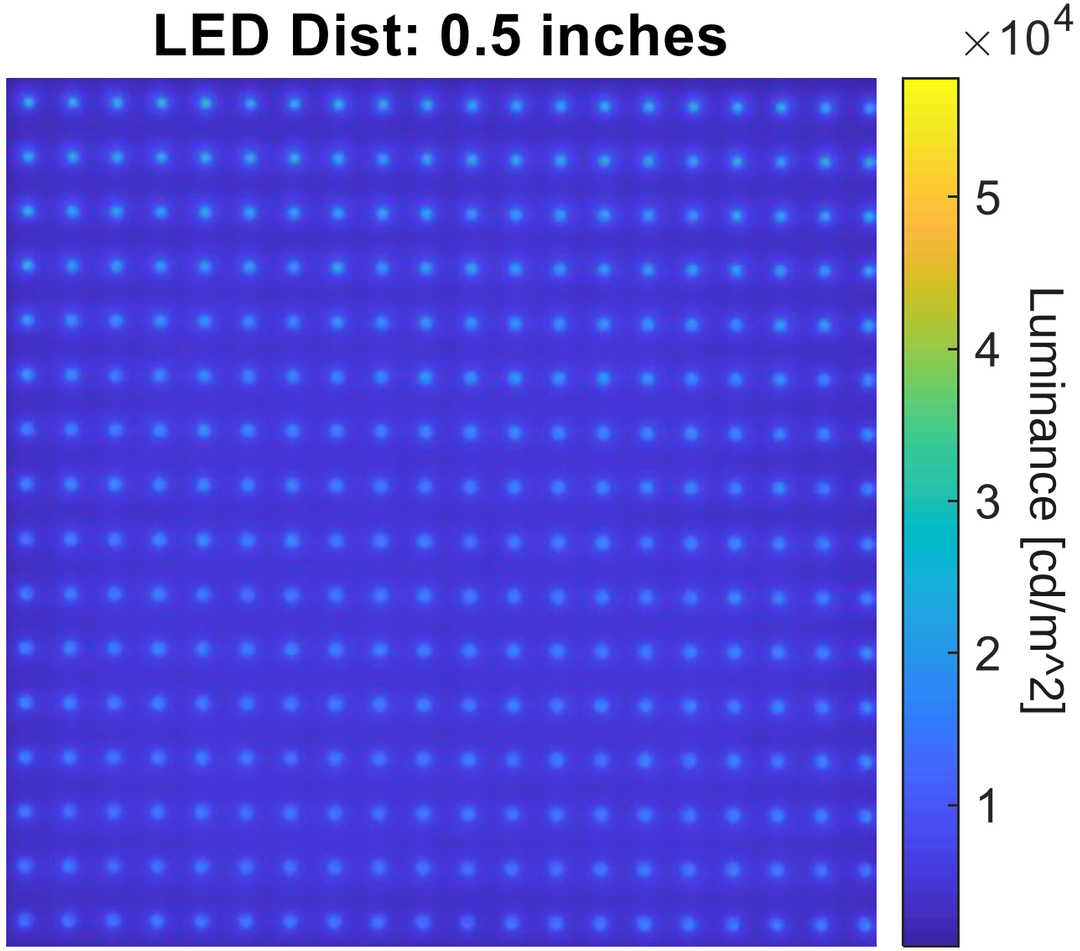
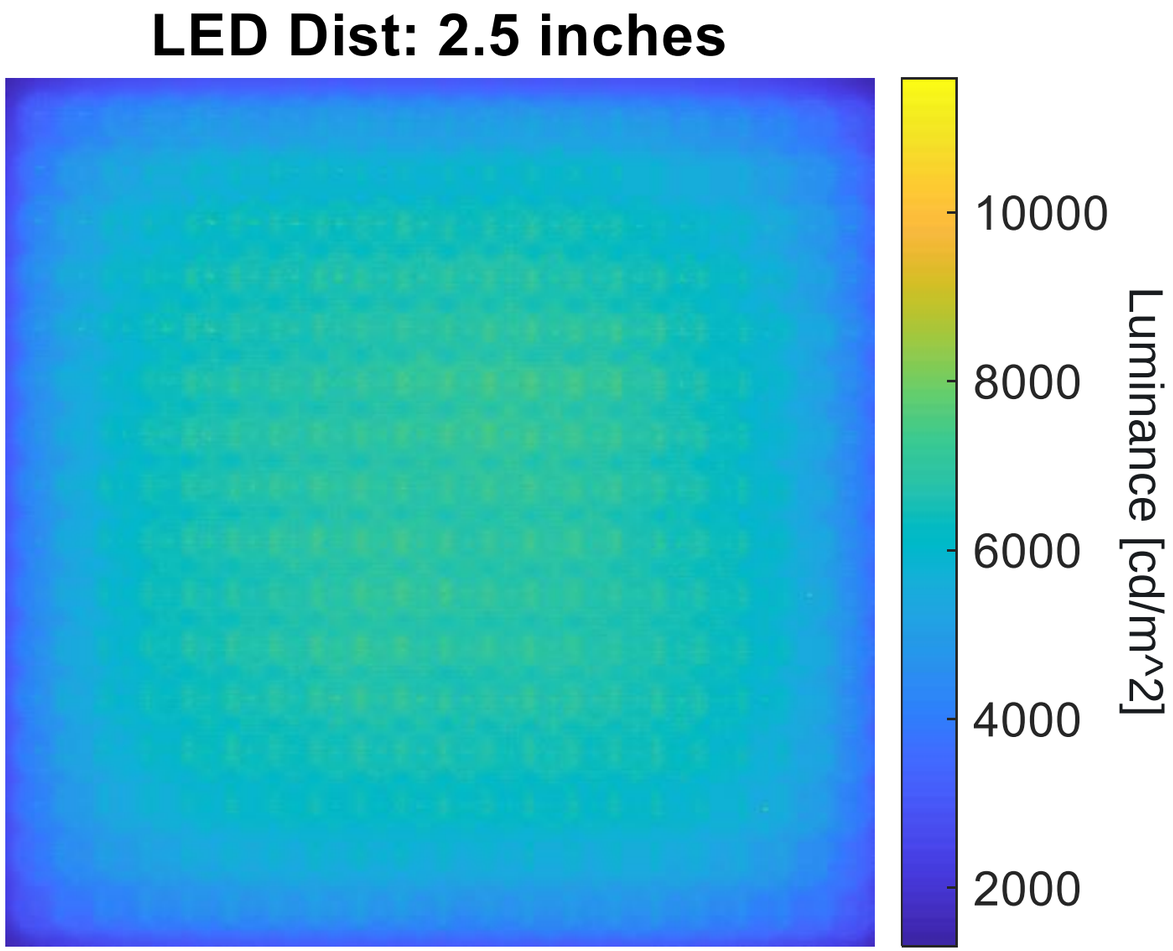


