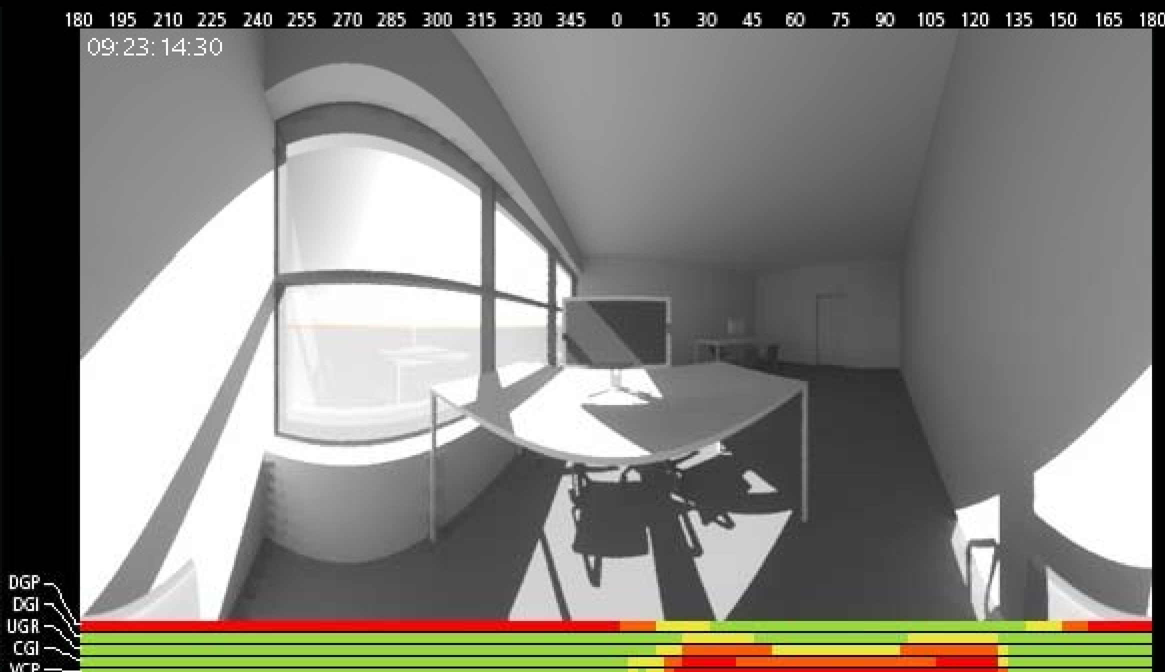
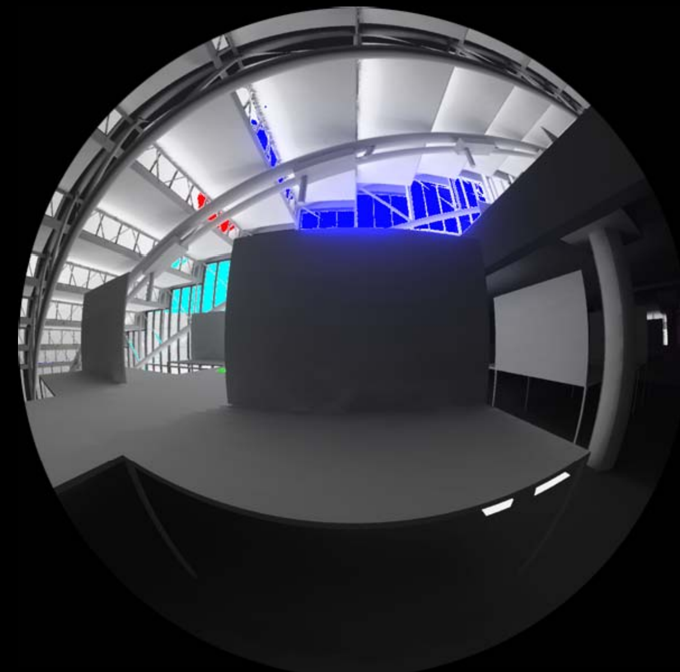
The Use of Glare Metrics in the Design of Daylit Spaces: Recommendations for Practice



Directional View-Dependant Discomfort Glare Probabilities



Rendering with Glare Sources Colored

Alstan Jakubiec and Christoph Reinhart

9th International Radiance Workshop; September 20-21, 2010

Harvard Design School

Glare is a measure of the physical discomfort of an occupant caused by excessive light or contrast in a specific field of view.

- Disability Glare
- Veiling Glare
- Discomfort Glare

The Problem: Discomfort Glare

Student-built shading device in Gund Hall

The Problem: Discomfort Glare

How does one design for visual comfort in spaces?

- Measurement of subjective human response – discomfort.
- Often no physically observable characteristics unlike veiling and disability glare.
- May not correlate well with quantifying metrics like workplane illuminance.
- Many different metrics, space types and computer programs available.
- View dependant.

The Problem: Discomfort Glare

Why now?

- Many metrics are available; however, nobody uses them.
  - Not in LEED, for example.
  - Also not in practice.
- Analysis is becoming computationally feasible.
- As glazing on modern buildings increases, so does the likelihood of glare.

Metrics: How is Glare Defined?

Luminance of Glare Source

Size of Glare Source

$$Glare = \sum_{i=1}^{n} \frac{L_{si}^{\exp}\,\omega_{si}}{L_{b}^{\exp}\,P_{i}^{\exp}}$$

Scene Luminance

Position Index

- Brighter luminance, larger source size, and a more-centered location in the viewing field increase probability of experiencing glare.
- Brighter average scene luminance decreases probability of experiencing glare.
- Basic concept was fit to many datasets with differing measurement and space criteria, resulting in many different glare indices.

Metrics: Daylight Glare Index (DGI)

$$DGI = 10 \times \log_{10} 0.48 \sum_{i=1}^{n} \frac{L_{si}^{1.6}\, \omega_{pos.si}^{0.8}}{L_b + (0.07\, \omega_{si}^{0.5}\, L_{si})}$$

Scale:	> 31	Intolerable
	< 18	Barely Perceptible

- Developed by Hopkinson at Cornell in 1972 based on earlier work for luminaire-sources glare performed at the BRE.
- First metric which considered large glare sources: the sky viewed through the window.
- User polling and testing conditions were published.
- Direct sunlight and reflections typically not accounted for, but they can be.

Metrics: CIE Glare Index (CGI)

$$CGI = 8 \times \log_{10} 2 \frac{(1+(E_d/500))}{E_d+E_i} \sum_{i=1}^{n} \frac{L_{si}^2 \omega_{si}}{P^2}$$

Scale:	> 28	Intolerable
	< 13	Barely Perceptible

- Published by Einhorn in 1969 and adopted by the CIE.
- Calculations require both direct and diffuse illuminances.
- For luminaire sources of glare.

Metrics: Visual Comfort Probability (VCP)

$$VCP = 279 - 110\left[\log_{10}\sum_{i=1}^{n}\left(\frac{0.5\,L_{si}(20.4\,\omega_{si} + 1.52\,\omega_{si}^{0.2} - 0.075)}{P \times E_{avg}^{0.44}}\right)^{(n^{-0.0914})}\right]$$

Scale: Percentage of people predicted to feel comfortable in a space.

- Massive system of equations adopted by the IESNA.
- Only valid for typically-sized luminaire sources of light (no halogens or visible skies).

Metrics: CIE Unified Glare Rating (UGR)

$$UGR = 8 \times \log_{10} \frac{0.25}{L_b} \sum_{i=1}^{n} \frac{L_{si}^2 \omega_{si}}{P^2}$$

Scale:	> 28	Intolerable
	< 13	Barely Perceptible

- Established by CIE Technical Committee 3-13 in 1995.
- Simplification of CGI now preferred by the CIE. Separation of direct and diffuse illuminances no longer needed.
- No discussion of testing methods or derivation conditions given.

