Reflections on Daylight Glare Evaluations in Built Environments

Joint Biennial CNC-CIE, CIE-USNC & CORM Conference 2023

Educational Session on Glare Metrics, Models and Standards

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Daylight Glare Evaluations in Built Environments

- Daylight Glare in built environments
- Daylight Glare Metrics
  - Field measurements
  - Simulations
- Surrogate metrics used commonly in practice to detect glare
- Competing goals (glare versus circadian entrainment) in built environments

What is glare?

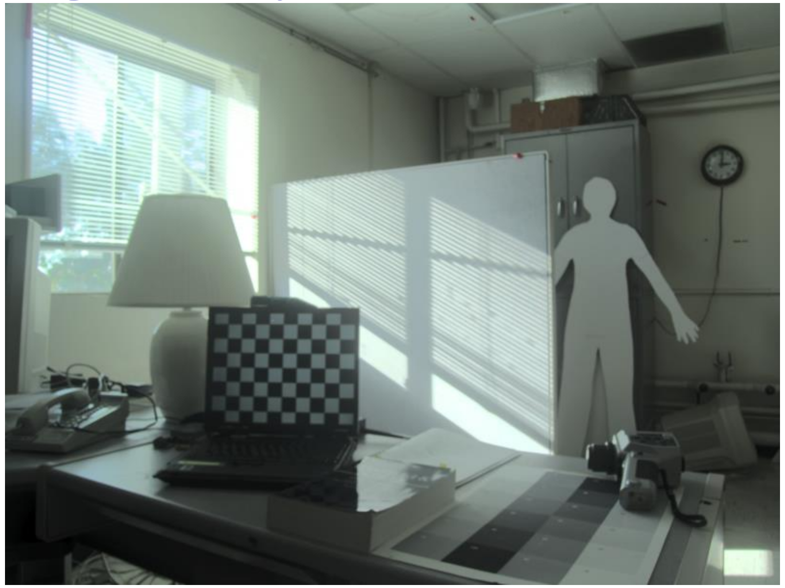
“There are two aspects of glare which have to be watched in interior lighting design, glare which arises because of harsh contrast between juxtaposed areas, and glare which arises because areas are of excessive brightness that the visual mechanism is saturated.”

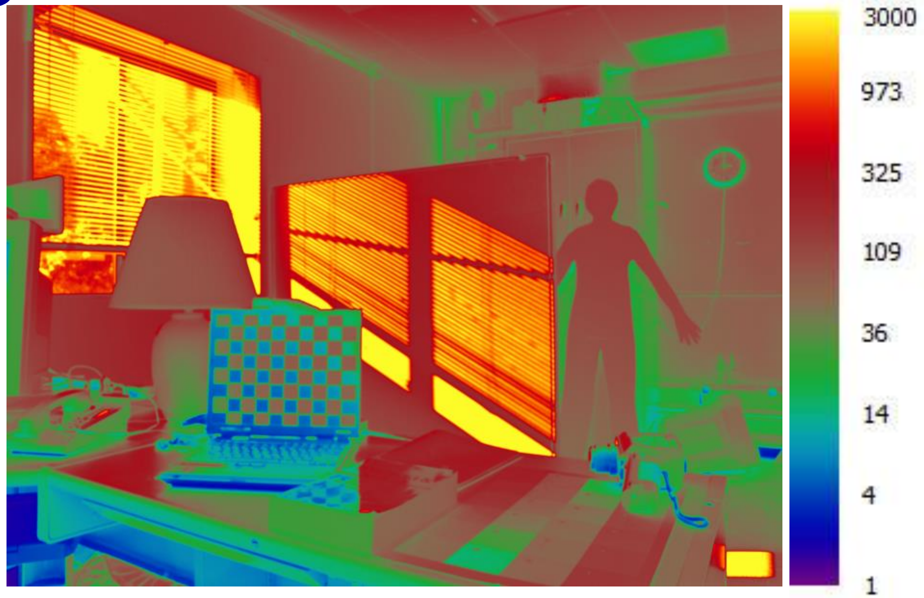
(Hopkinson RG. “Glare from daylighting in buildings, *Applied Ergonomics*, 3(4), 1972, 206–215)

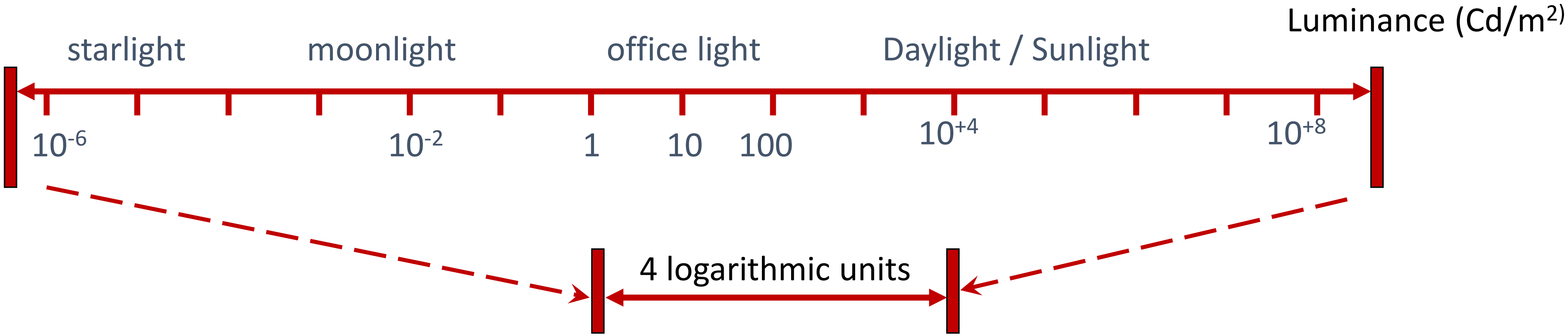
Glare is a “condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme contrasts”

(CIE 232:2019 *Discomfort Caused by Glare from Luminaires with a Non-Uniform Source*)

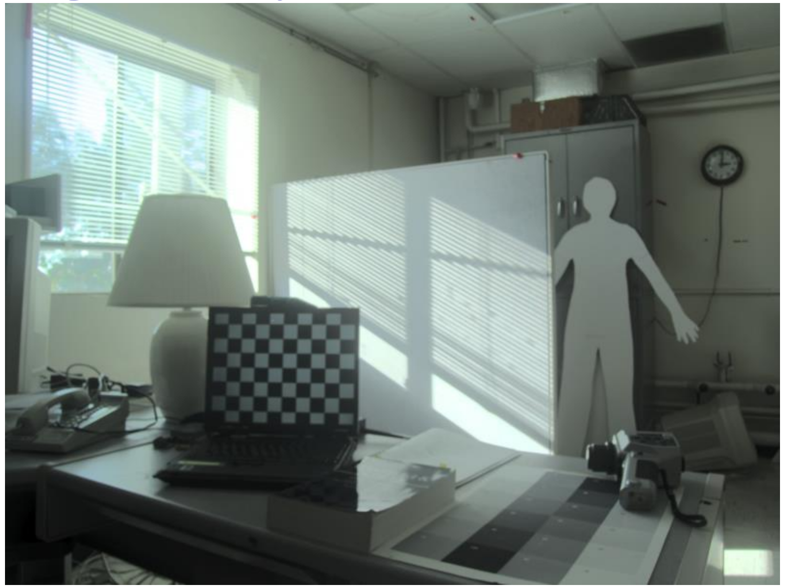
High Dynamic Range of Human vision

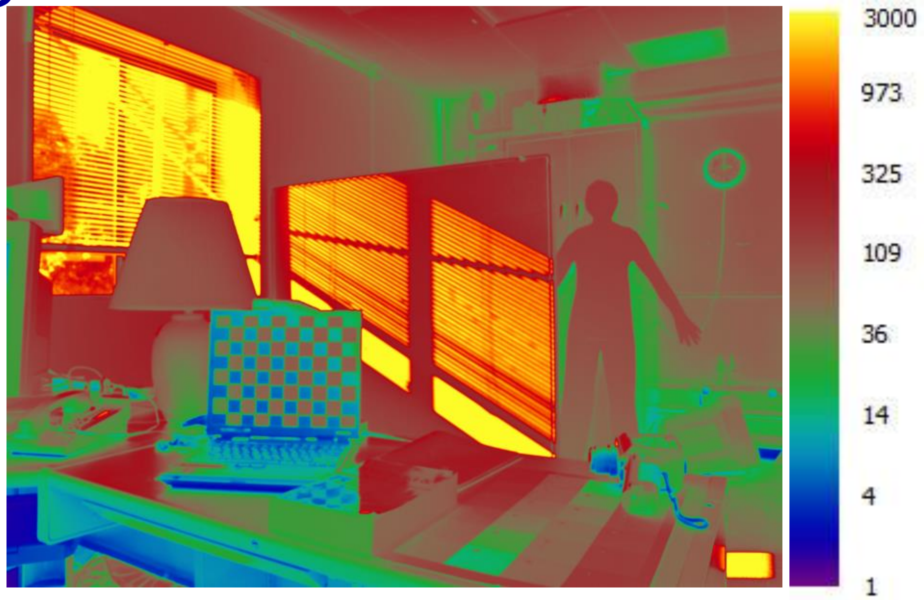






High Dynamic Range of Human vision





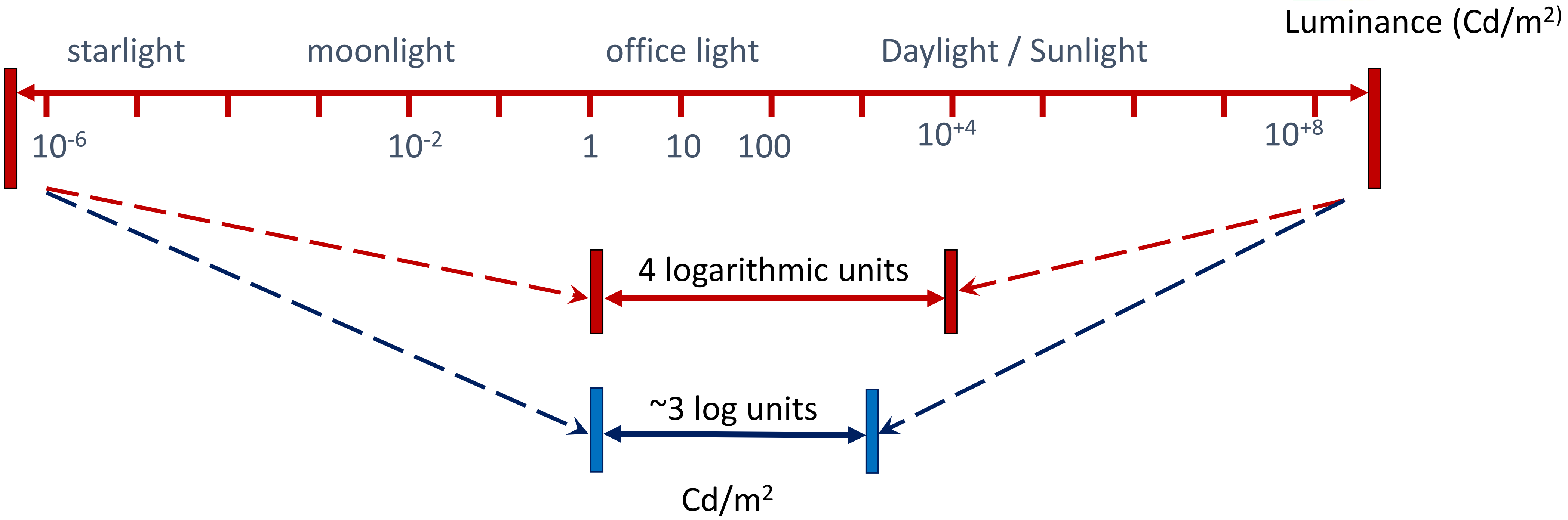


Image credits: Yue Liu, Alireza Hashemloo

Image credit: Dan Belcher

Metrics

- Scene (image)-based daylight glare indices
  Daylight Glare Index (DGI)
  Daylight Glare Probability (DGP)

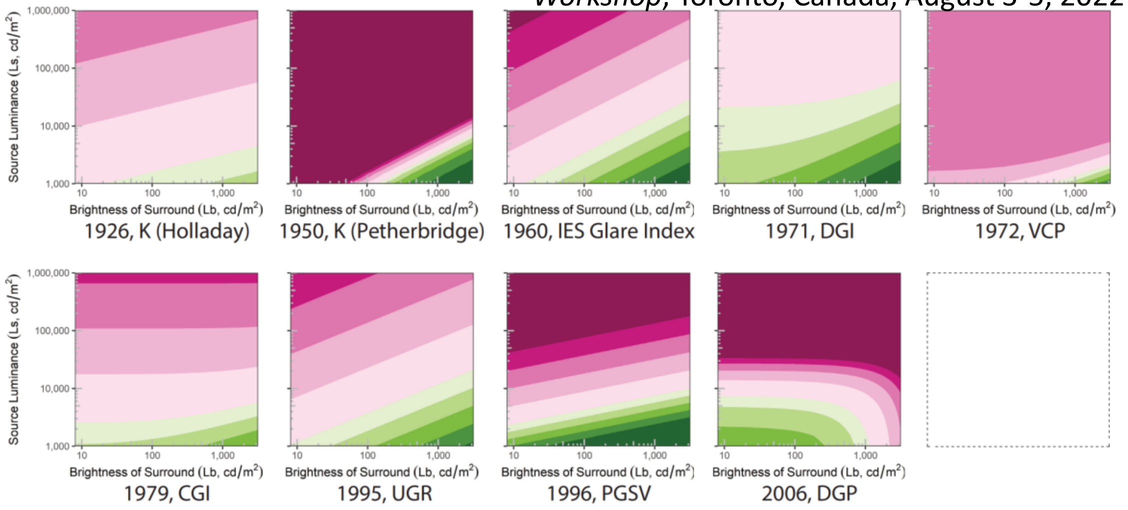
- Vertical Illuminance-based glare metrics

- Surrogate metrics:
  Luminance (overlit) thresholds
  Horizontal illuminance (overlit) thresholds
  Annual Solar Exposure (IES LM-83)