Material 1: LED Distance Extremes

LED Dist: 0.5 inches



LED Dist: 2.5 inches



Material 2 Luminance Maps

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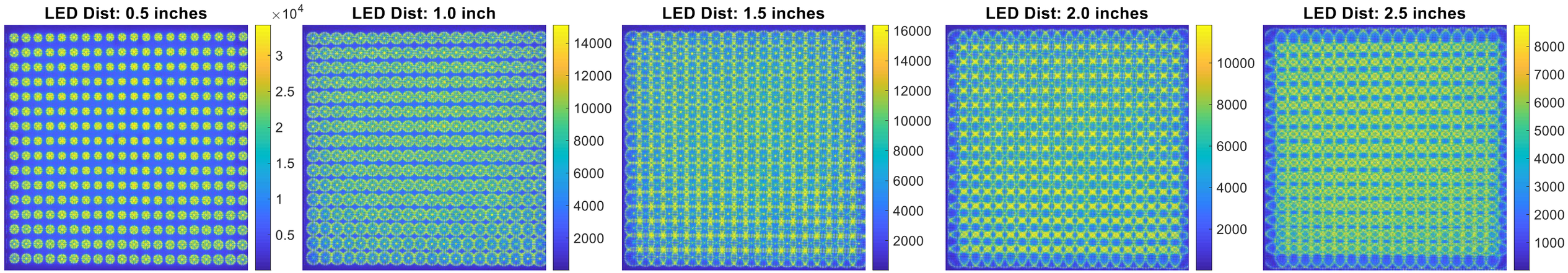