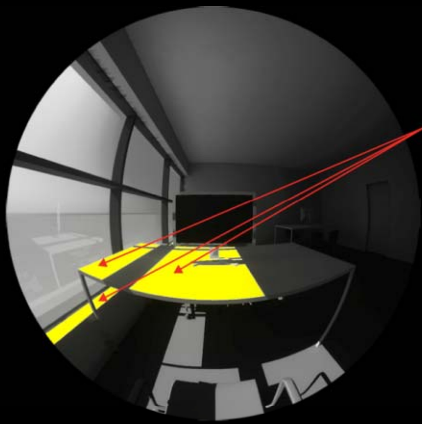
Metrics: Daylight Glare Probability (DGP)

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-5} \log_{10}\left(1 + \sum_{i=1}^{n} \frac{L_{si}^2 \omega_{si}}{E_v^{1.87} P_i^2}\right)$$

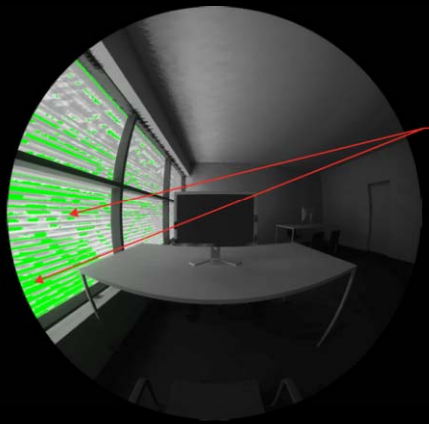
Scale:	> .45	Intolerable
	< .3	Barely Perceptible

- Calculations now broken into two parts:
  1. Typical glare metric calculations.
  2. Portion based solely on total eye illuminance.
- Glare sources detected by contrast ratios, so direct daylight and specular reflections are considered while a dim visible sky might not be.
- Very careful measurement and user polling conditions from two independent experiments