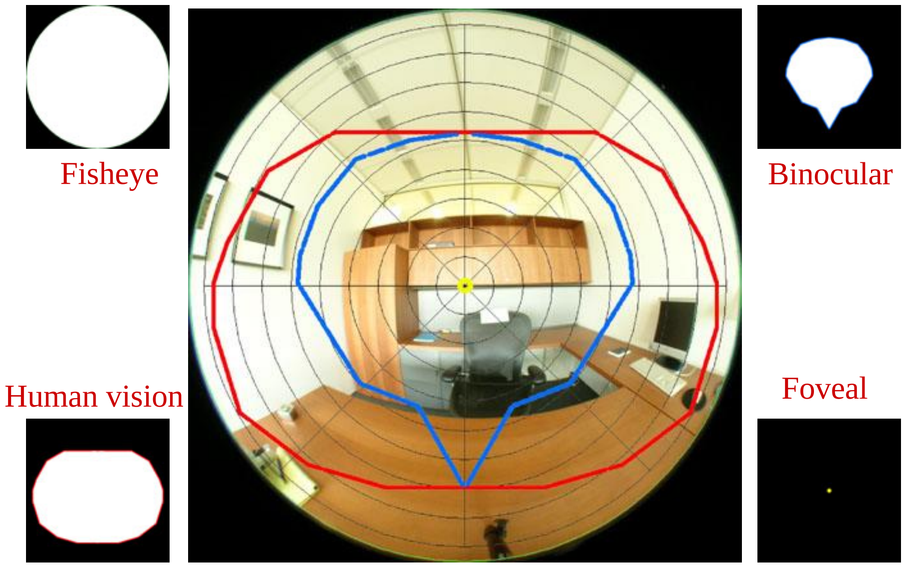
Glare metrics, in general

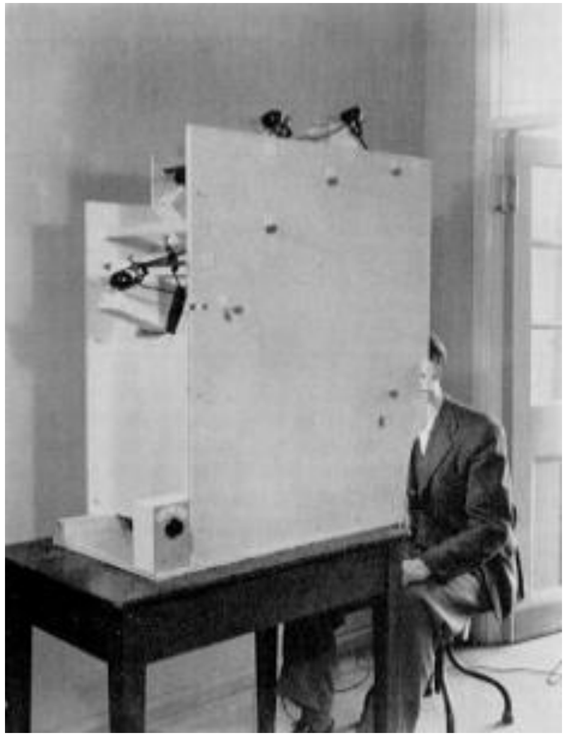
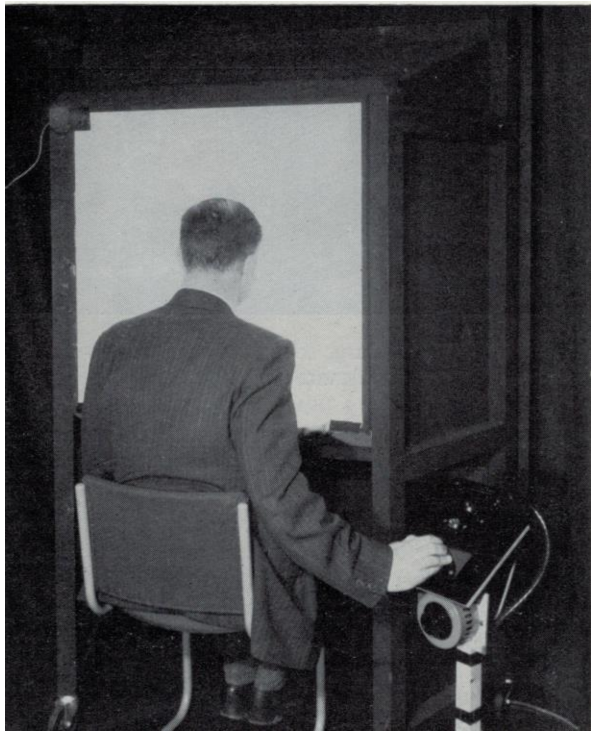
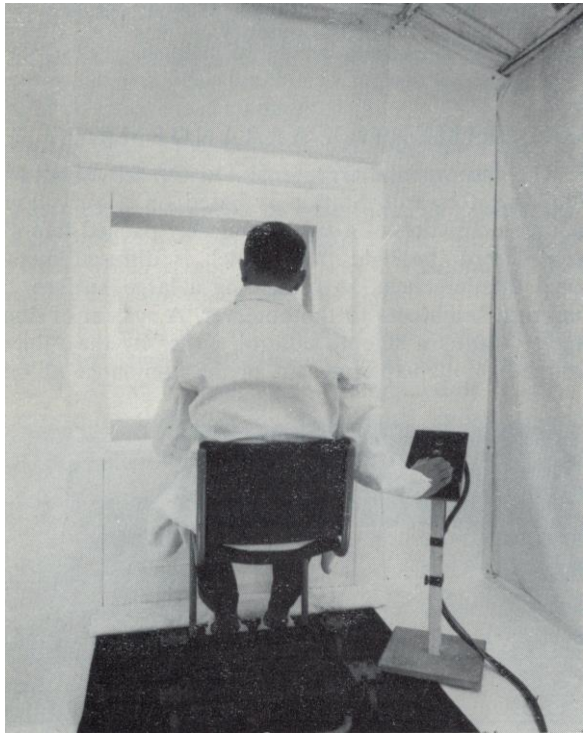
Jakubiec A. "A historical comparison of glare metrics," *20th International Radiance Workshop*, Toronto, Canada, August 3-5, 2022

- Luminance of glare source
- Adaptation (expressed as luminance or vertical illuminance)



- Size of the glare source
- Position of the glare source



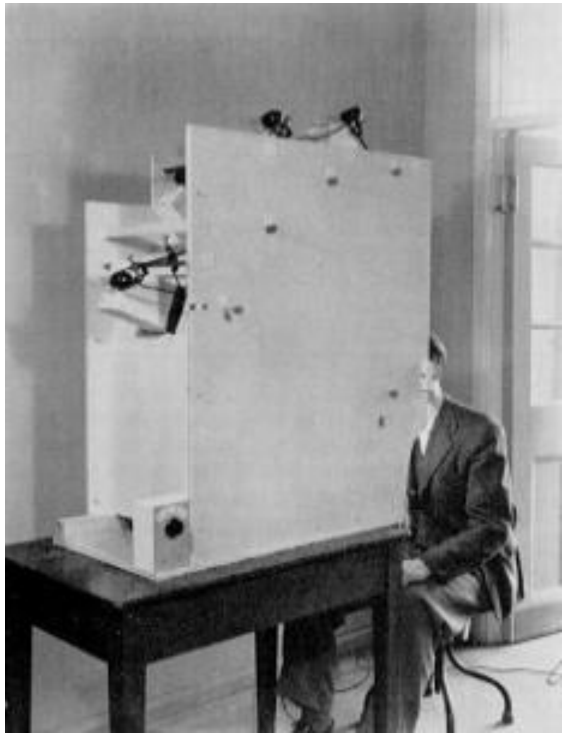




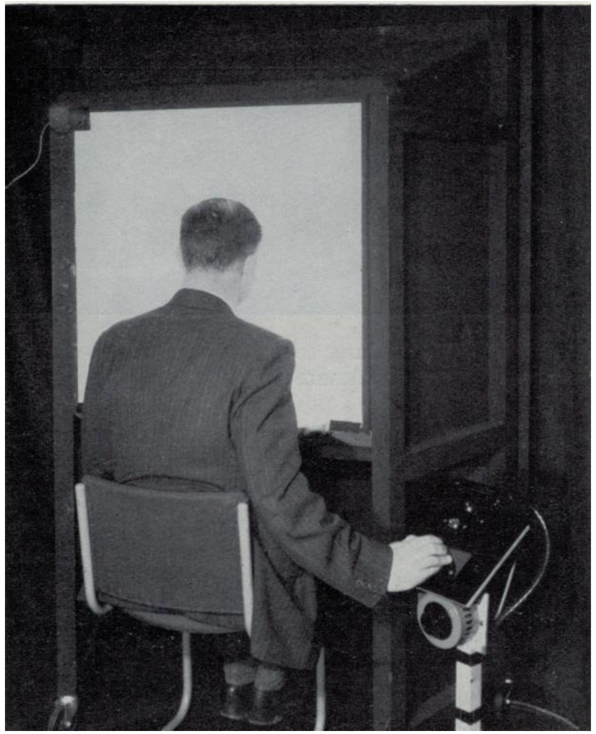
Daylight Glare Index

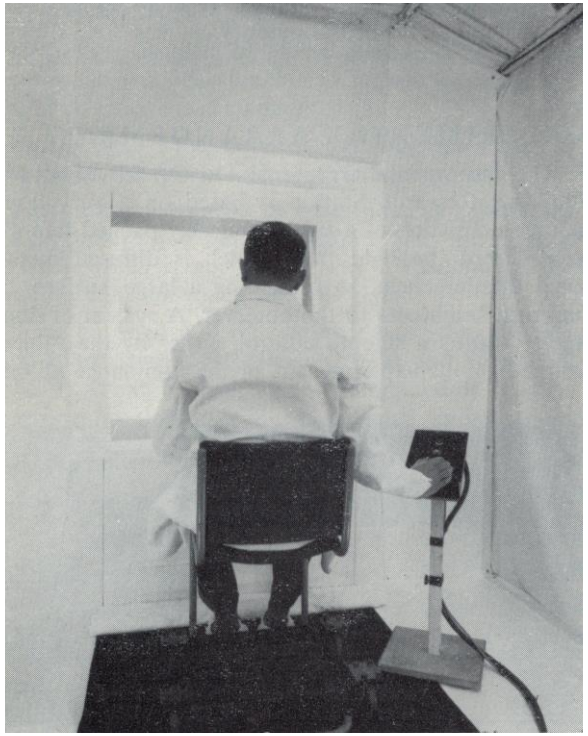
Building Research Station
Cornell University
(1956-1972)

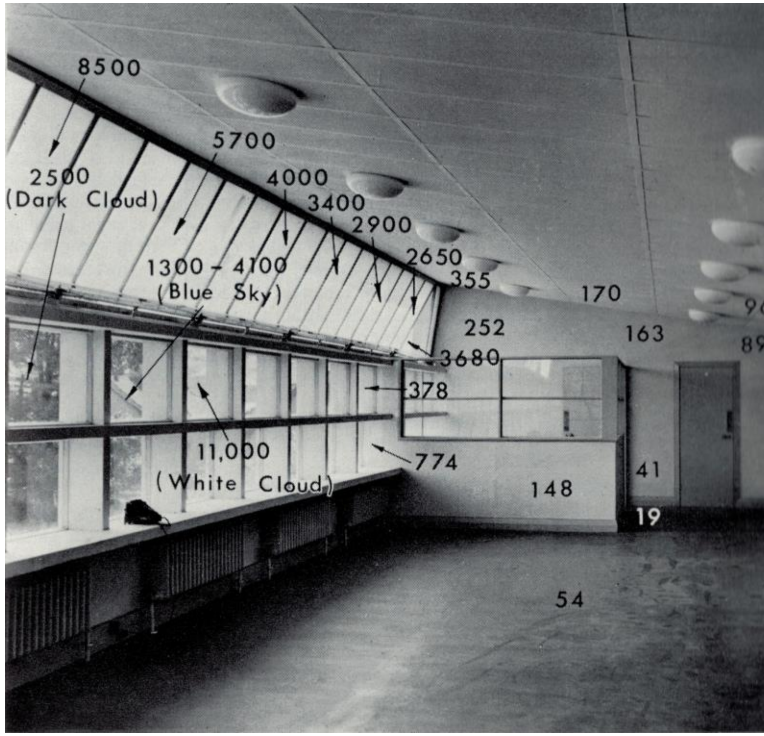
Closely packed fluorescent lamps of light diffused by an opal plastic screen
Uniform brightness between 3 – 15,000 cd/m^2
Multiple criterion method (**just** perceptible, acceptable, uncomfortable, intolerable)
4 observers at BRS, a small group of students at Cornell (aged 18-25, all male)

Hopkinson RG. "Glare from daylighting in buildings," *Applied Ergonomics*, 3(4), 1972, 206–215.
Hopkinson RG. *Architectural Physics: Lighting*. London: Her Majesty's Stationery Office, 1963.









Field studies in classrooms and hospital ward

Daylight Glare Index
Building Research Station
Cornell University
(1956-1972)

$$DGI = 10 * \log_{10} 0.4777 * \sum_{i=1}^{n} \frac{L_{s,i}^{1.6} \left(\frac{w_{s,i}}{P_{s,i}^{2}}\right)^{0.8}}{L_b + 0.07 * w_{s,i}^{0.5} * L_{s,i}}$$

extreme contrast

Luminance of glare source
Size of the glare source
Position of the glare source
Background luminance

Degree of glare	
Just perceptible	16
Just acceptable	20
Just uncomfortable	26
Just intolerable	28

Hopkinson RG. “Glare from daylighting in buildings,” *Applied Ergonomics*, 3(4), 1972, 206–215.
Hopkinson RG. *Architectural Physics: Lighting*. London: Her Majesty’s Stationery Office, 1963.
Chauevel et al. “Glare from windows: current views of the problem,” Lighting Research and Technology, 14(1), 1982.

Daylight Glare Probability

Danish Building Research Institute
Fraunhofer Institute for Solar Energy Systems
(2003-2004)

Two identical experiment rooms, one for subjects and the other for photometric measurements
Rooms can be rotated, subjects are seated parallel to the window or diagonally toward the window
Window sizes can be varied, with glazing light transmissions of 72% (Denmark) and 56% (Fraunhofer)
Venetian blinds (white blinds, specular blinds, vertical louvers)
Luminance measurements with High Dynamic Range Photography (TechnoTeam) + illuminance measurements
76 subjects

Wienold J and Christofferson J. “Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras” *Energy and Buildings, 38, 2006*

Daylight Glare Probability

Danish Building Research Institute
Fraunhofer Institute for Solar Energy Systems
(2003-2004)

$$DGP = 5.87 * 10^{-5} * E_v + 9.18 * 10^{-2} \log\left(1 + \sum_i \frac{L_{s,i}^2 * w_{s,i}}{E_v^{1.87} * P_i^2}\right) + 0.16$$

% of disturbed persons

Luminance of glare source
Size (solid angle) of the glare source
Position index of the glare source
Vertical illuminance

Wienold J and Christofferson J. “Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras” *Energy and Buildings, 38, 2006*

Daylight Glare Probability

Original DGP (captured or simulated fisheye image)

$$DGP = \underbrace{5.87 * 10^{-5} * E_v}_{\textit{excessive light}} + \underbrace{9.18 * 10^{-2} \log\left(1 + \sum_i \frac{L_{s,i}^2 * w_{s,i}}{E_v^{1.87} * P_i^2}\right)}_{\textit{extreme contrast}} + 0.16$$

Simplified $\mathrm{DGP_s}$ (no image, only vertical illuminance)

$$DGP_s = 5.87 * 10^{-5} * E_v + 0.16$$

Enhanced simplified $\mathrm{DGP_s}$ (vertical illuminance and a simplified image)

Wienold J. "Dynamic Daylight Glare Evaluation", Building Simulation 2019, Glasgow, UK.

Wienold J and Christofferson J. "Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras" *Energy and Buildings, 38, 2006*

Original DGP (captured or simulated fisheye image)

$$\underbrace{DGP = 5.87 * 10^{-5} * E_v}_{\textit{excessive light}} + \underbrace{9.18 * 10^{-2} \log\left(1 + \sum_i \frac{L_{s,i}^2 * w_{s,i}}{E_v^{1.87} * P_i^2}\right)}_{\textit{extreme contrast}} + 0.16$$

Simplified DGP_s

$$DGP_s = 5.87 * 10^{-5} * E_v + 0.16$$

Simplified DGP_s (*calculated from the formula above*)

Imperceptible glare: E_v < 2657 Lx

Noticeable glare: E_v 2657 – 3339 Lx

Disturbing glare: E_v 3339 - 4532 Lx

Intolerable glare: E_v > 4532 Lx

E_v = **13900 Lx** saturates (DGP=1.0)

Degree of glare (revised Wienold et al., 2019)	
Imperceptible	≤ 0.34
Noticeable	0.34-0.38
Disturbing	0.38-0.45
Intolerable	≥ 0.45

Wienold et al. “Cross-validation and robustness of daylight glare metrics” Lighting Research and Technology, 5(7), 983-1013, 2019.

High dynamic range scene as sun is visible through the glazing

HDR photography method is employed to capture the scene:

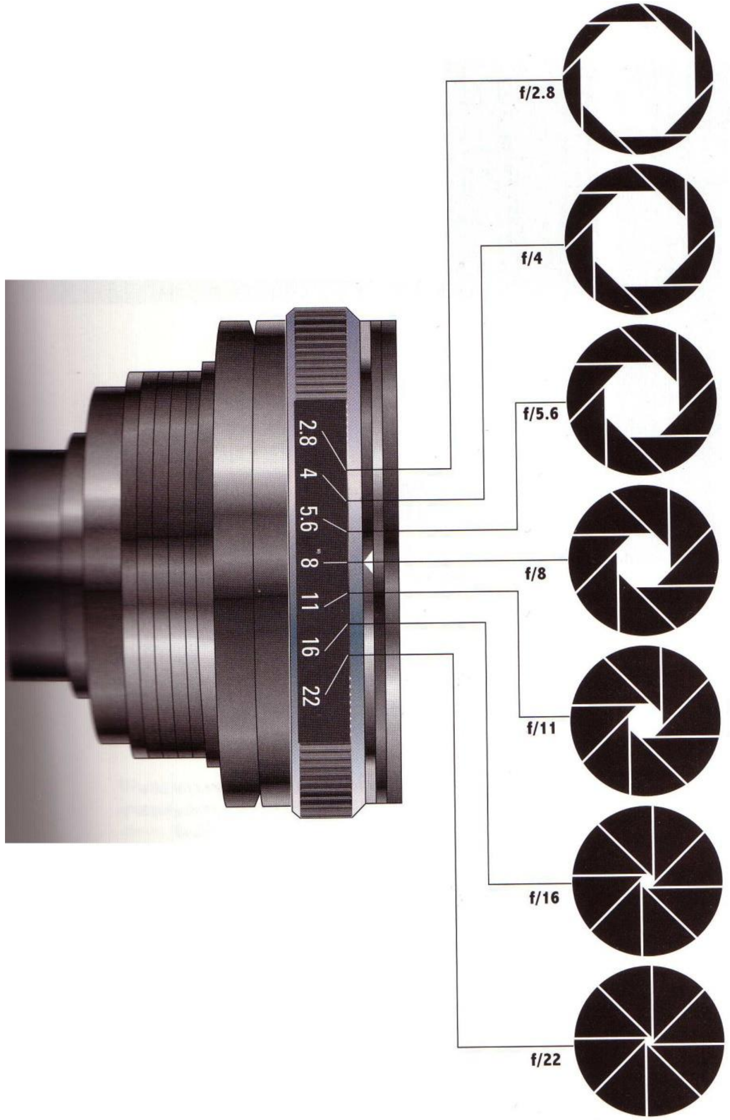
In a nutshell: camera, tripod, fisheye lens
Use a fixed aperture size, vary shutter speed
Fix white balance, ISO

Merge multiple exposures into a single hdr image
Correct for optical and geometric aberrations
Fine-tune with a luminance reading of a gray card

Works for many scenes
but…

how do we capture the sun?