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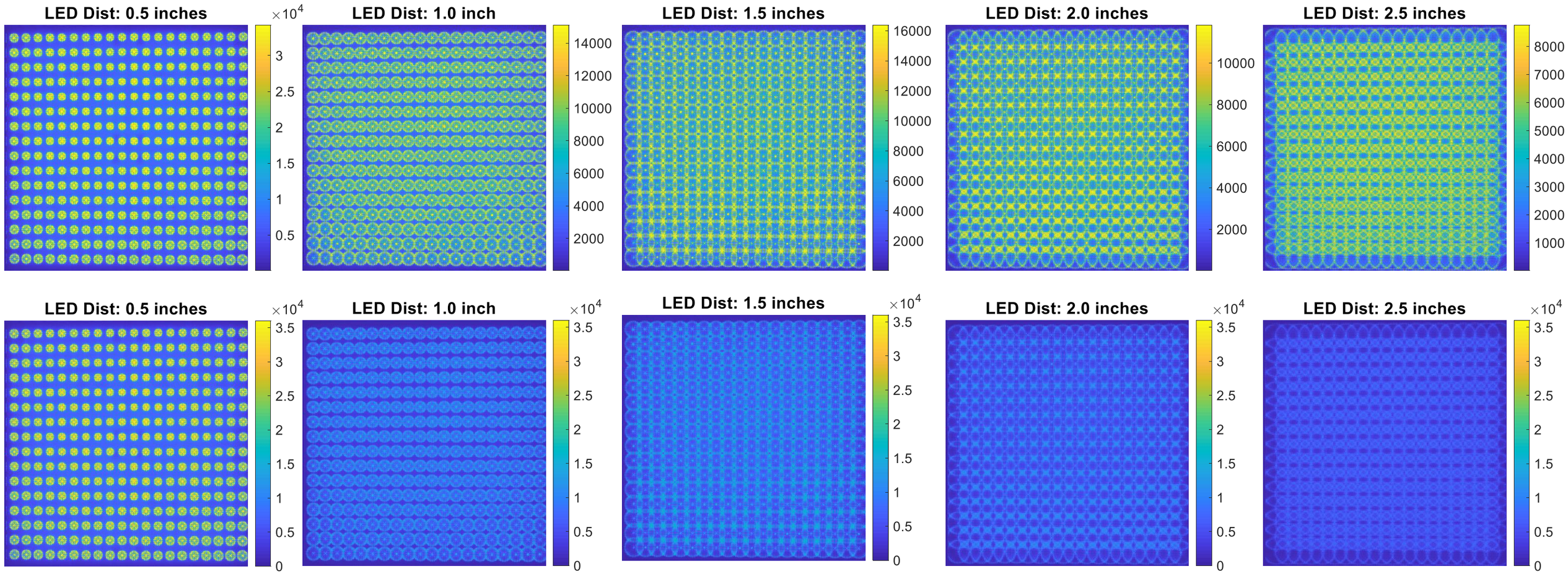