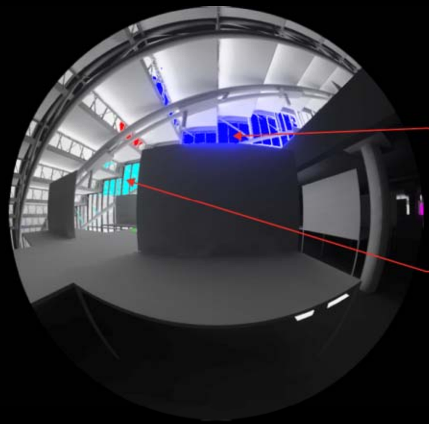
Three Simulated Spaces



Unshaded Sidelit Office

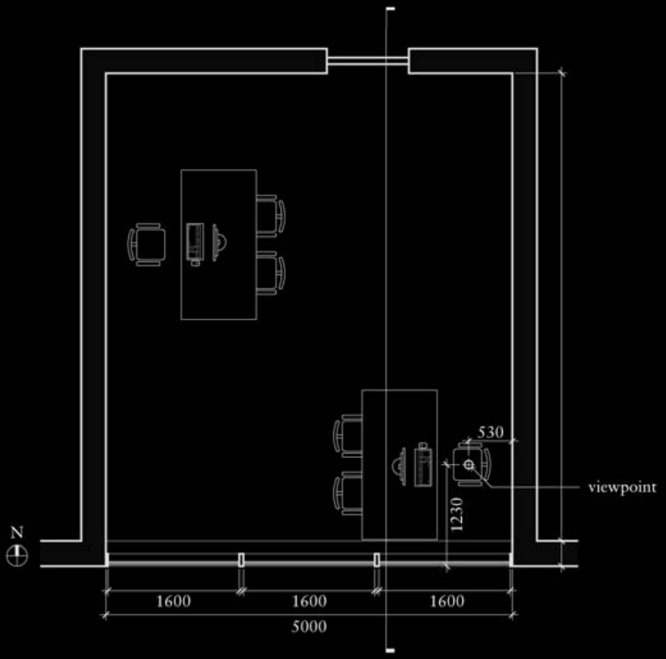


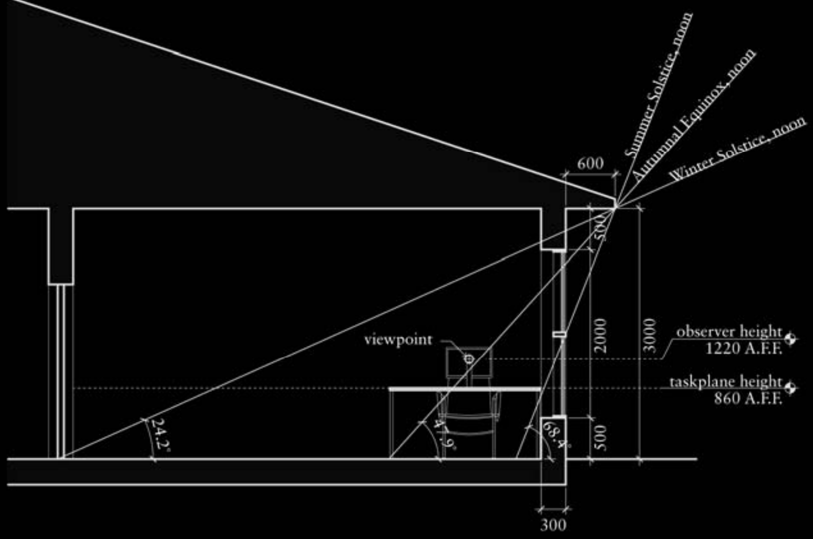
Sidelit Office w/ Venetian Blinds



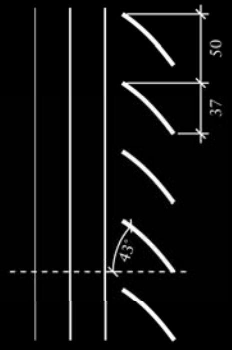
Gund Hall

Sidelit Office Typology



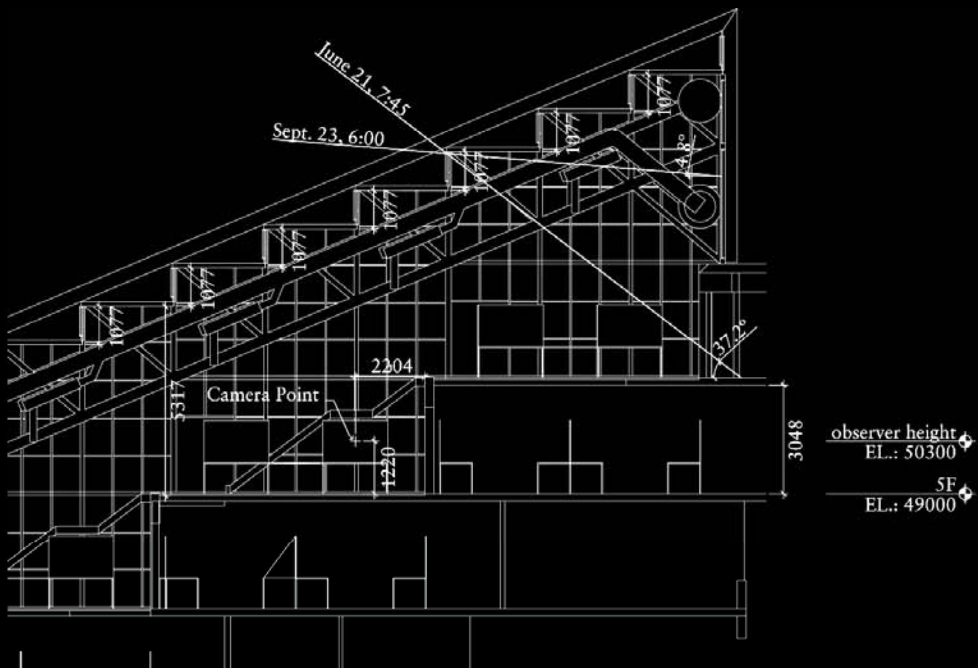


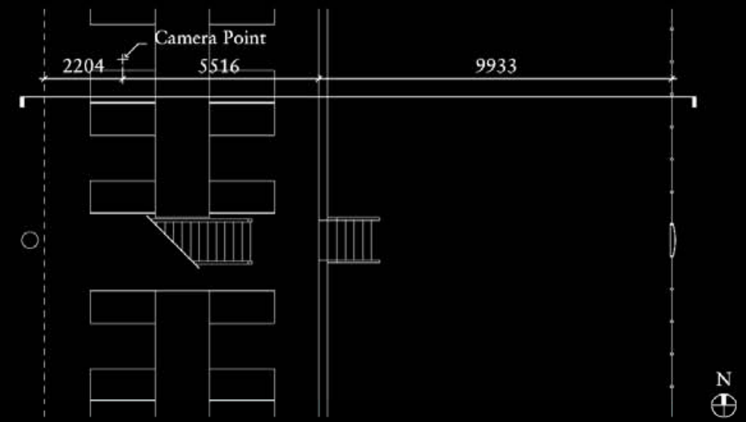
Unshaded Sidelit Office



Venetian Blinds

Clerestory-Lit Open Plan Space





Gund Hall Trays at Harvard Graduate School of Design

Radiance Simulation Parameters

Radiance Simulation Parameters	
Ambient Bounces (ab)	6
Ambient Accuracy (aa)	.15
Ambient Divisions (ad)	3000
Ambient Super-Samples (as)	16

Material Properties	
Floors	20% Reflectance
Walls	50% Reflectance
Ceilings	80% Reflectance
Desk Surfaces	50% Reflectance
Outside Ground	20% Reflectance
Glazing	72% Transmittance

- Three simulated spaces:
  1. sidelit office space
  2. sidelit office space with venetian blinds (always lowered)
  3. Gund Hall
- 144 sky conditions

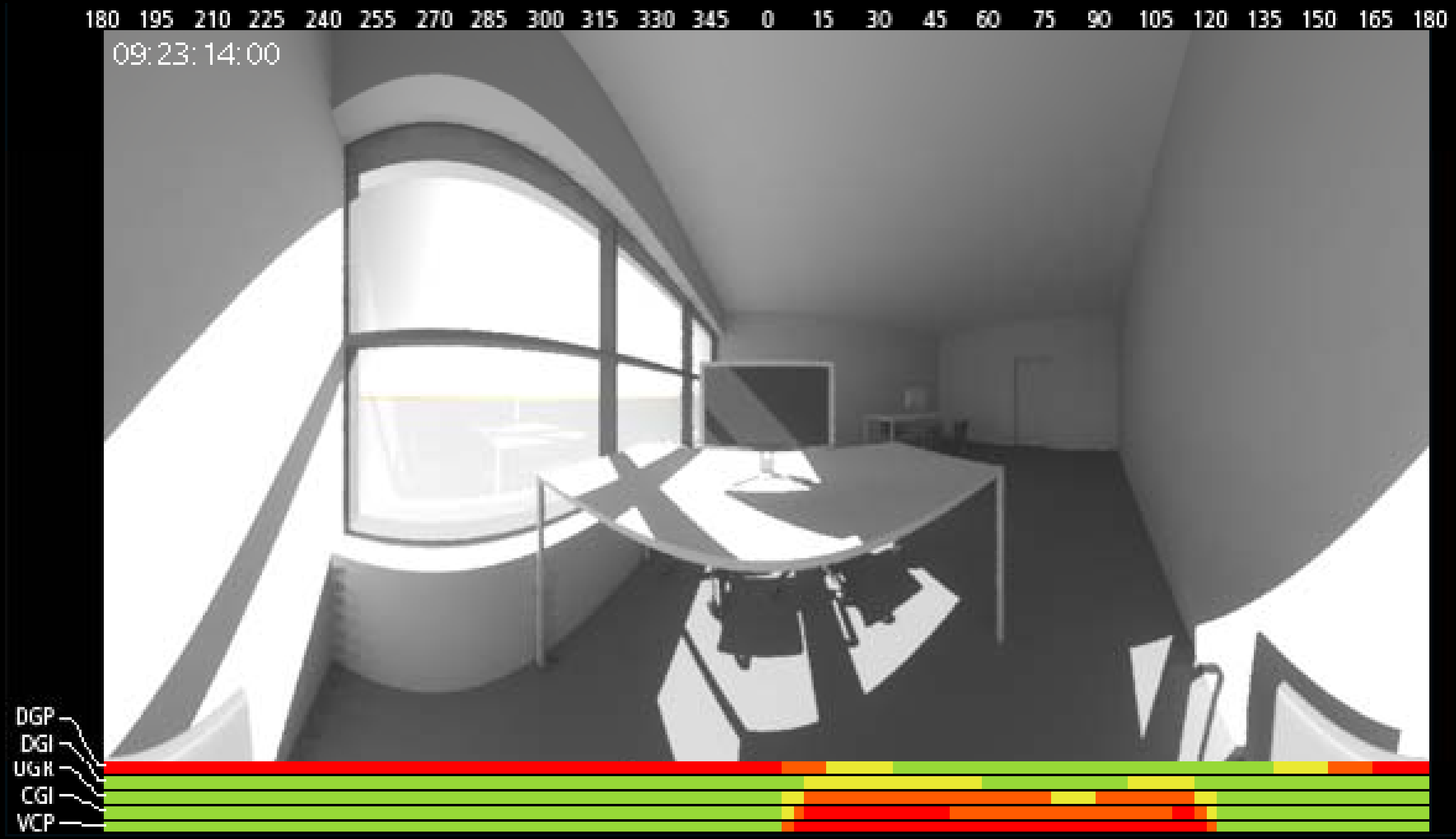
July 21	9am – 9pm, 15 minute intervals
September 23	9am – 9pm, 15 minute intervals
December 21	9am – 9pm, 15 minute intervals