Current recommendations for Capturing the interior views



Accuracy of common interior surfaces vs the sun

- f/4 captures approximately up to 100,000 cd/m^2
- f/11 captures approximately up to 1,000,000 cd/m^2
- f/22 captures approximately up to 3,200,000 cd/m^2
- f/22 causes a significant amount of lens flare, impairing accuracy for the rest of the scene

Jakubiec A, van den Wymelenberg K, Inanici M, and Mahic A. "Accurate Measurement of Daylit Interior Scenes using High Dynamic Range Photography," CIE Lighting Quality and Energy Efficiency Conference, Melbourne, Australia, March 3-5, 2016.
Inanici M. "Evaluation of High Dynamic Range Photography as a Luminance Data Acquisition System," Lighting Research and Technology, 38(2): 123-136, 2006.

Current recommendations for Capturing the interior views

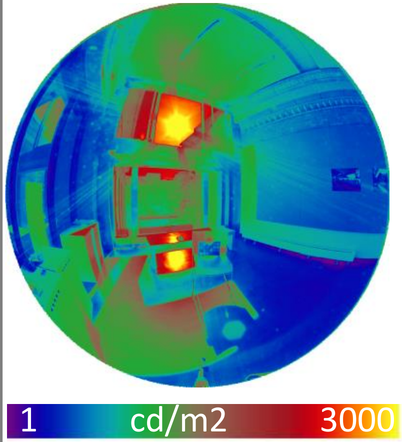
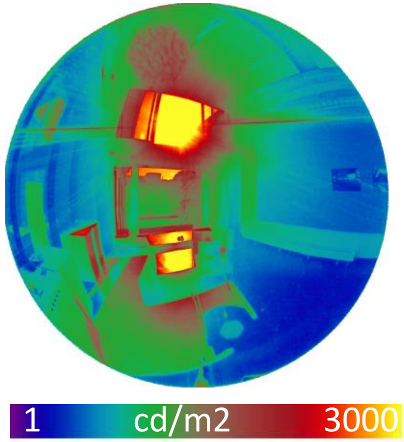
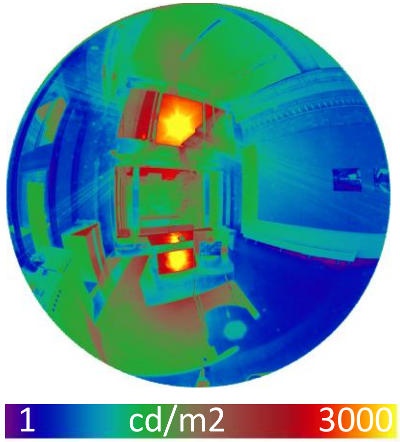
- Is 1,000,000 cd/m^2 enough to capture the sun disc to calculate glare? Is it important to capture higher luminances?

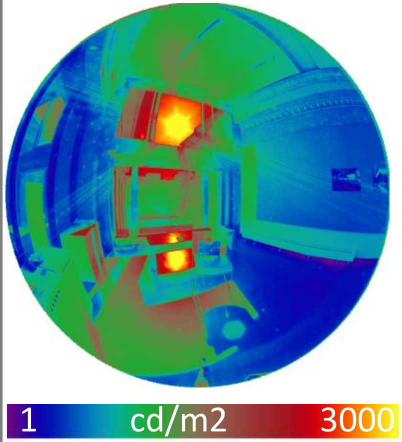
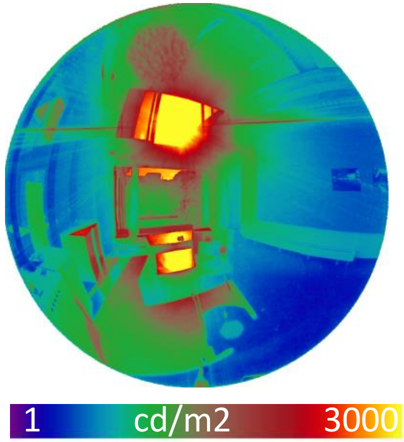
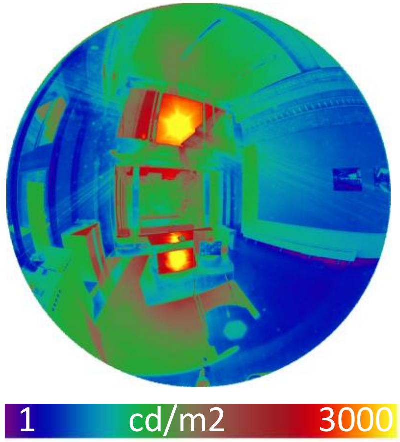
1. f/11, No filter

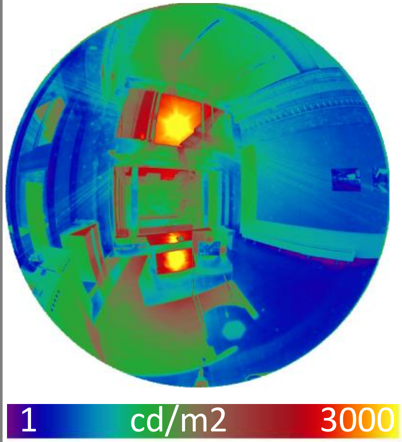
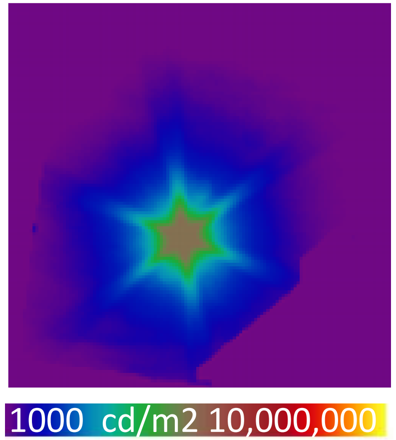
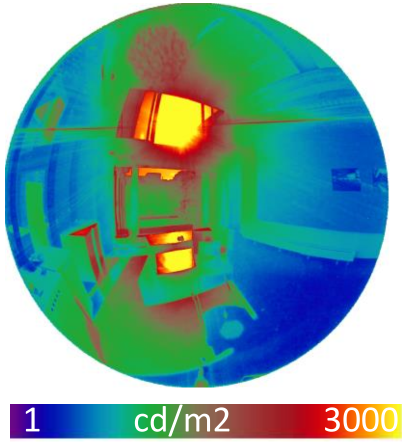
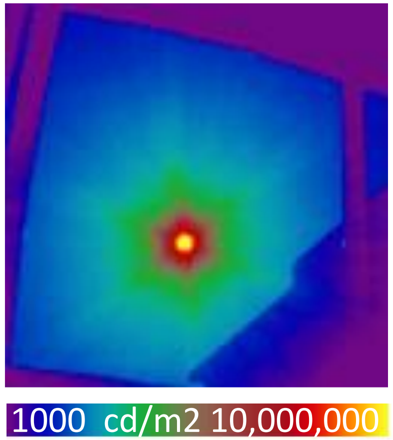
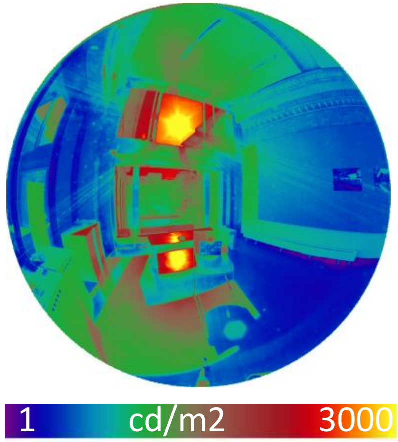
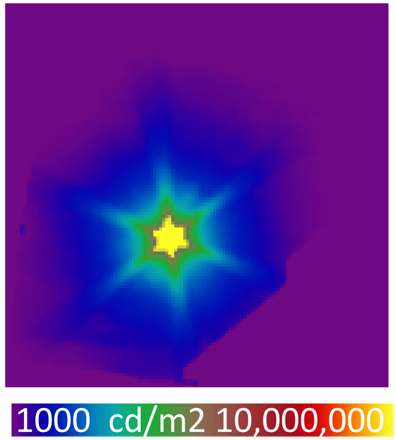
2. Neutral density filters ND1, ND2 or ND3 could be utilized to increase the dynamic range.

3. Luminous overflow of the sun can also be corrected as a post-processing with an additional calibration of illuminance measured at the camera lens.

4. Exposures can be taken with a combination of ‘no filters’ and ND3 (typical method to capture image-based sky models); increases the complexity of fieldwork and post-processing

HDR f/11 No Filter (NF)	HDR f/11 Neutral Density Filter #3	HDR f/11 NF – Overflow correction
		
Measured = 74800 Lx	Measured E = 74900 Lx	Measured E = 74800 Lx

HDR f/11 No Filter	HDR f/11 Neutral Density Filter #3	HDR f/11 – Overflow correction
		
Measured = 74800 Lx	Measured E = 74900 Lx	Measured E = 74800 Lx
L_range = 0.5 - ~ 100K cd/m^2 Derived Ev = 601 Lx	L_range = 12 - ~ 200 M cd/m^2 Derived Ev = 18552 Lx	L_range = 0.5 – ~100 M cd/m^2 Derived Ev = 77677 Lx

HDR f/11 No Filter	HDR f/11 Neutral Density Filter #3	HDR f/11 – Overflow correction
 	 	 
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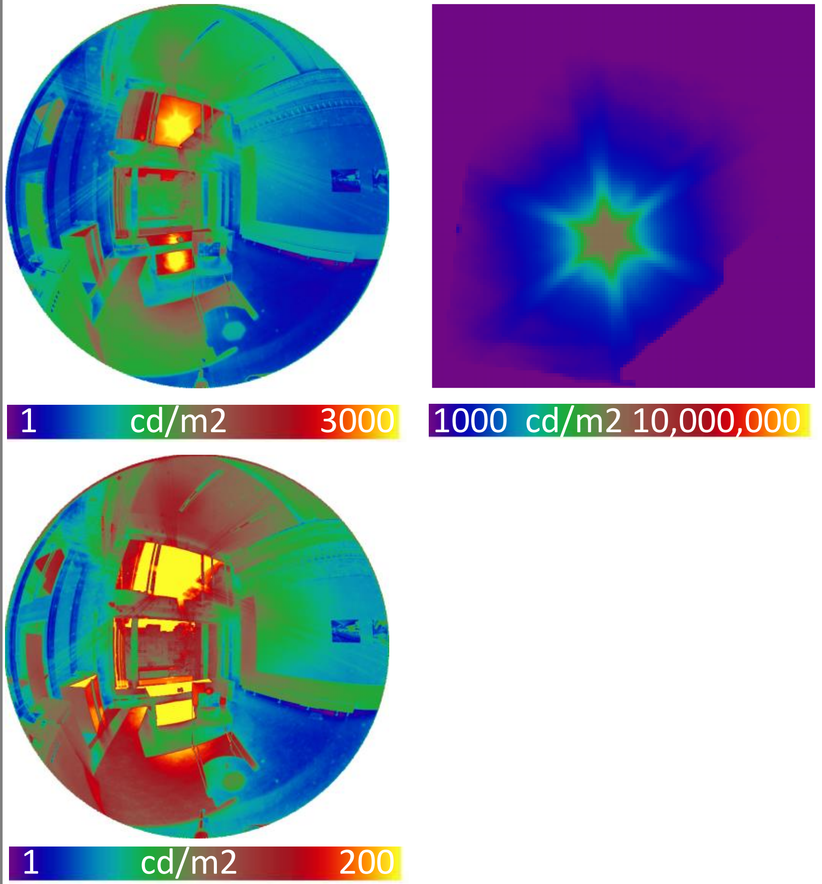
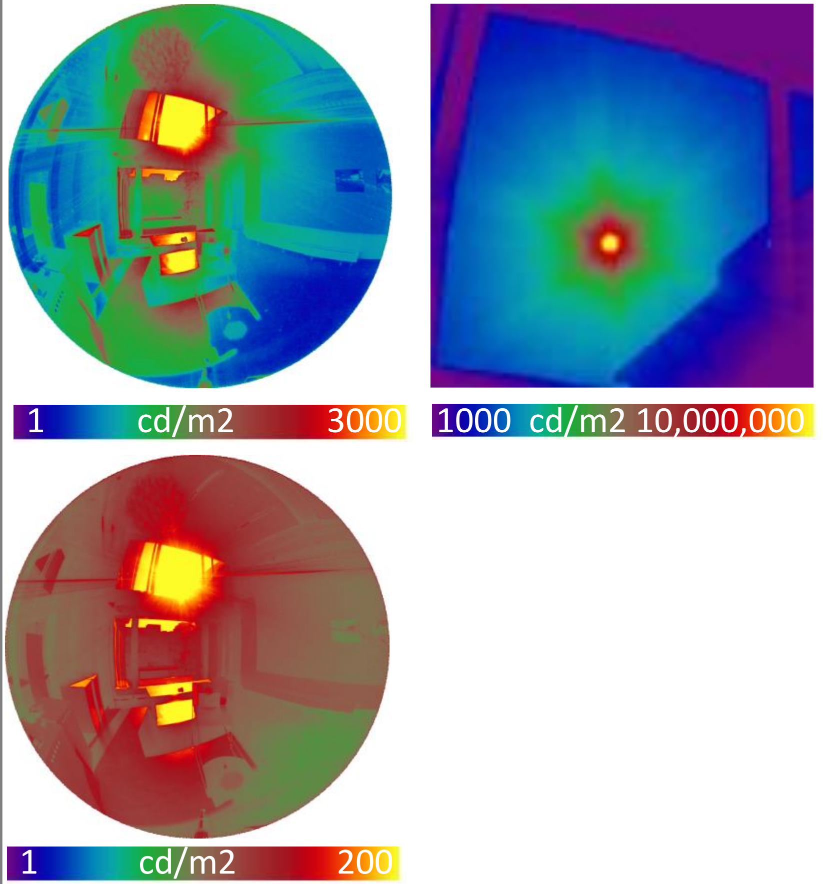
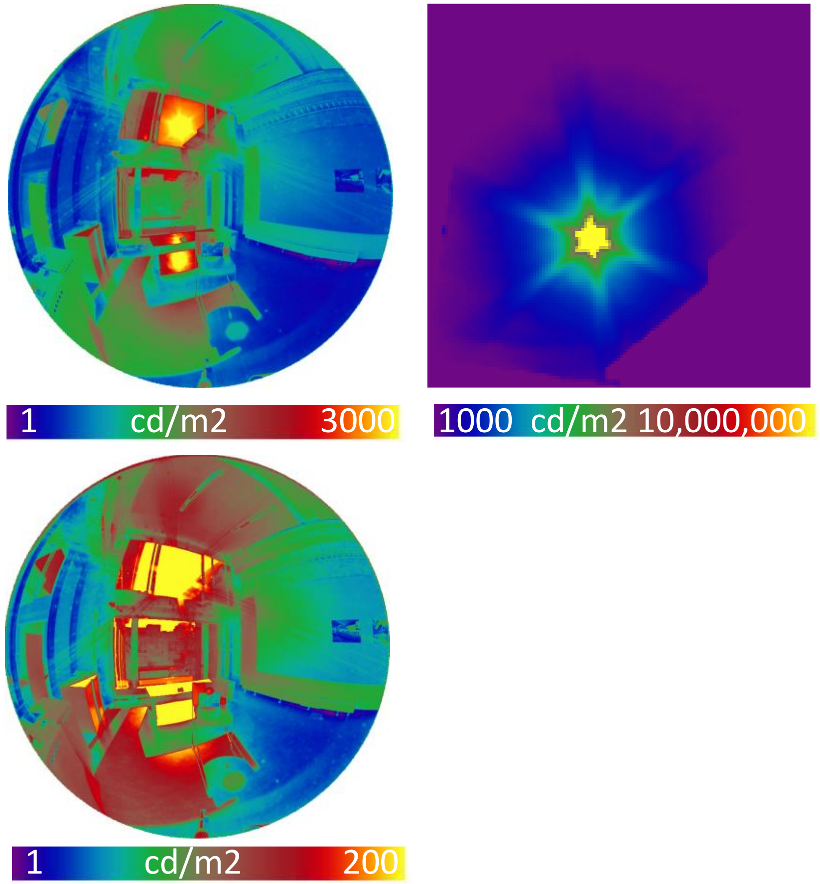
L_range = 0.5 - ~ 100K cd/m^2 Derived E = 601 Lx	L_range = 12 - ~ 200 M cd/m^2 Derived E = 18552 Lx	L_range = 0.5 – ~100 M cd/m^2 Derived E = 77677 Lx
	If E_v > 13900, DGP reaches to 1.0	