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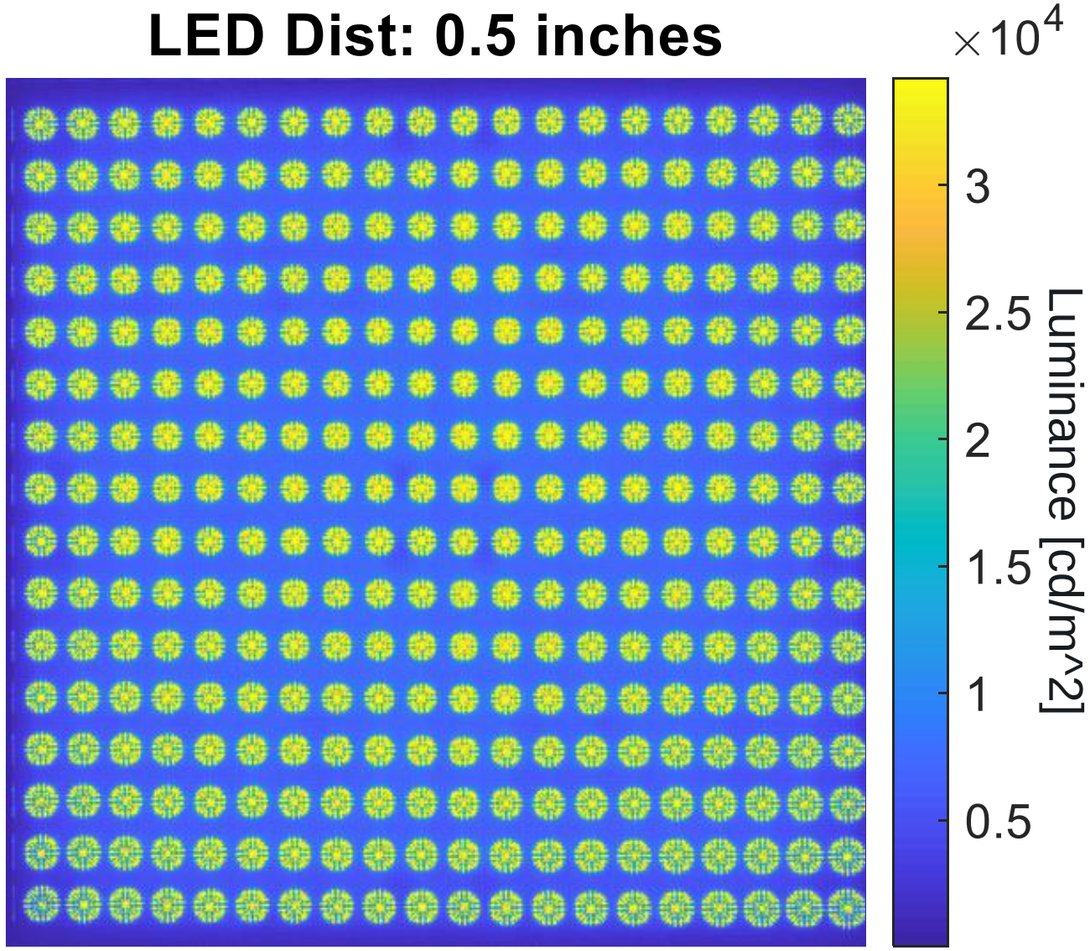