- 120 rotational variants per sky condition

Multidirectional Time-Lapse Simulations

120 Hemispheric Images Generated for a Single Animation Frame, September 23 14:00

Multidirectional Time-Lapse Simulations



Resultant Visualization Frame, September 23 14:00

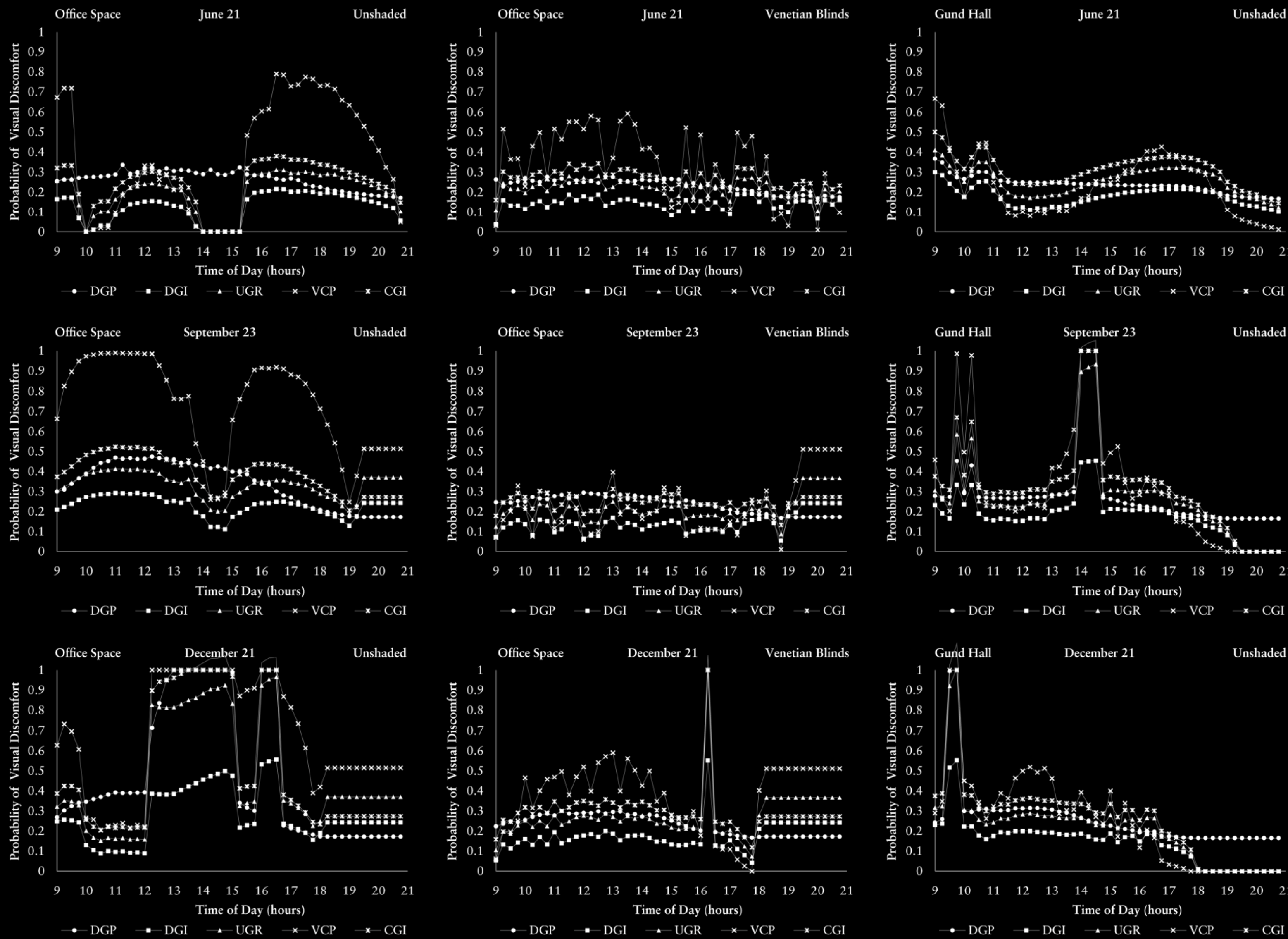
Green	Imperceptible Glare
Yellow	Perceptible Glare
Orange	Disturbing Glare
Red	Intolerable Glare

Multidirectional Time-Lapse Simulations

Color	Glare Value Ranges				
	DGP	DGI	UGR	CGI	VCP
Green	< .35	< 18	< 13	< 13	80 - 100
Yellow	.35 - .40	18 - 24	13 - 22	13 - 22	60 - 80
Orange	.4 - .45	24 - 31	22 - 28	22 - 28	40 - 60
Red	> .45	> 31	> 28	> 28	< 40

Green	Imperceptible Glare
Yellow	Perceptible Glare
Orange	Disturbing Glare
Red	Intolerable Glare

Initial Results (Fixed View)



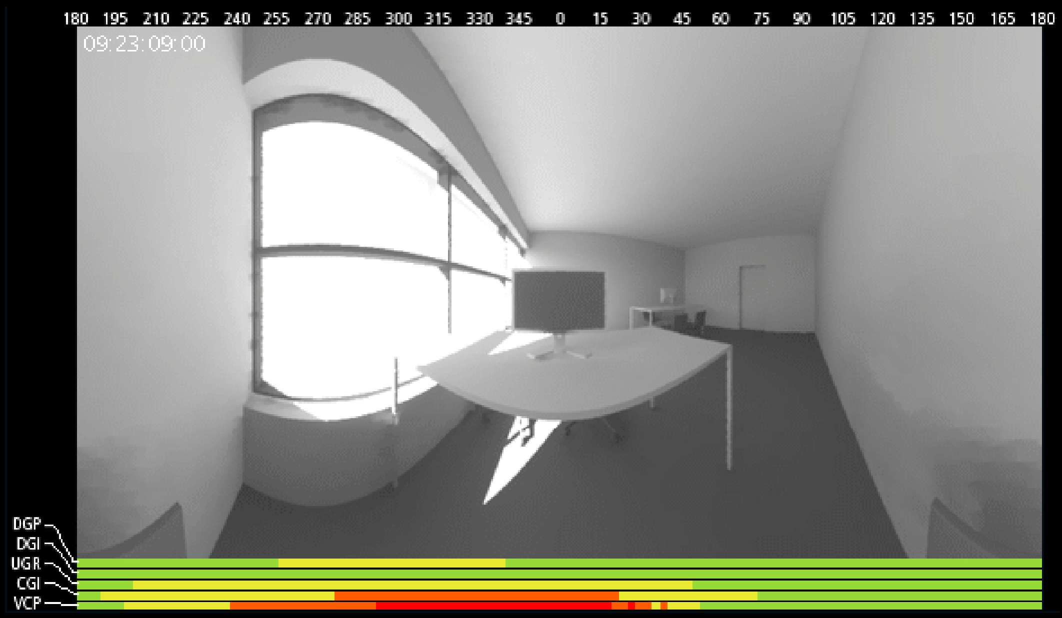
Observed Conditions

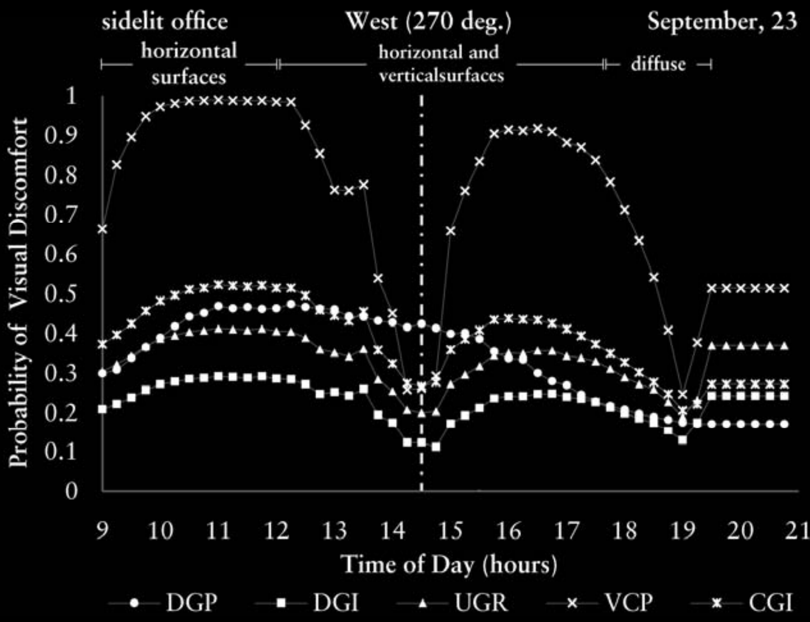
September 23, 15 minute time step simulations.

Simulation Model	Lighting Conditions and Time Ranges Observed		
sidelit office space	light falling on horizontal surfaces 9:00 - 12:00 local time	light falling on horizontal and vertical surfaces 12:15 - 17:30 local time	diffuse light from windows with visible sky 17:45 - 19:15 local time
sidelit office space w. blinds	window as near-uniform diffuse light source 9:00 - 19:15 local time		
Gund Hall	light falling on horizontal surfaces 9:00 - 13:45 local time	sun directly visible 14:00 - 14:30 local time	diffuse light from clerestory and south windows 16:00 - 19:15 local time

Multidirectional Time-Lapse Simulations

September 23, 15 minute time step simulations.