<table>
<tr><th>HDR f/11 No Filter</th><th>HDR f/11 Neutral Density Filter #3</th><th>HDR f/11 – Overflow correction</th></tr>
<tr><td>
</td><td>
</td><td>
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L_range = 12 - ~ 200 M cd/m^2</td><td>Derived E = 77677 Lx
L_range = 0.5 – ~100 M cd/m^2</td></tr>
<tr><td>DPG = 0.28 (Imperceptible)
DGPs = 0.19 (Imperceptible)</td><td>DPG = 1.0 (Disturbing)
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DGPs = 1.0 (Disturbing)</td></tr>
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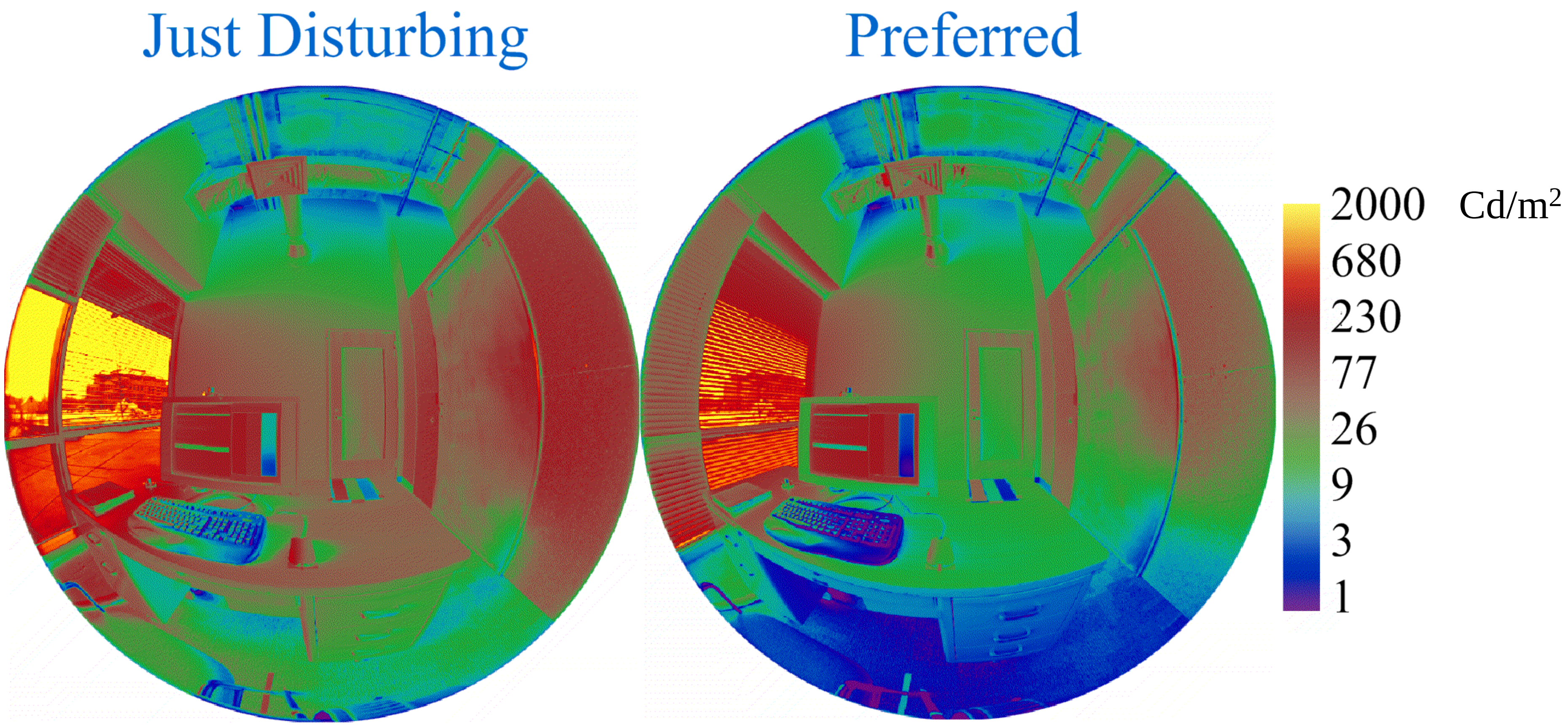
Glare Source Detection

- Predetermined absolute luminance threshold
  - >2000 cd/m2 (false-color threshold in studies such as Inanici 2005, Lee et al. 2005)
  - DGP (*evalglare*) default since 2018

- Scene-based mean Luminance Threshold
  - > 7* scene average, as implemented in Radiance *findglare* module (DGI) (circa 1993)
  - > 5 * scene average, as implemented as default in DGP (*evalglare*) in 2006 (until 2018)

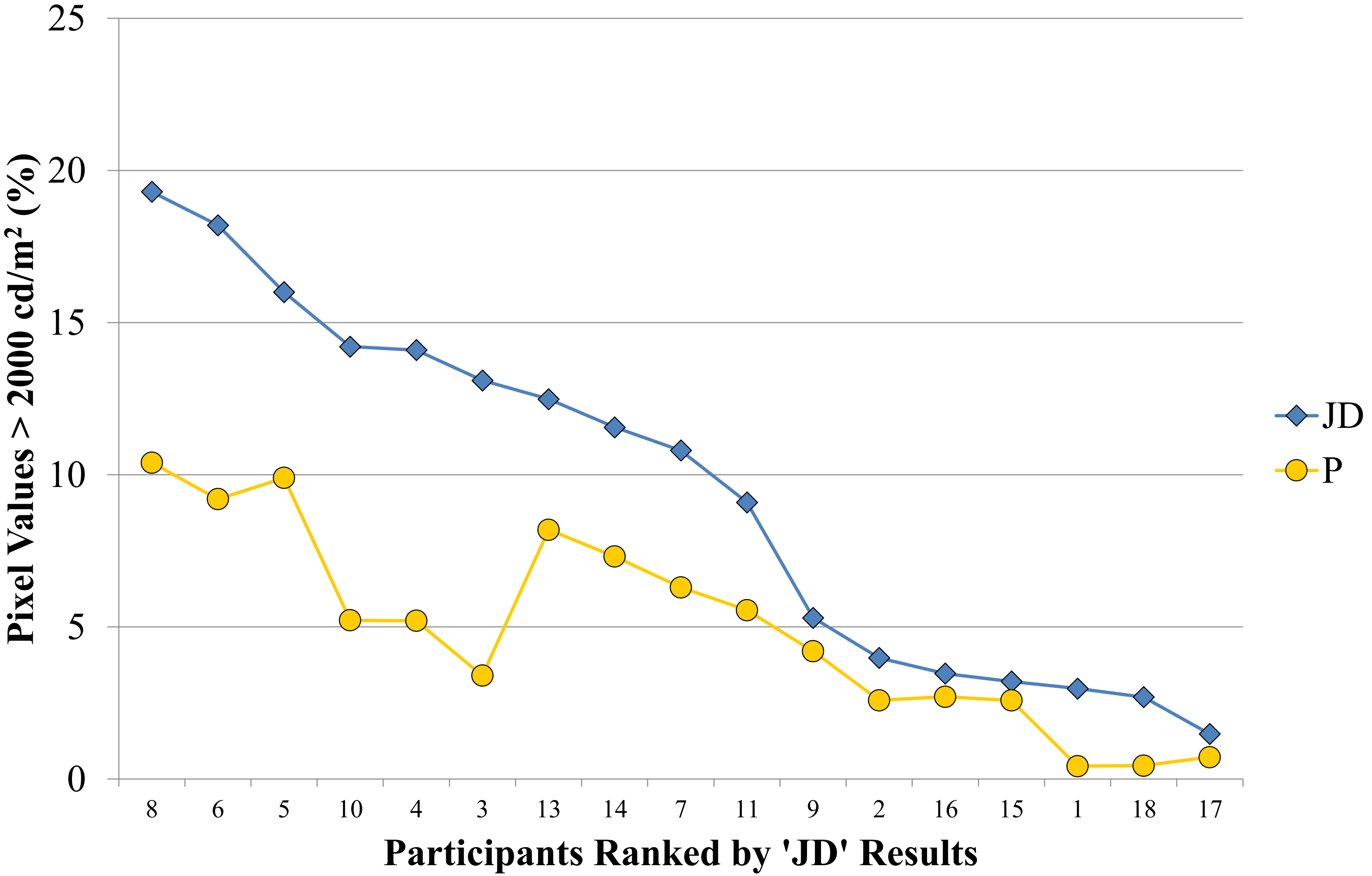
- Task-based mean Luminance Threshold
  - > 5*task average, as implemented in DGP (*evalglare*)

Participants responses



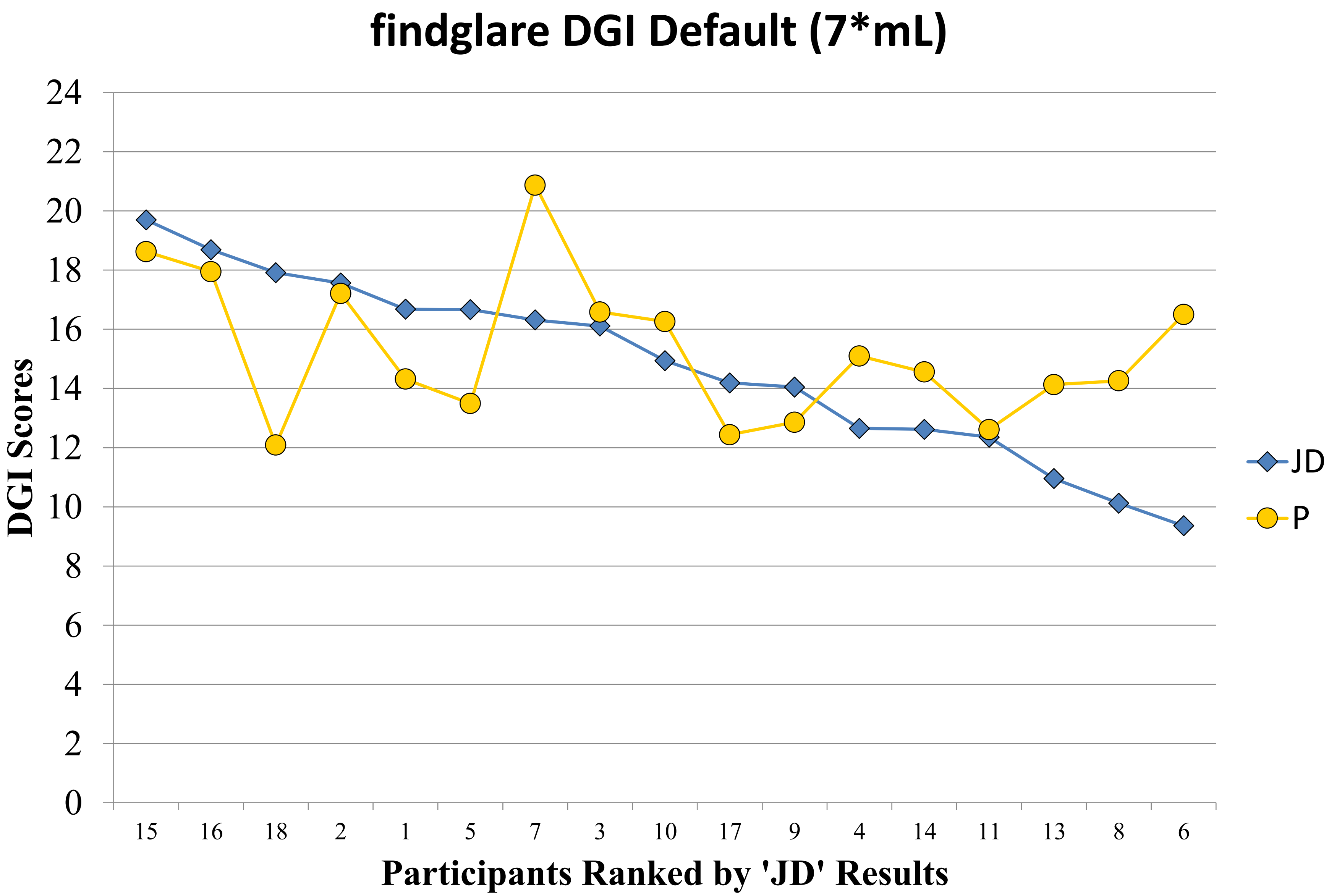
Van den Wymelenberg K, Inanici M, and Johnson P. "The Effect of Luminance Distribution Patterns on Occupant Preference in a Daylit Office Environment," *Leukos*, 7(2): 103-122, 2010.

Predetermined absolute Luminance Threshold



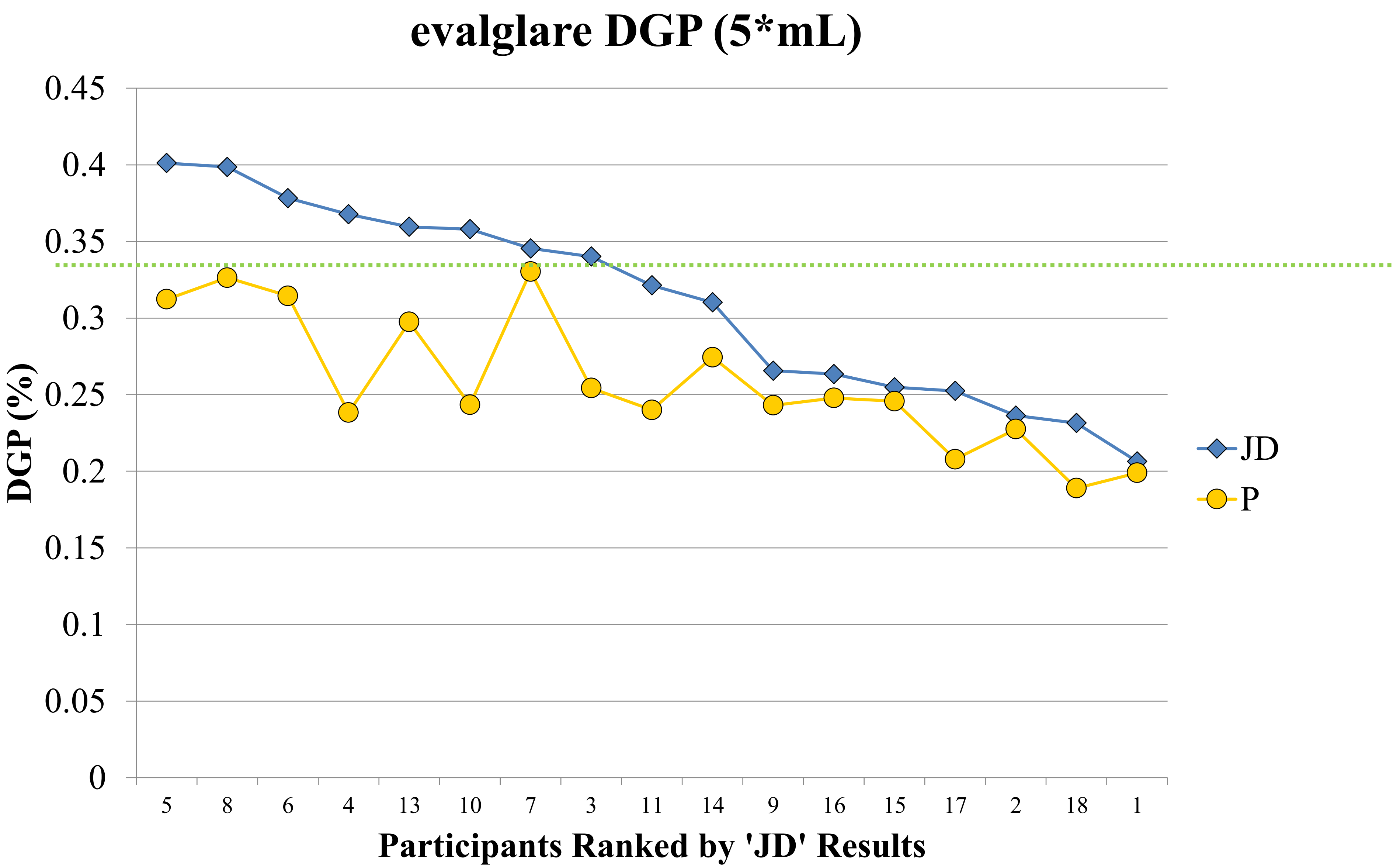
Van den Wymelenberg K, Inanici M, and Johnson P. "The Effect of Luminance Distribution Patterns on Occupant Preference in a Daylit Office Environment," *Leukos*, 7(2): 103-122, 2010.

Daylight Glare Index (DGI)



Van den Wymelenberg K, Inanici M, and Johnson P. “The Effect of Luminance Distribution Patterns on Occupant Preference in a Daylit Office Environment,” *Leukos*, 7(2): 103-122, 2010.

Daylight Glare Probability (DGP)



Van den Wymelenberg K, Inanici M, and Johnson P. "The Effect of Luminance Distribution Patterns on Occupant Preference in a Daylit Office Environment," *Leukos*, 7(2): 103-122, 2010.