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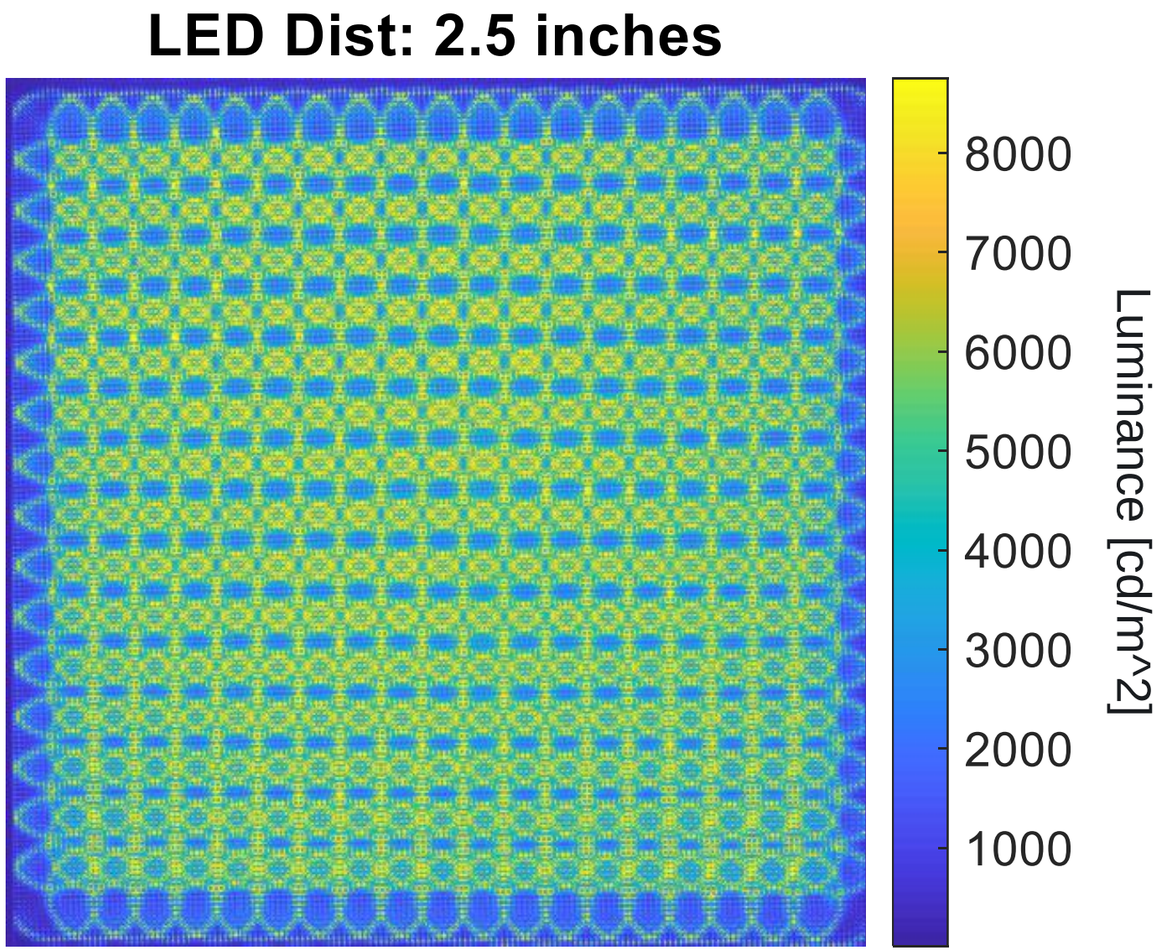