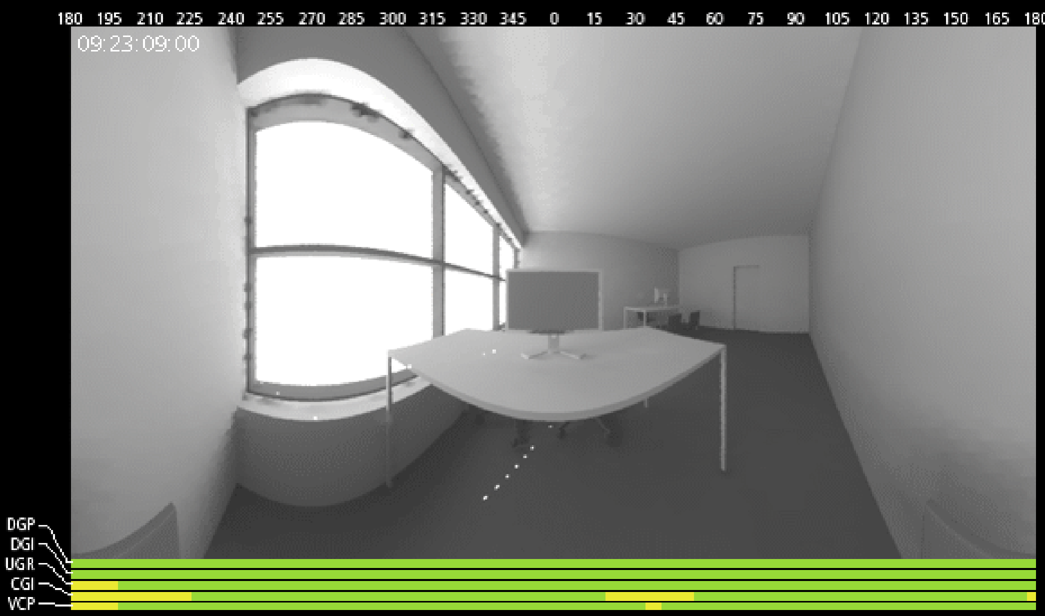


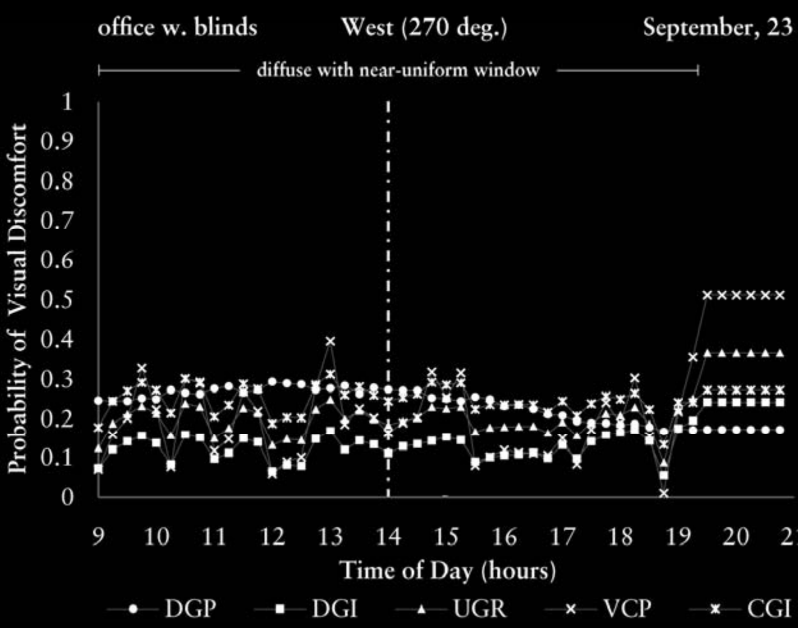
Unshaded Office Space, West User Orientation

Green	Imperceptible Glare
Yellow	Perceptible Glare
Orange	Disturbing Glare
Red	Intolerable Glare

Multidirectional Time-Lapse Simulations

September 23, 15 minute time step simulations.





Office Space with Venetian Blinds, West User Orientation

Green Imperceptible Glare
Yellow Perceptible Glare
Orange Disturbing Glare
Red Intolerable Glare

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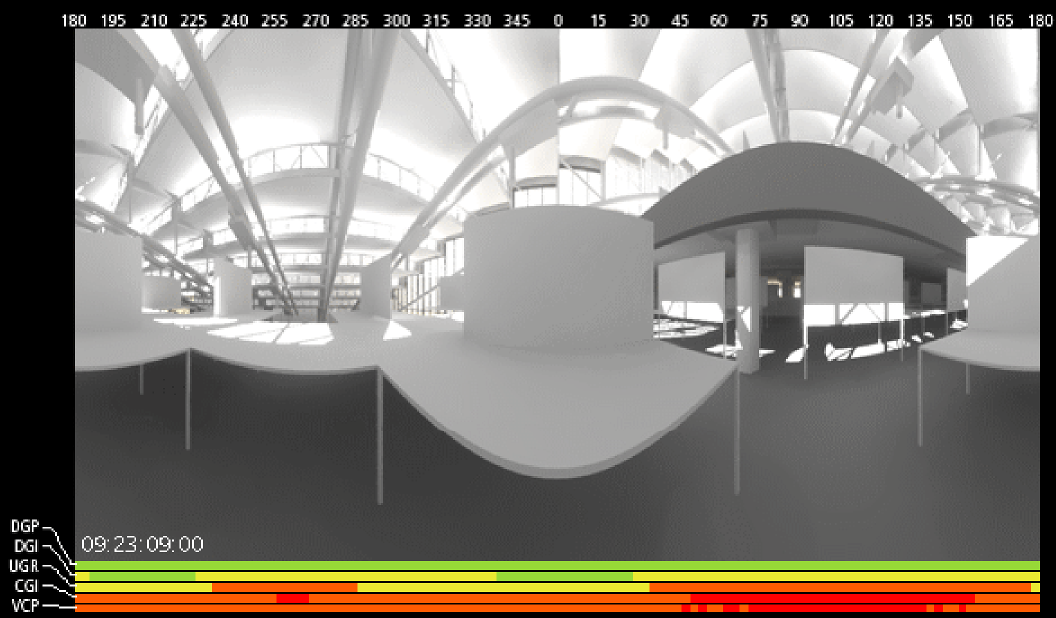
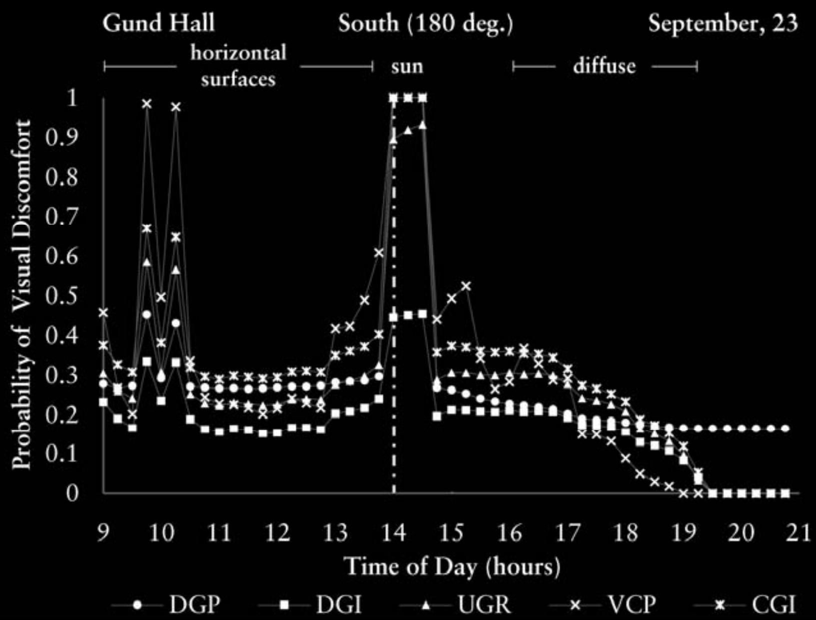
Multidirectional Time-Lapse Simulations

September 23, 15 minute time step simulations.