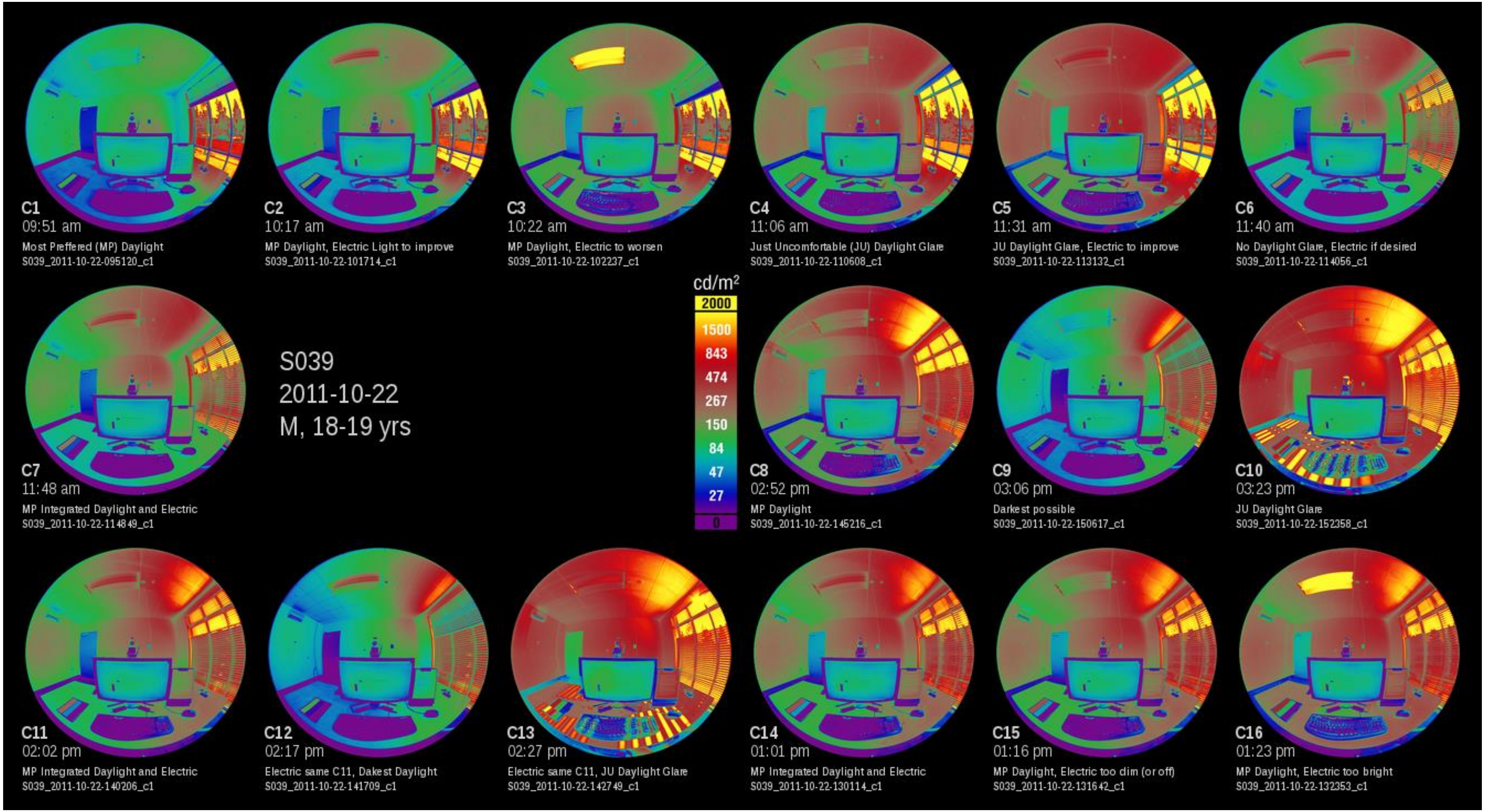
6 month long study (Summer Solstice to Winter Solstice)

48 Participants (ages 18-70, gender balanced)

Participants rated visual comfort and preference factors: 1488 discreet appraisals

Subjective results were correlated against over luminance-based metrics , including glare

van den Wymelenberg K and Inanici M. “Evaluating a New Suite of Luminance-Based Design Metrics for Predicting Human Visual Comfort in Offices with Daylight,” *Leukos*, 12(3): 113-138, 2016.
van den Wymelenberg K and Inanici M. “A Critical Investigation of Common Lighting Design Metrics for Predicting Human Visual Comfort in Offices with Daylight,” *Leukos*, 10(3): 145-164, 2014.


C1
09:51 am
Most Preffered (MP) Daylight
S039_2011-10-22-095120_c1
C2
10:17 am
MP Daylight, Electric Light to improve
S039_2011-10-22-101714_c1
C3
10:22 am
MP Daylight, Electric to worsen
S039_2011-10-22-102237_c1
C4
11:06 am
Just Uncomfortable (JU) Daylight Glare
S039_2011-10-22-110608_c1
C5
11:31 am
JU Daylight Glare, Electric to improve
S039_2011-10-22-113132_c1
C6
11:40 am
No Daylight Glare, Electric if desired
S039_2011-10-22-114056_c1
C7
11:48 am
MP Integrated Daylight and Electric
S039_2011-10-22-114849_c1
S039
2011-10-22
M, 18-19 yrs
cd/m²
2000
1500
843
474
267
150
84
47
27
0
C8
02:52 pm
MP Daylight
S039_2011-10-22-145216_c1
C9
03:06 pm
Darkest possible
S039_2011-10-22-150617_c1
C10
03:23 pm
JU Daylight Glare
S039_2011-10-22-152358_c1
C11
02:02 pm
MP Integrated Daylight and Electric
S039_2011-10-22-140206_c1
C12
02:17 pm
Electric same C11, Dakest Daylight
S039_2011-10-22-141709_c1
C13
02:27 pm
Electric same C11, JU Daylight Glare
S039_2011-10-22-142749_c1
C14
01:01 pm
MP Integrated Daylight and Electric
S039_2011-10-22-130114_c1
C15
01:16 pm
MP Daylight, Electric too dim (or off)
S039_2011-10-22-131642_c1
C16
01:23 pm
MP Daylight, Electric too bright
S039_2011-10-22-132353_c1

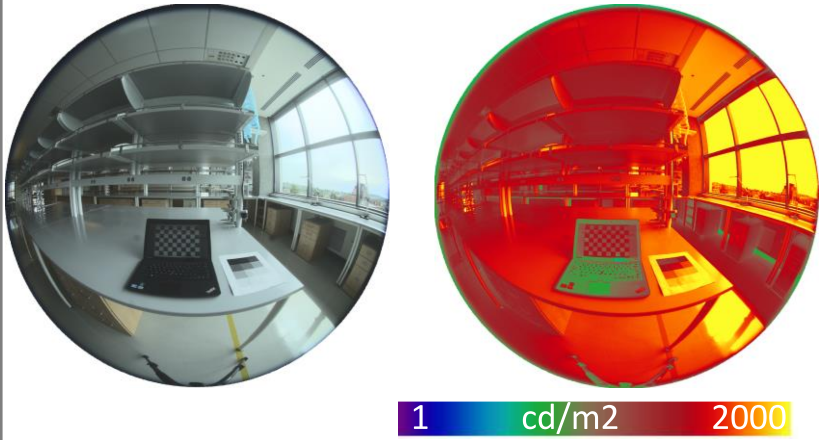
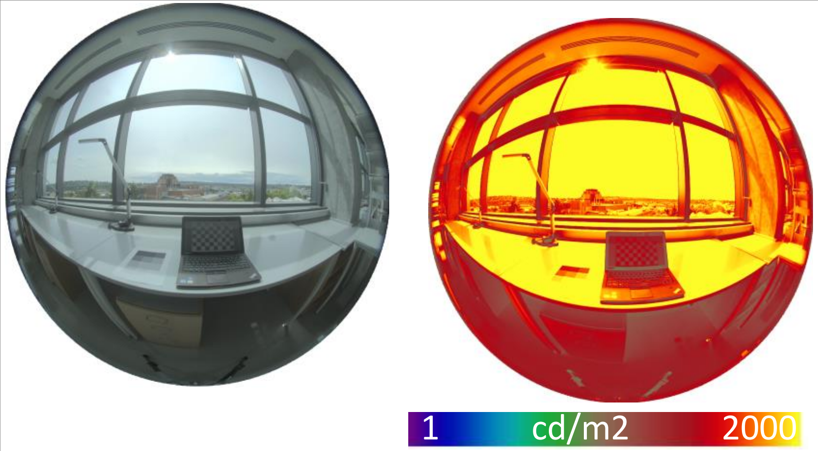
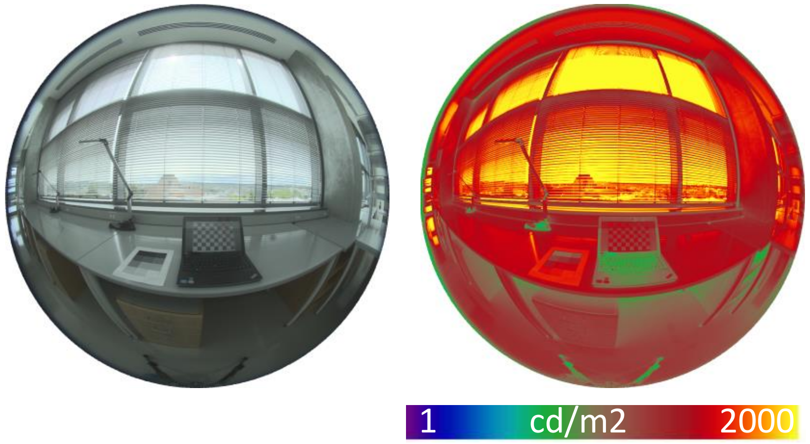
Glare Source Detection

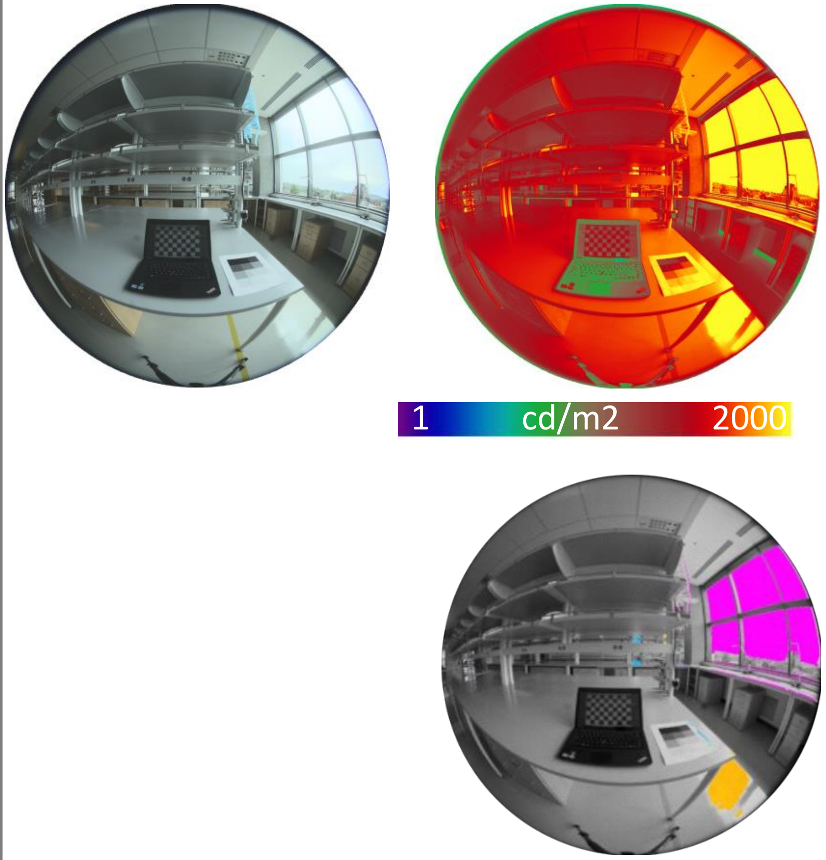
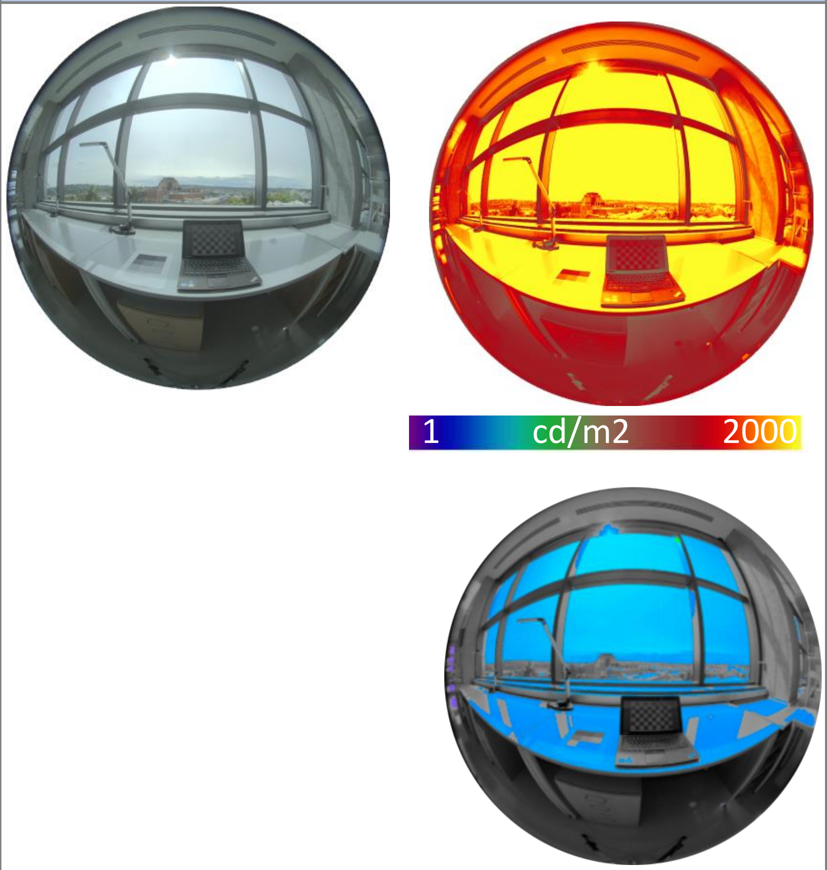
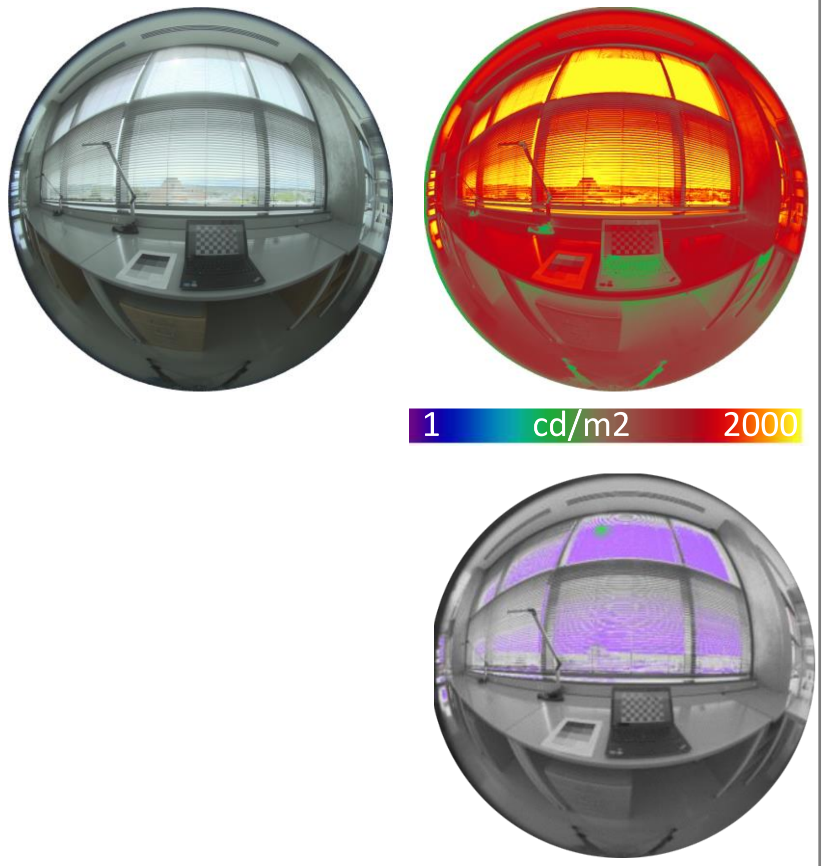
All Conditions (MP + JU) DGP Results