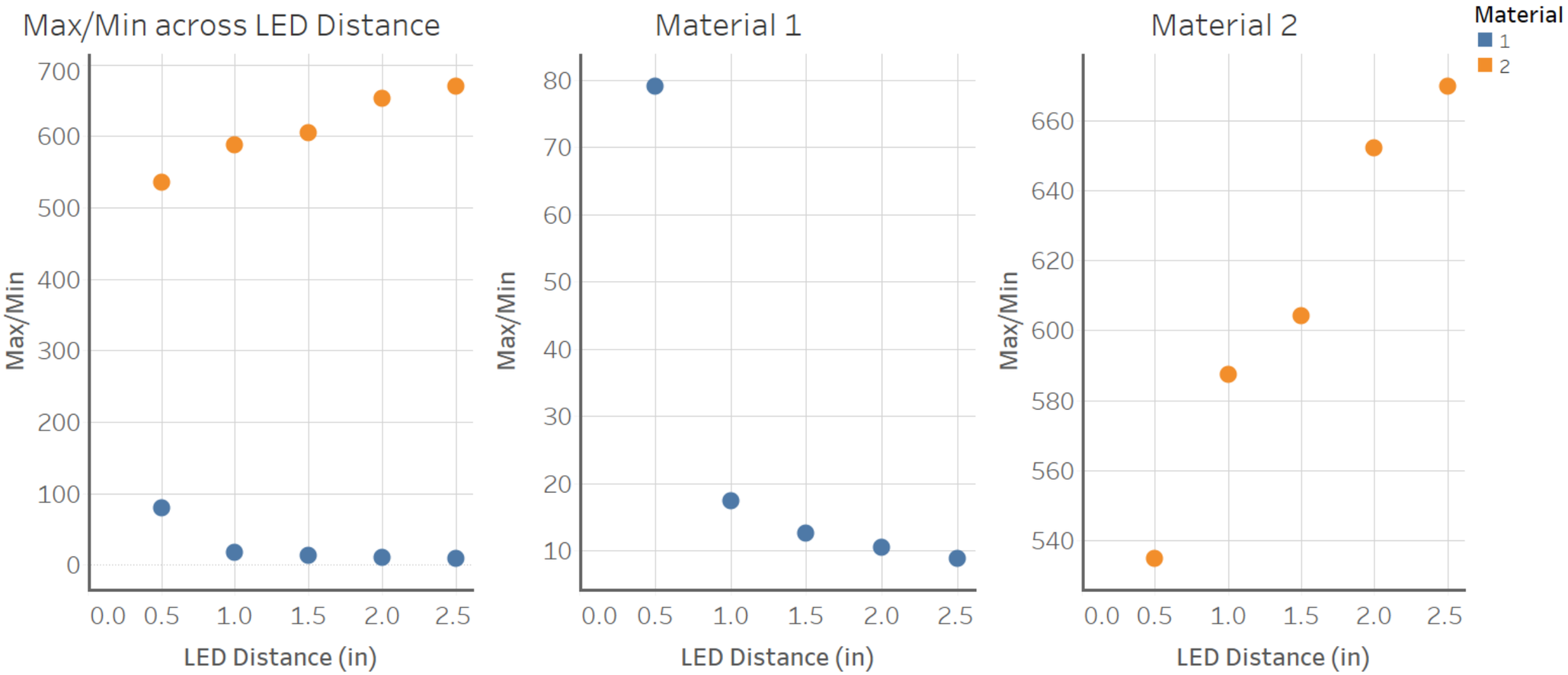
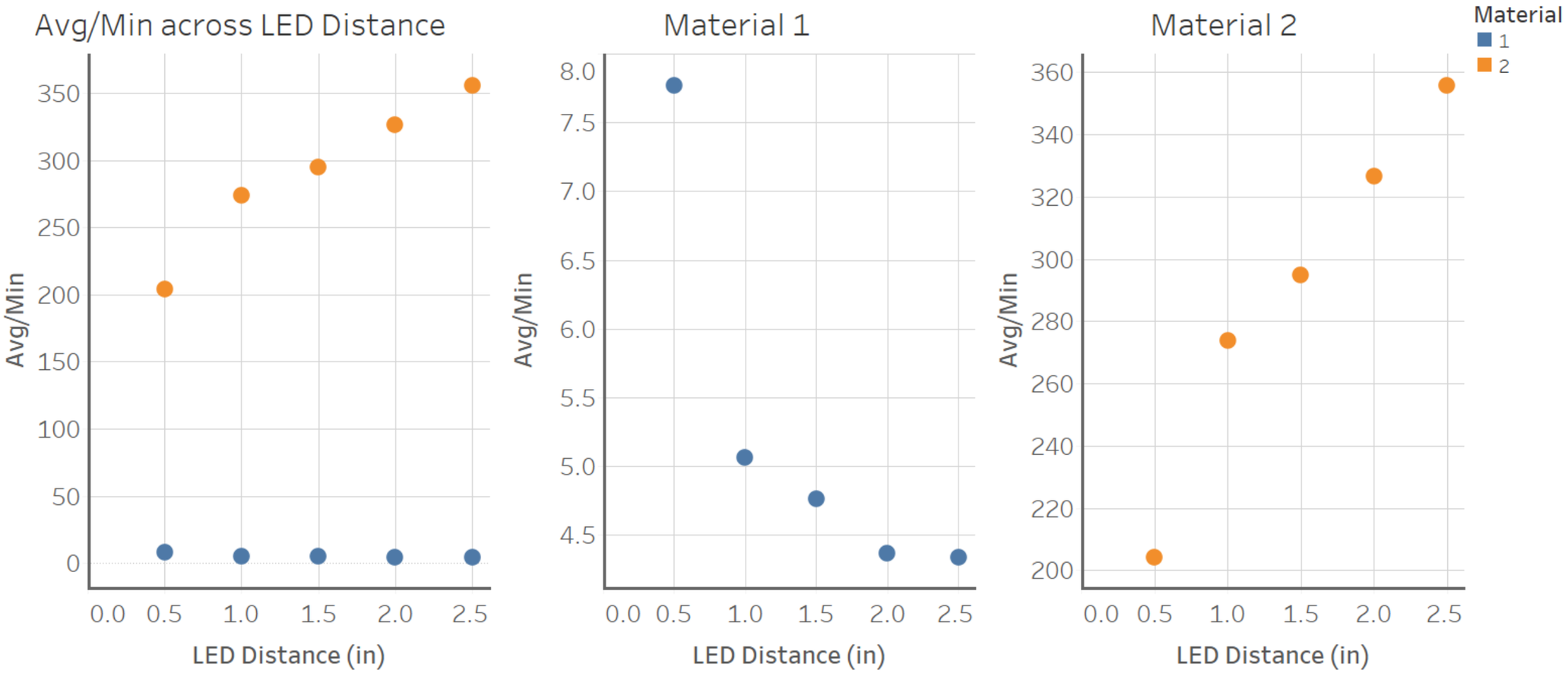