Gund Hall, South User Orientation

Green	Imperceptible Glare
Yellow	Perceptible Glare
Orange	Disturbing Glare
Red	Intolerable Glare

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Multidirectional Time-Lapse Simulations

Under daylit conditions,

- VCP (Visual Comfort Probability)
  Predicts very high levels of visual discomfort.

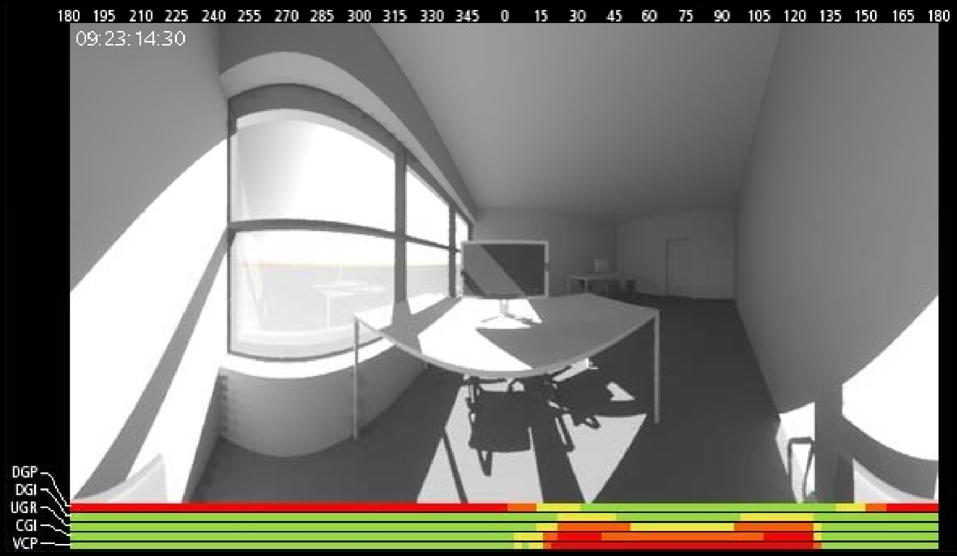
- DGI, UGR, and CGI all correlate strongly.
  CGI (CIE Glare Index) predicts the highest likelihood of discomfort.
  DGI (Daylight Glare Index) predicts the lowest.

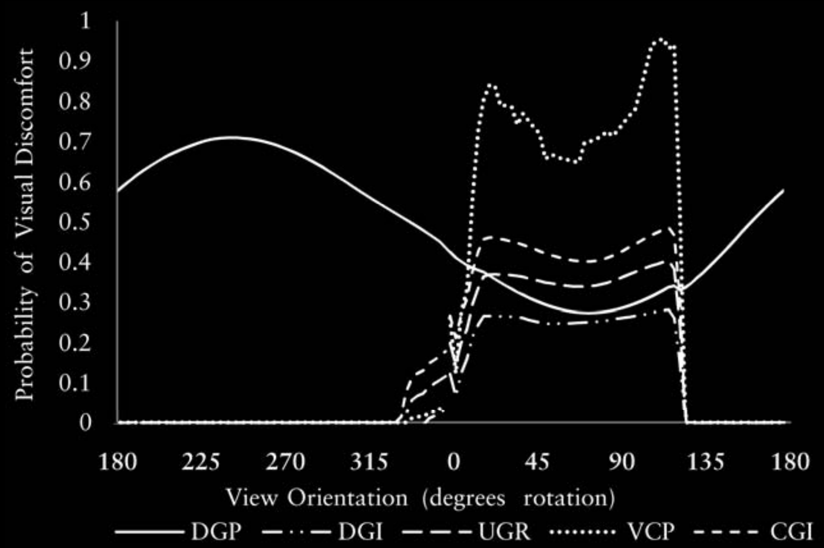
- DGP (Daylight Glare Probability) predicts within the range established by CGI and DGI **when they produce reasonable estimates**.

But there are several interesting cases to be observed…

Observed Conditions

Unshaded Office Space, September 23, 14:30



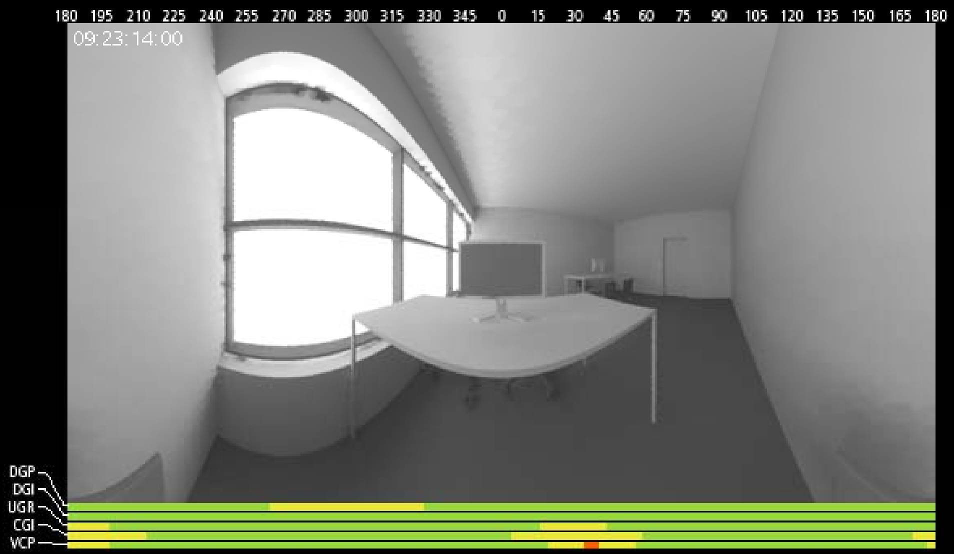


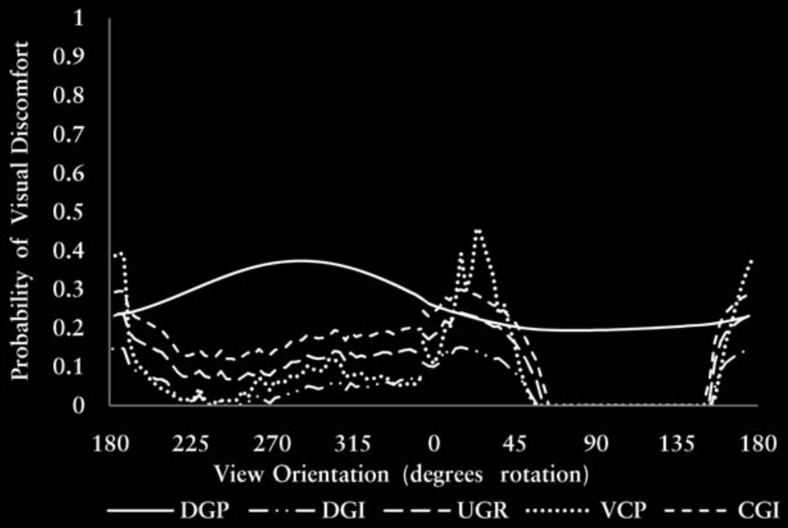
Green	Imperceptible Glare
Yellow	Perceptible Glare
Orange	Disturbing Glare
Red	Intolerable Glare

- Extreme brightness of scene prevents contrast-based metrics from identifying the probability for discomfort except when facing away from the window (bright sky) and direct light.
- Because DGP uses total eye illuminance as a measurement of glare caused by overly bright scenes, it produces reasonable glare predictions for all view directions.