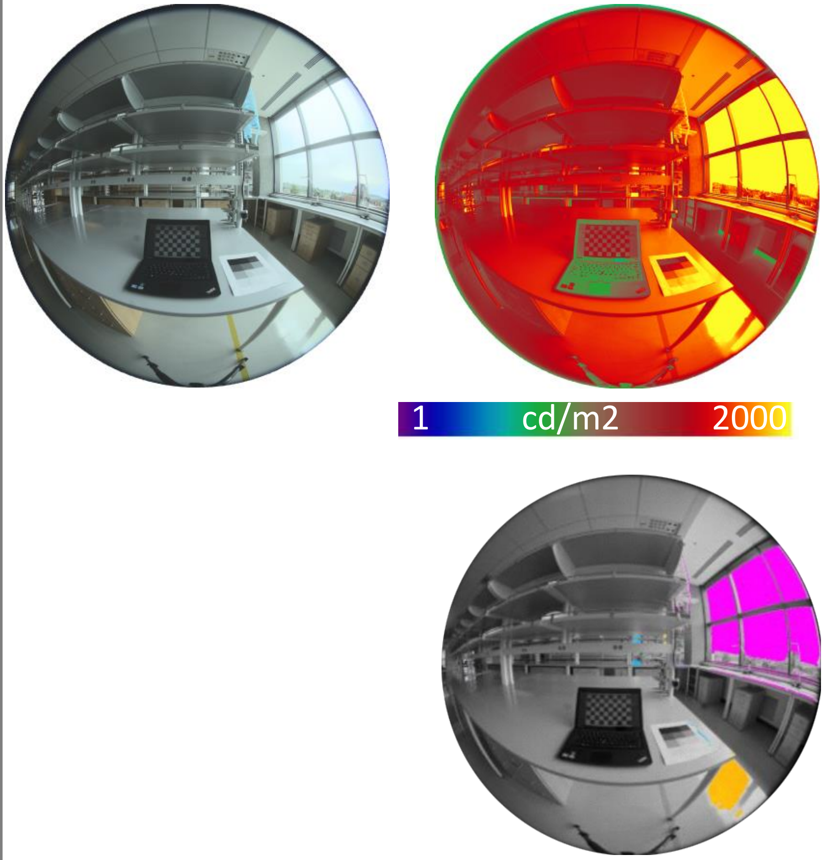
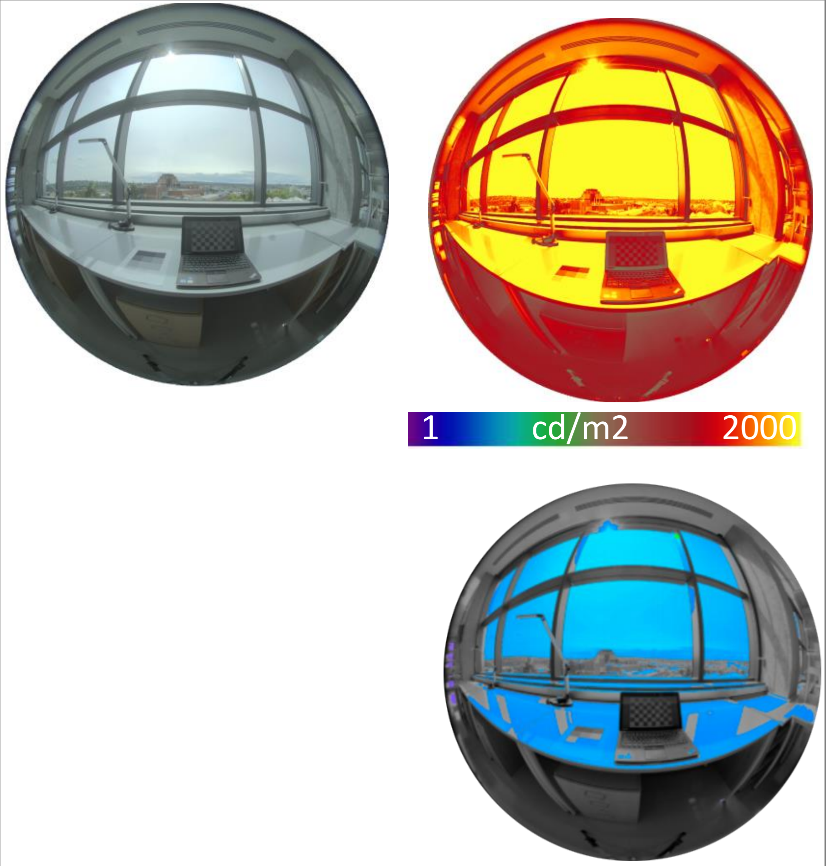
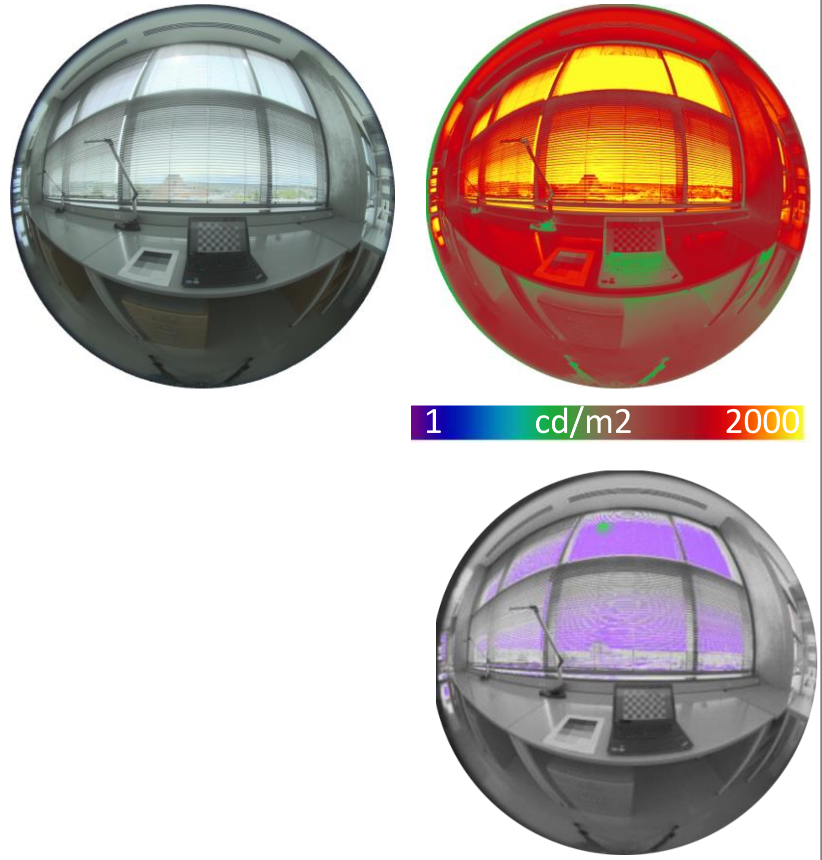
DGP Metric	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Task_average * 5	0.16	0.19	0.22	0.22	0.24	0.44
Scene_average * 5	0.16	0.19	0.22	0.22	0.24	0.45
Luminance threshold > 2000 cd/m2	0.16	0.19	0.22	0.22	0.24	0.44
Luminance threshold > 5000 cd/m2	0.16	0.19	0.21	0.22	0.24	0.45

$$DGP = \underbrace{5.87 * 10^{-5} * E_v}_{\textit{excessive light}} + \underbrace{9.18 * 10^{-2} \log\left(1 + \sum_i \frac{L_{s,i}^2 * w_{s,i}}{E_v^{1.87} * P_i^2}\right)}_{\textit{extreme contrast}} + 0.16$$

van den Wymelenberg K and Inanici M. “Evaluating a New Suite of Luminance-Based Design Metrics for Predicting Human Visual Comfort in Offices with Daylight,” *Leukos*, 12(3): 113-138, 2016.
van den Wymelenberg K and Inanici M. “A Critical Investigation of Common Lighting Design Metrics for Predicting Human Visual Comfort in Offices with Daylight,” *Leukos*, 10(3): 145-164, 2014.

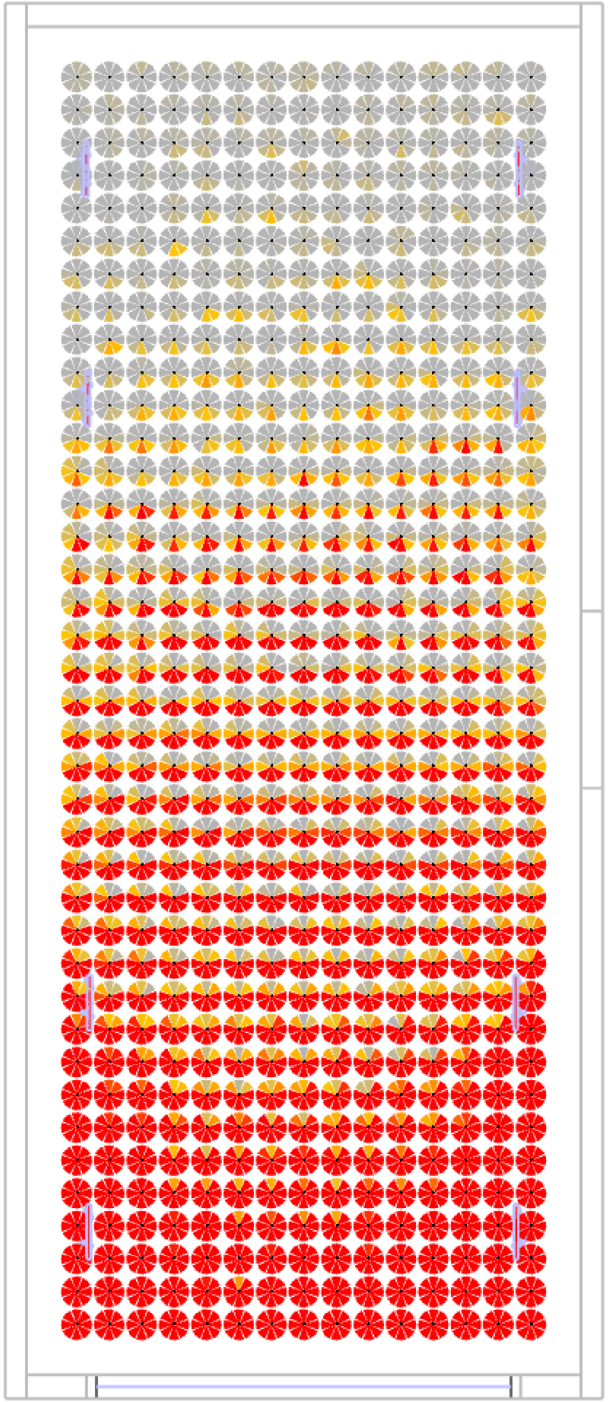
Scene parallel to window	Scene facing window – no blinds	Scene facing window – with blinds
		
Vertical E = 2926 Lx	Vertical E = 15312 Lx	Measured E = 4889 Lx
DGPs (excessive light) = 0.33	DGPs (excessive light) > 1.0	DGPs (excessive light) = 0.45

Scene parallel to window	Scene facing window – no blinds	Scene facing window – with blinds
		
Vertical E = 2926 Lx	Vertical E = 15312 Lx	Measured E = 4889 Lx
DGPs (excessive light) = 0.33 Min:Max L (10 percentile) = 1: 143 8.5% of pixels > 2000 cd/m^2	DGPs (excessive light) > 1.0 Min:Max L (10 percentile) = 1: 219 30% of pixels > 2000 cd/m^2	DGPs (excessive light) = 0.45 Min:Max L (10 percentile) = 1: 242 10.5% of pixels > 2000 cd/m^2

Scene parallel to window	Scene facing window – no blinds	Scene facing window – with blinds
		
Vertical E = 2926 Lx	Vertical E = 15312 Lx	Measured E = 4889 Lx
Total DGP = 0.34 DGPs (excessive light) = 0.33 Contrast_based glare = 0.01 Min:Max L (10 percentile) = 1: 143 8.5% of pixels > 2000 cd/m^2	Total DGP = 1.0 DGPs (excessive light) > 1.0 Contrast_based glare = 0.03 Min:Max L (10 percentile) = 1: 219 30% of pixels > 2000 cd/m^2	Total DGP = 0.47 DGPs (excessive light) = 0.45 Contrast_based glare = 0.02 Min:Max L (10 percentile) = 1: 242 10.5% of pixels > 2000 cd/m^2

Metrics

- Image-based (point-in-time) daylight glare indices
- Vertical Illuminance-based (simplified annual) glare indices
- Surrogate metrics:
  - Luminance (overlit) thresholds
  - Horizontal illuminance (overlit) thresholds
  - Horizontal Annual Solar Exposure (IES LM-83)



Annual Glare

Calculated at eye level in multiple gaze directions

Mainly driven by Vertical Illuminance, may include a contrast measurement based on solar disc

Showing results from Climate Studio

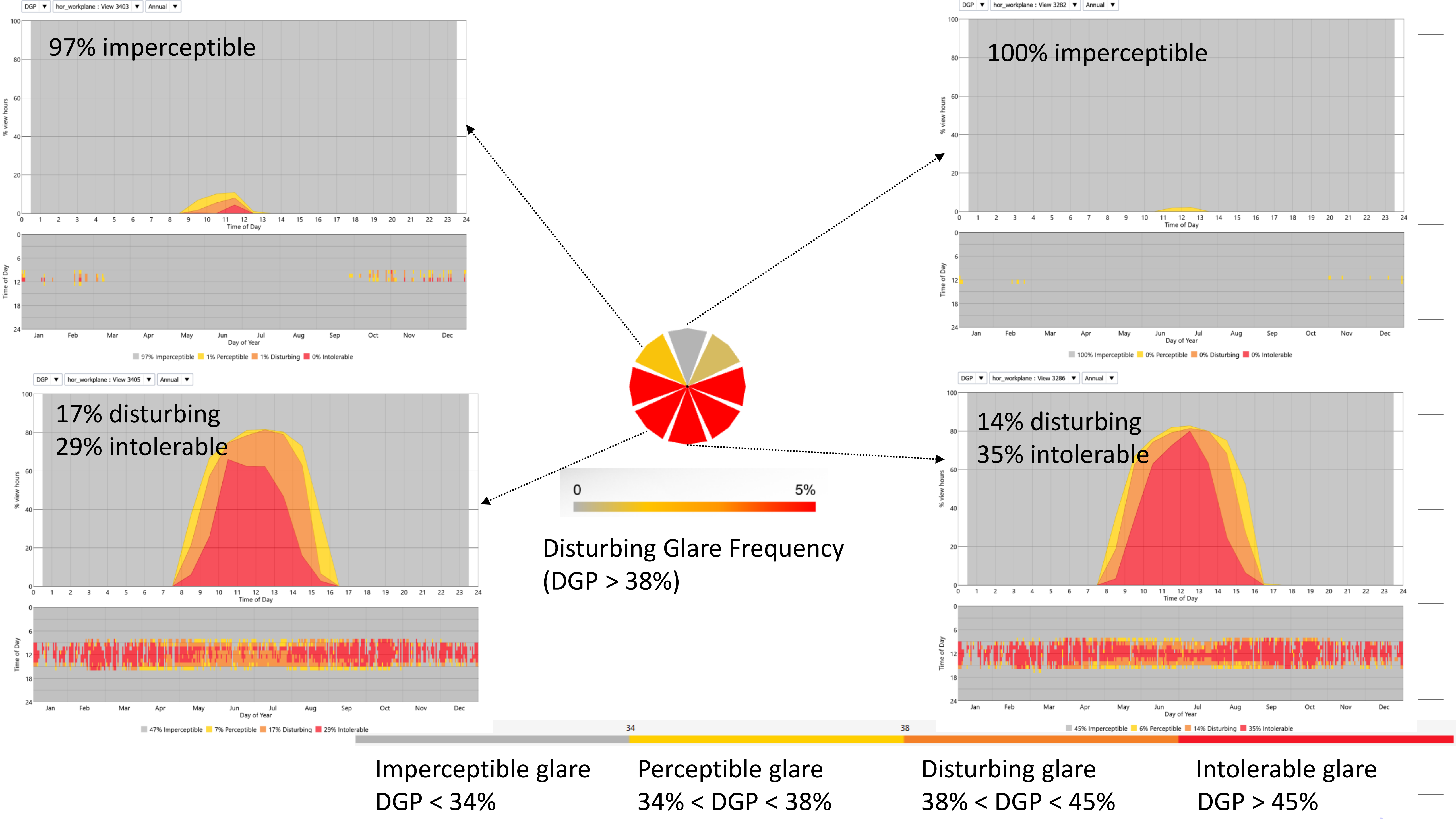
Disturbing Glare Frequency (DGP > 38%)