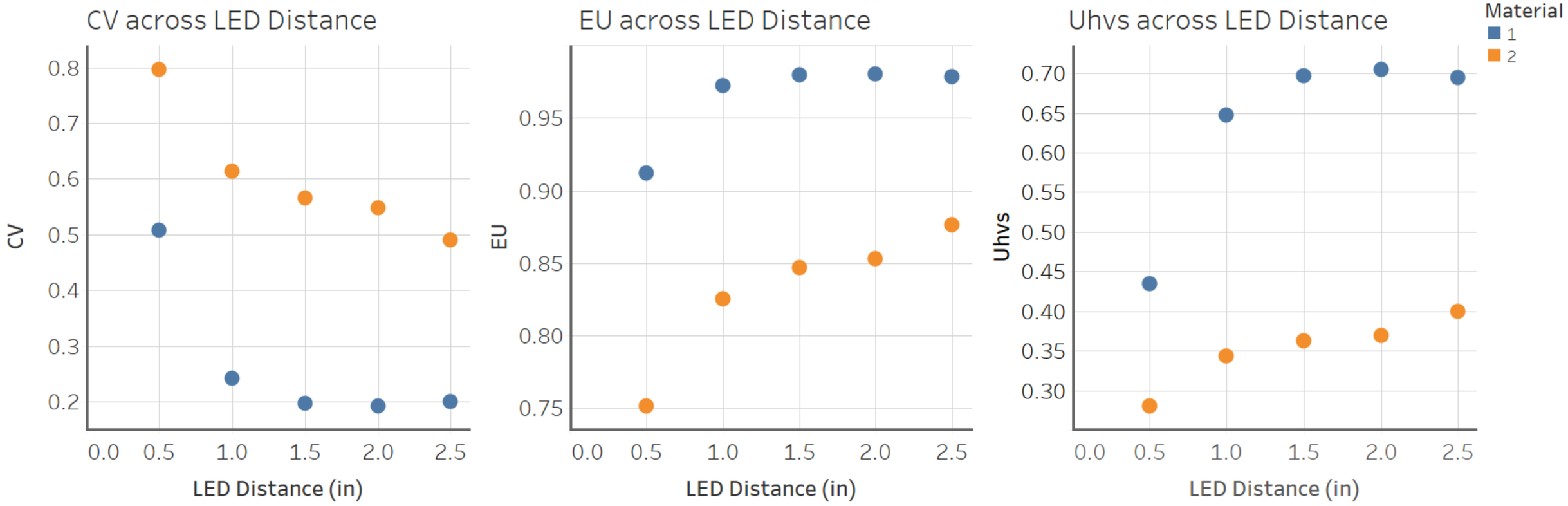
Uniformity Metrics: Max/Min



Uniformity Metrics: Avg/Min



Uniformity Metrics



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- The uniformity of luminance distributions can be quantified by evaluating HDR images
- Future work
  - Examine the performance of uniformity metrics in relation to subjective ratings
  - Develop a stray light correction matrix for further accuracy

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