Observed Conditions

Office Space w. Blinds, September 23, 14:00





Green Imperceptible Glare

Yellow Perceptible Glare

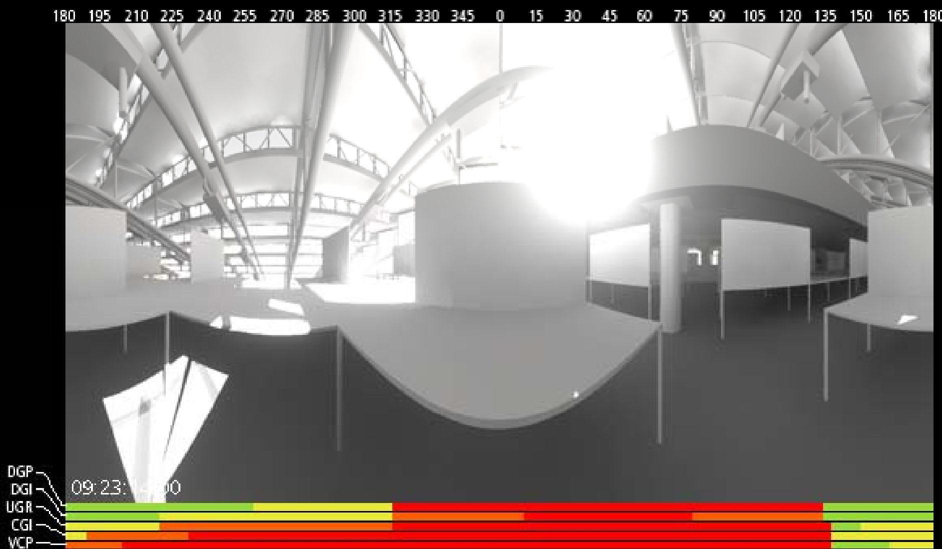
Orange Disturbing Glare

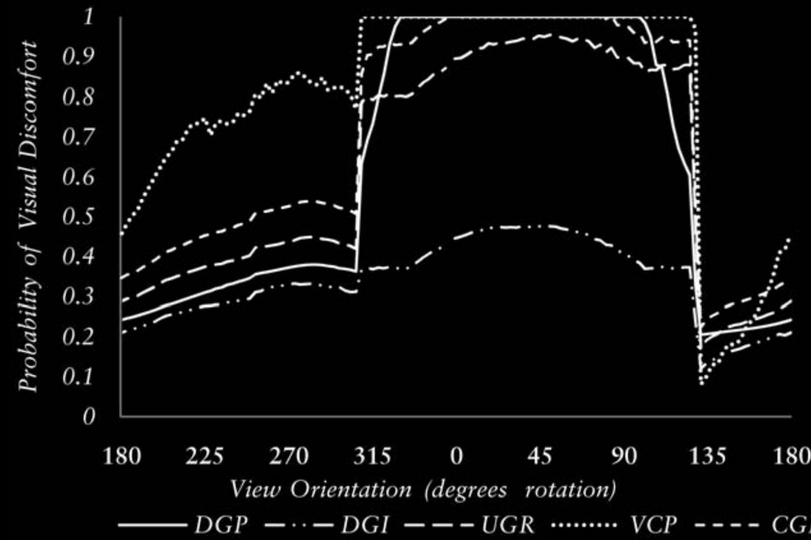
Red Intolerable Glare

- With large, diffuse light sources very little discomfort is predicted by all metrics.

Observed Conditions

Gund Hall, September 23, 14:00





Green	Imperceptible Glare
Yellow	Perceptible Glare
Orange	Disturbing Glare
Red	Intolerable Glare

- Very little glare predicted unless a very bright sky or the sun is directly visible for this scene.
- DGI predicts relatively little glare when the sun is directly visible.

Discussion of Metrics

Based on observed results…

DGI

DGI should only be applied under conditions where direct sunlight will not enter the space; however, CGI provides relatively similar data while predicting a worse-case discomfort scenario.

CGI

CGI predicts the highest likelihood of discomfort glare for diffuse daylit conditions as a worst case scenario for comparison between designs.

VCP

Under sunlit conditions, VCP produces the values least in line with other metrics. As it was developed only for very specific, artificially-lit circumstances, it is not recommended for use with daylit scenes.

UGR

Much as DGI, UGR is only useful under conditions where direct sunlight will not enter the space.

DGP

We have found DGP to be the most robust metric that generates the most plausible results under the investigated scenes and daylighting conditions. DGP responds predictably to most daylight situations including those with many or large solid angle direct or specular luminance sources. For this reason, the automation of many iterative time-step simulations can be achieved and their results compared with less chance of erroneous results.

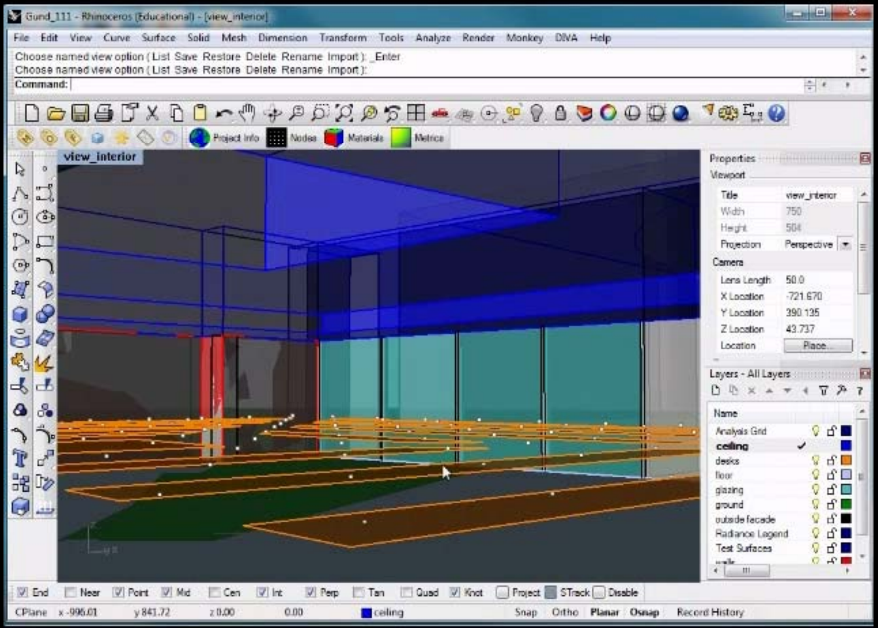
Generation of Single-Sky Glare Predictions