Imperceptible glare
DGP < 34%

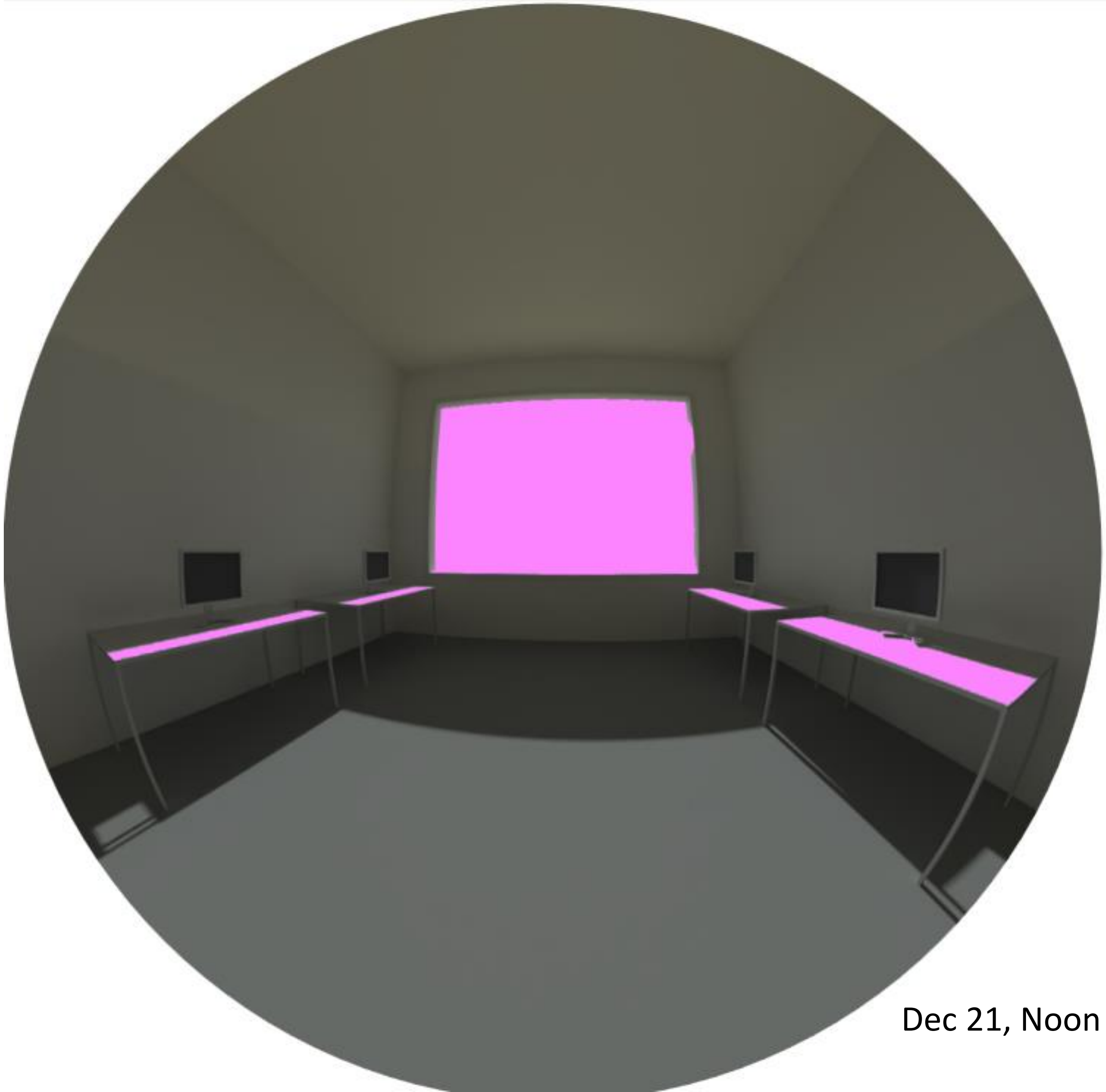
Perceptible glare
34% < DGP < 38%

Disturbing glare
38% < DGP < 45%

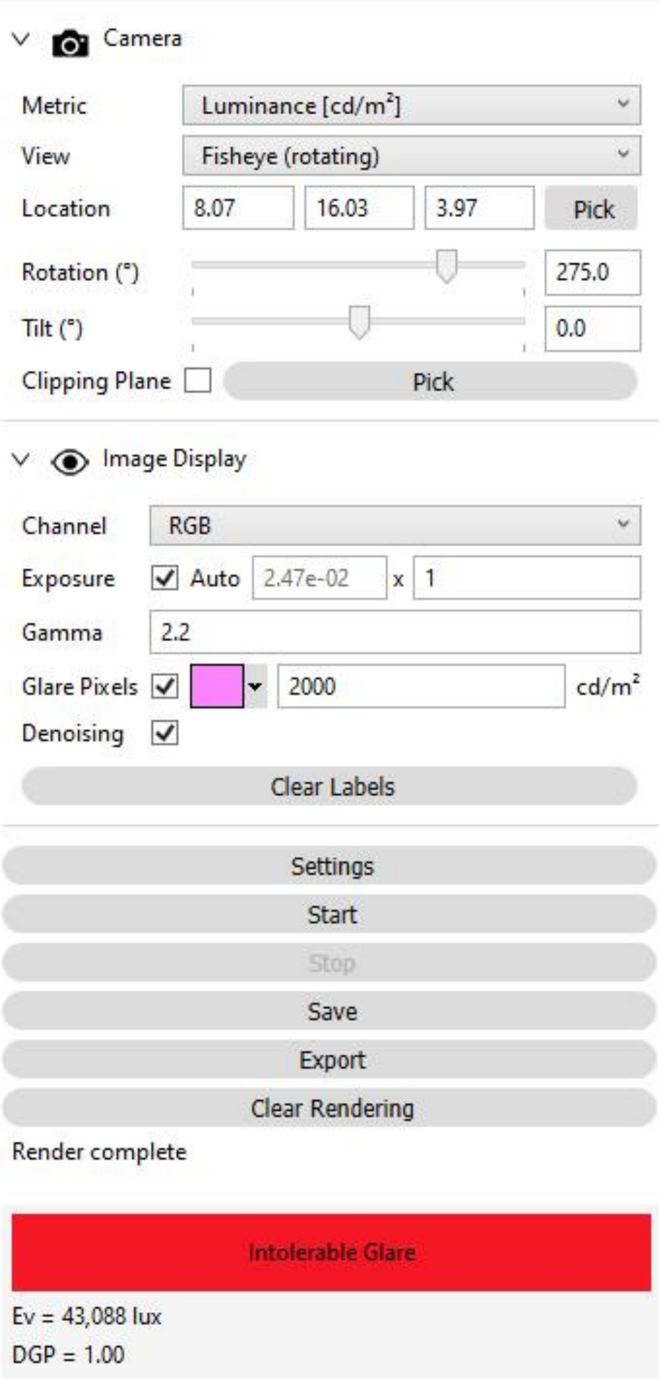
Intolerable glare
DGP > 45%

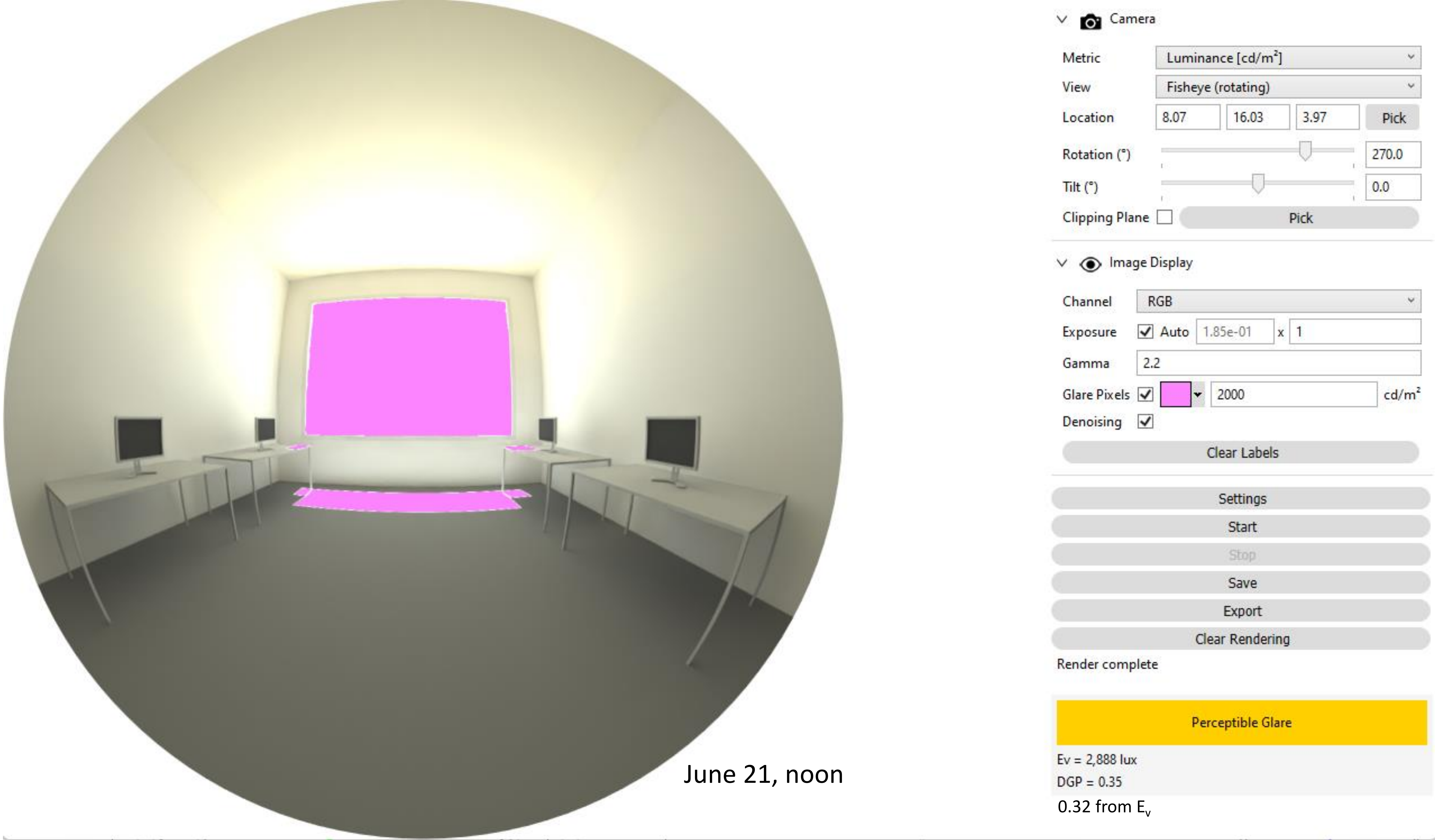


DGP
hor_workplane : View 3403
Annual
97% imperceptible
% view hours
Time of Day
Day of Year
97% Imperceptible
1% Perceptible
1% Disturbing
0% Intolerable
DGP
hor_workplane : View 3282
Annual
100% imperceptible
100% Imperceptible
0% Perceptible
0% Disturbing
0% Intolerable
DGP
hor_workplane : View 3405
Annual
17% disturbing
29% intolerable
47% Imperceptible
7% Perceptible
17% Disturbing
29% Intolerable
DGP
hor_workplane : View 3286
Annual
14% disturbing
35% intolerable
45% Imperceptible
6% Perceptible
14% Disturbing
35% Intolerable
0
5%
Disturbing Glare Frequency
(DGP > 38%)
34
38
Imperceptible glare
DGP < 34%
Perceptible glare
34% < DGP < 38%
Disturbing glare
38% < DGP < 45%
Intolerable glare
DGP > 45%



Dec 21, Noon


Camera
Metric
Luminance [cd/m²]
View
Fisheye (rotating)
Location
8.07
16.03
3.97
Pick
Rotation (°)
275.0
Tilt (°)
0.0
Clipping Plane
Pick
Image Display
Channel
RGB
Exposure
Auto
2.47e-02
x
1
Gamma
2.2
Glare Pixels
2000
cd/m²
Denoising
Clear Labels
Settings
Start
Stop
Save
Export
Clear Rendering
Render complete
Intolerable Glare
Ev = 43,088 lux
DGP = 1.00

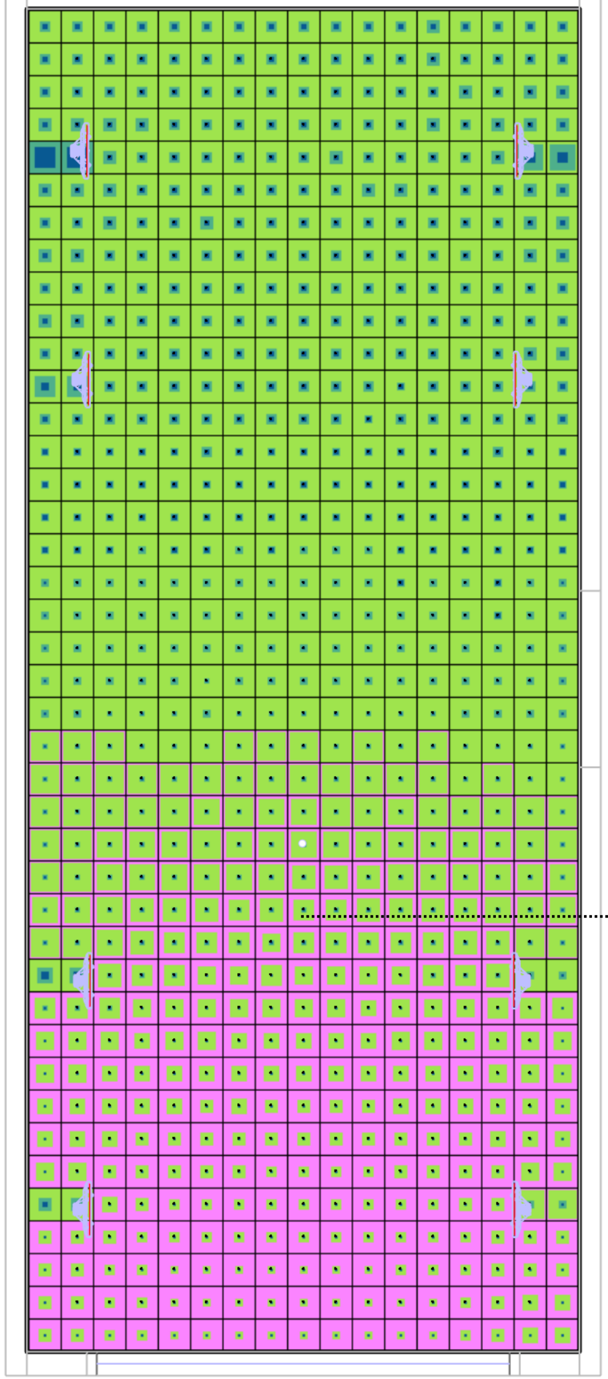


June 21, noon

0.32 from E_v

Metrics

- Image-based (point-in-time) daylight glare indices
- Vertical Illuminance-based (simplified annual) glare indices
- Surrogate metrics:
  - Luminance (overlit) thresholds
  - Horizontal illuminance (overlit) thresholds
  - Horizontal Annual Solar Exposure (IES LM-83)

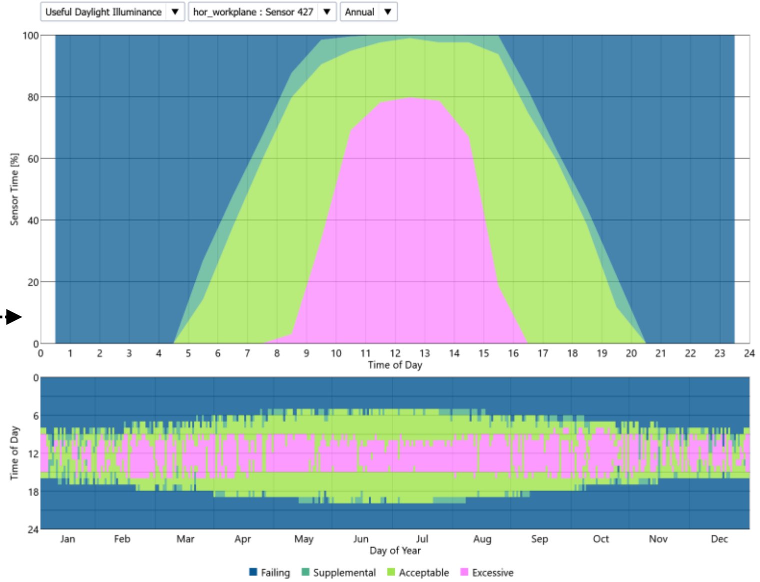


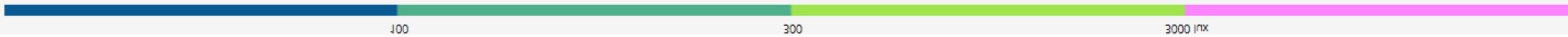
Useful Daylight Illuminance (UDI)

annual metric, measured on a horizontal task surface

300-3000 Lx is considered useful, >3000 is overlit

% of occupied hours that a grid is in a underlit, supplemental, useful, overlit bin





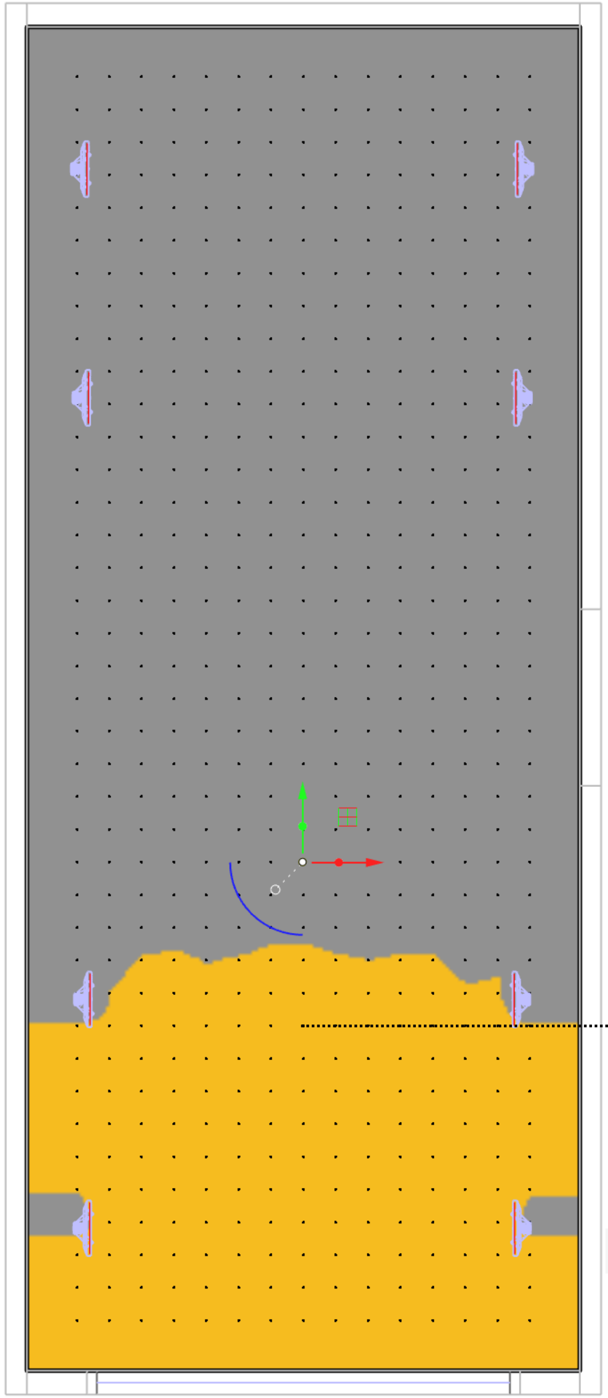
Underlit
<100 Lx

Supplemental
100 < Lx < 300

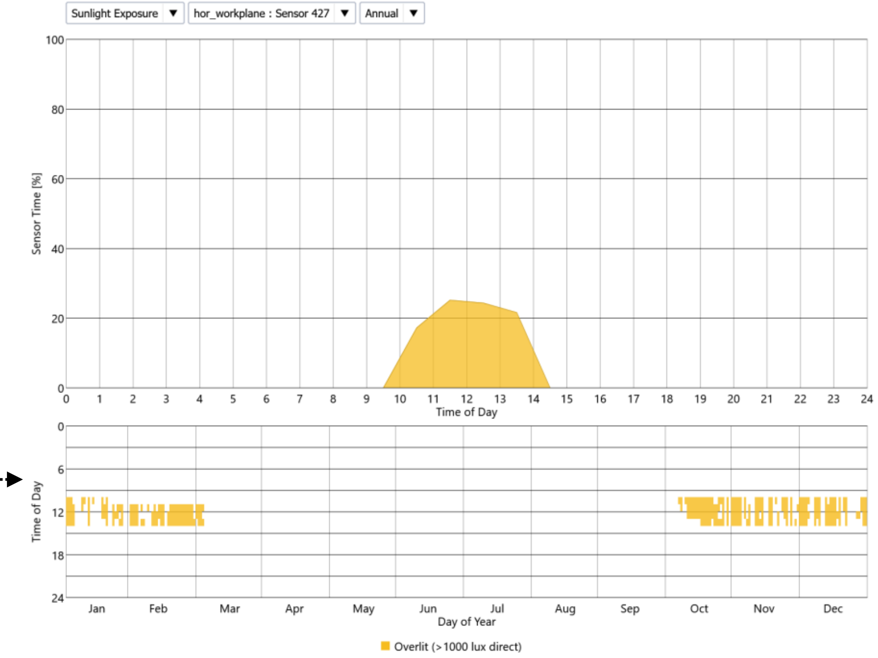
Useful
300 < Lx < 3000

Overlit
> 3000 Lx

Annual Solar Exposure (ASE)

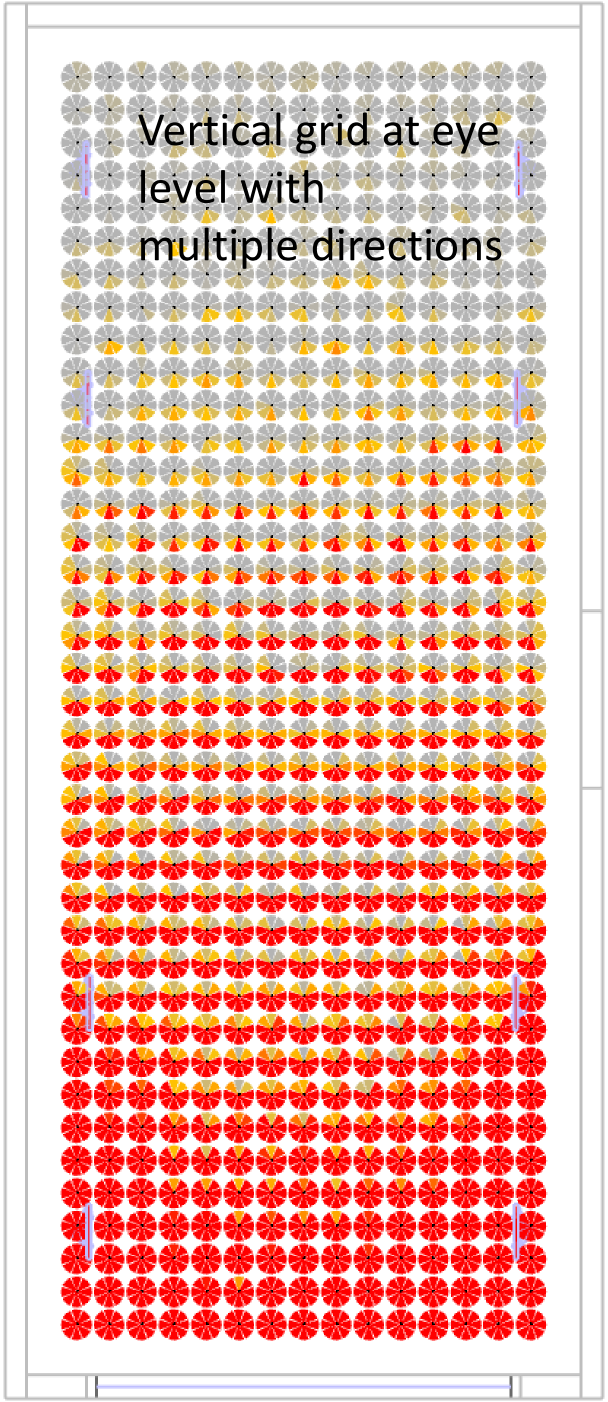


- Annual metric, measured on a horizontal task surface
- Direct exposure to sunlight
- Reports whether a grid point is exposed to direct sun over 250 hours

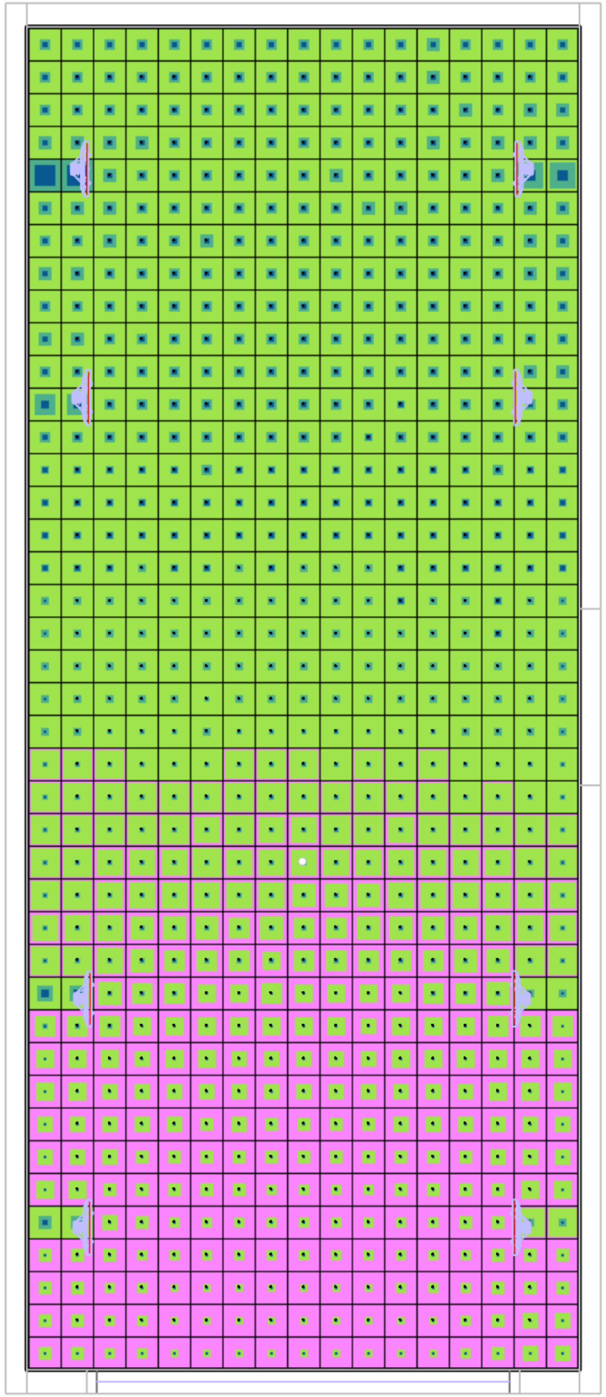


ASE < 250 hours, 1000 Lx

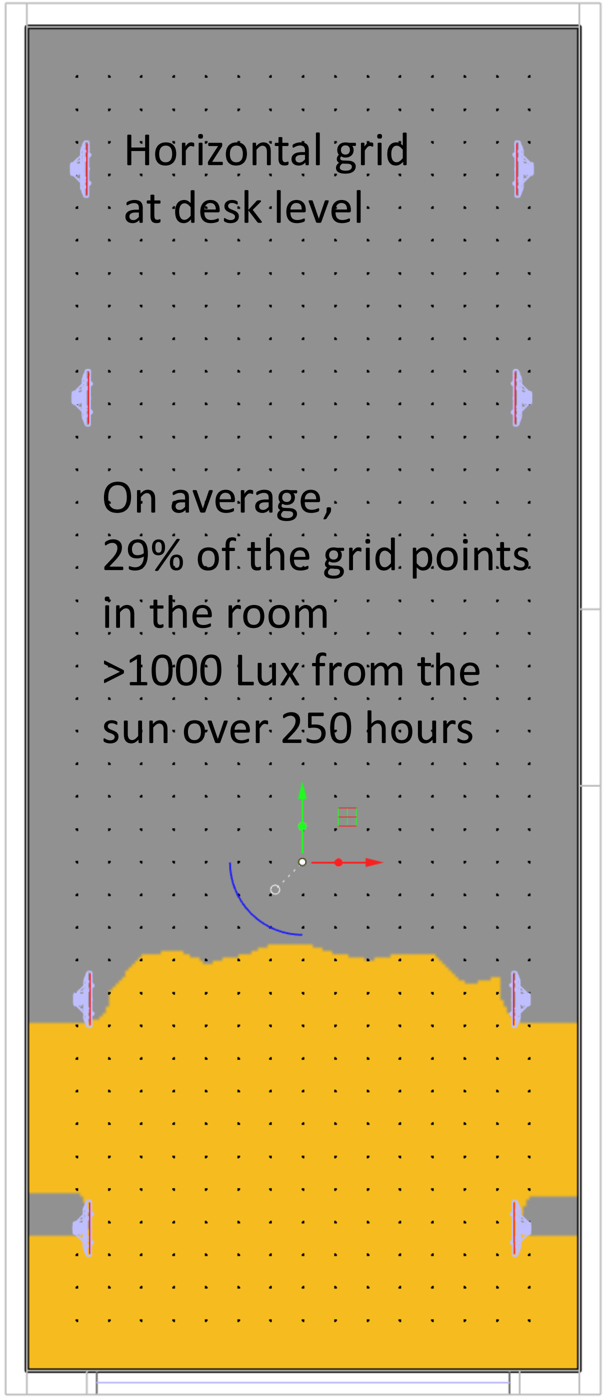
ASE > 250 hours, 1000 Lx



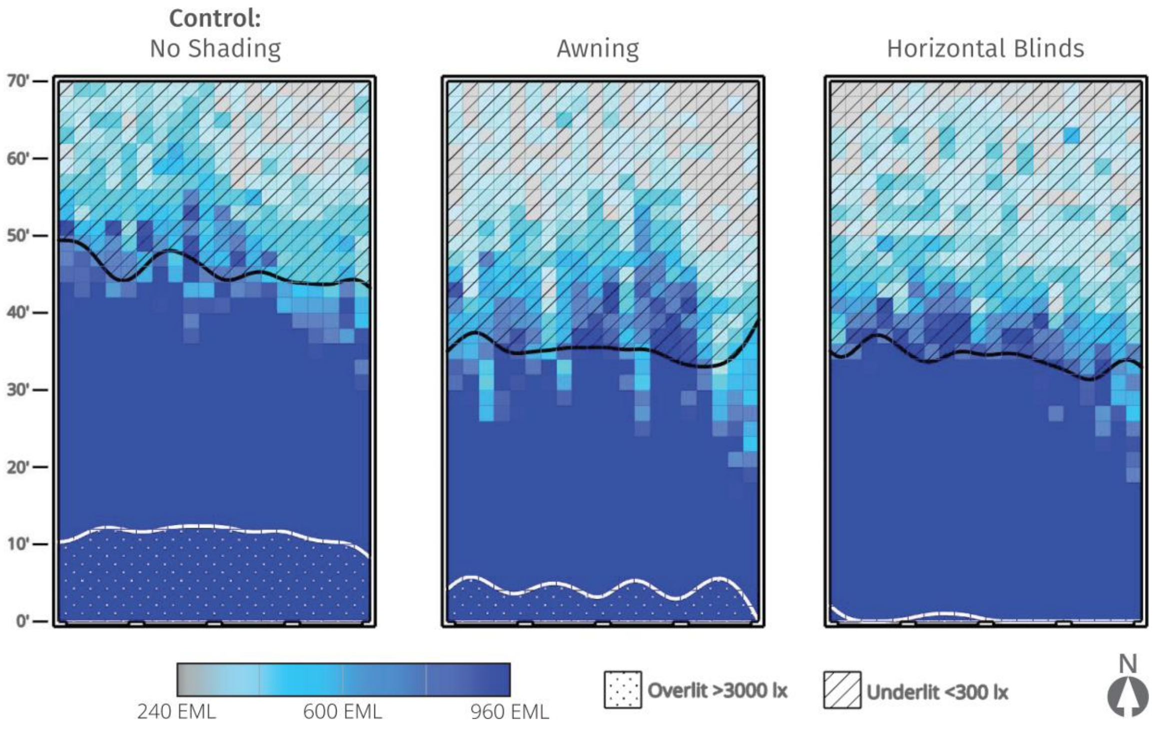
37% of the grid points have DGP > 0.38 more than 5% of the time

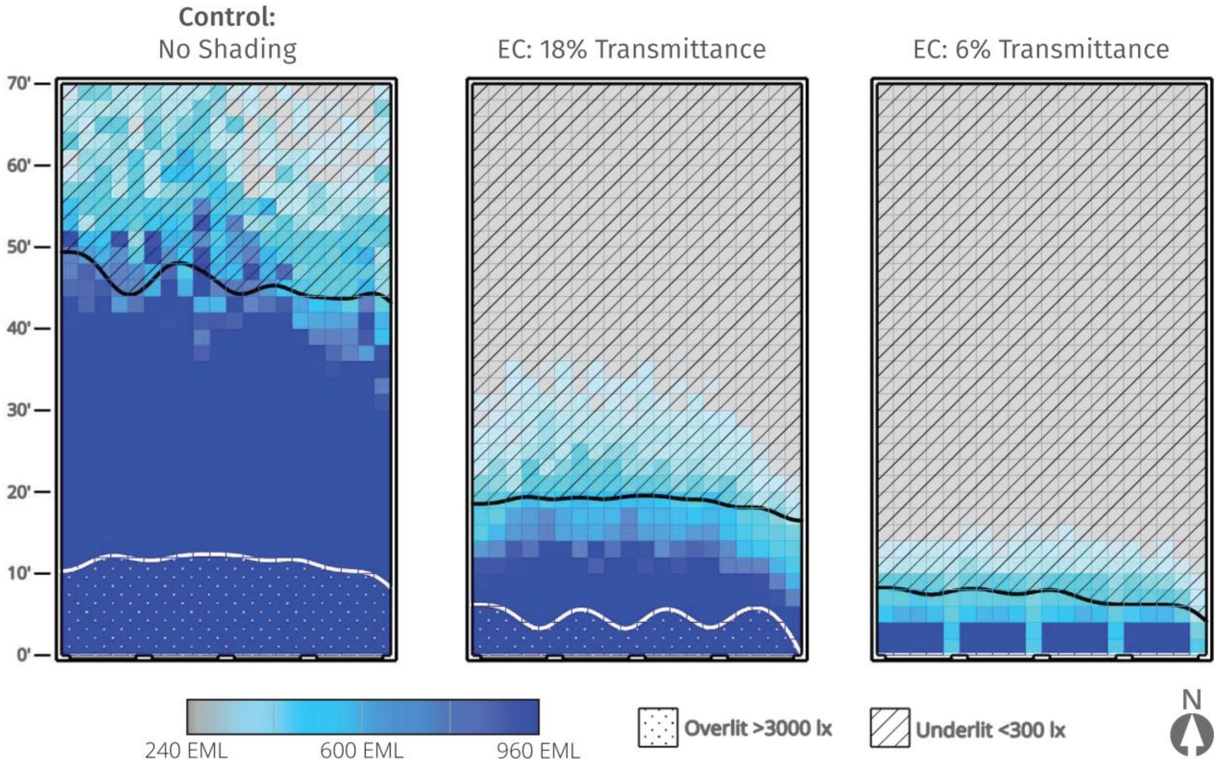


On average, 20% of the grid points in the room >3000 Lux



Glare vs Circadian Entrainment





Sep 21, 11 am
Occupant facing window

Altenberg Vaz N and Inanici M. "Syncing with the Sky: Daylight-Driven Circadian Lighting Design," *Leukos, the Journal of the Illuminating Engineering Society*, 17(3): 291-309, 2021

Conclusions

- Predicted energy savings frequently do not correlate with the actual operations of the buildings, as the intended use of the building systems are routinely altered in the presence of occupant dissatisfaction.

- Vertical illuminance is a single number, it does not provide information about the luminance distributions and the contrast in the visual field. It is effective in detecting excessive light levels as a discomfort glare source.

- Vertical illuminance is ineffectual in detecting discomfort glare as a result of high contrast among different portions of the visual field.

- Human visual comfort and health should be considered through a holistic approach.