DIVA – Design Iterate Validate Adapt

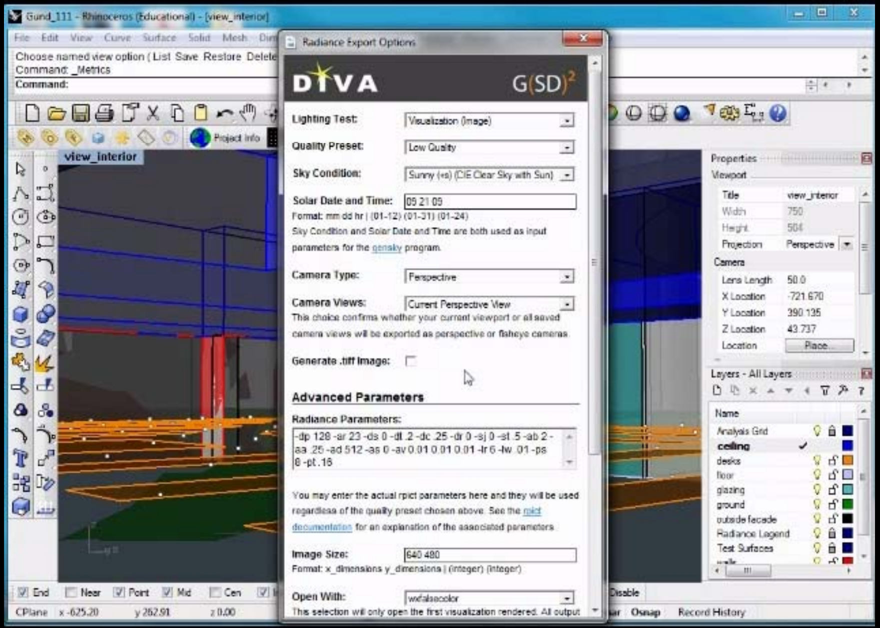
- Radiance and DAYSIM plugin for Rhinoceros 3d modeling software.
- Released for free over the Summer at http://www.diva-for-rhino.com/

- Visualizations (rpict)
- Yearly Radiation Studies (GenCumulativeSky with rpict or rtrace)
- Illuminance Analysis (rtrace)
- Climate Based Yearly Illuminance Metrics (DAYSIM)
- **Glare Analysis (rpict and EvalGlare)**

Generation of Single-Sky Glare Predictions



Rhinoceros Modeling Interface



DIVA Metrics Dialog

- DIVA can automate analysis for all five discussed metrics with the use of EvalGlare.
- EvalGlare can also be run independently of DIVA on RGBE format photos of certain rpict view types.

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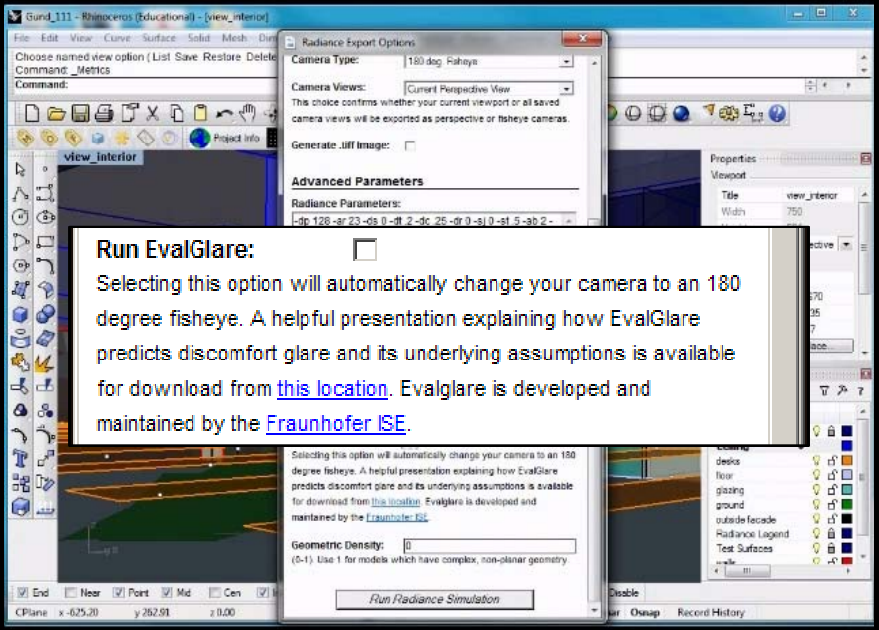
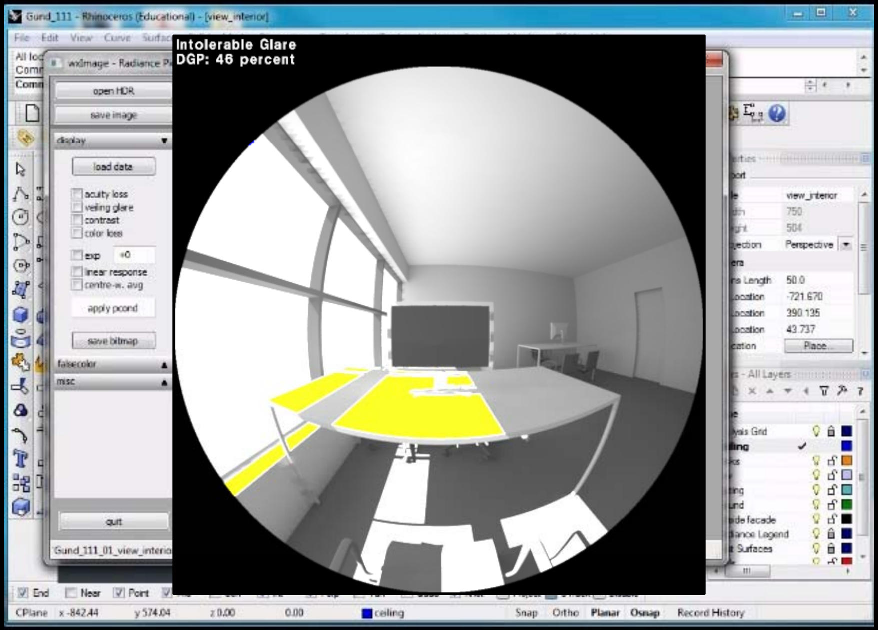
Generation of Single-Sky Glare Predictions



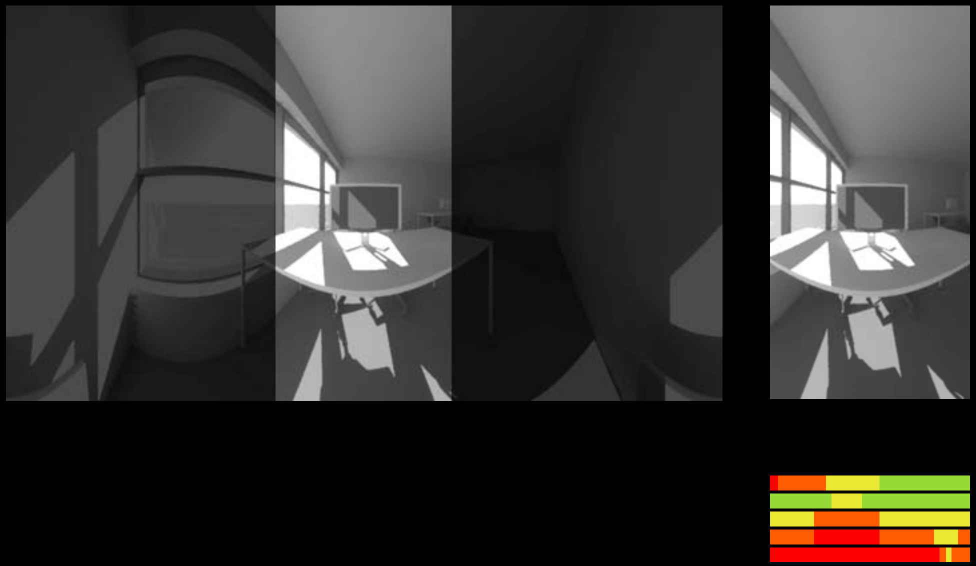
Option to Automate EvalGlare Analysis



Output by Radiance, EvalGlare and DIVA

- DIVA can automate analysis for all five discussed metrics with the use of EvalGlare.
- EvalGlare can also be run independently of DIVA on RGBE format photos of certain rpict view types.
- Original Radiance image and EvalGlare output kept for the user.

Flexible Space Use: Rotational Glare Reduction



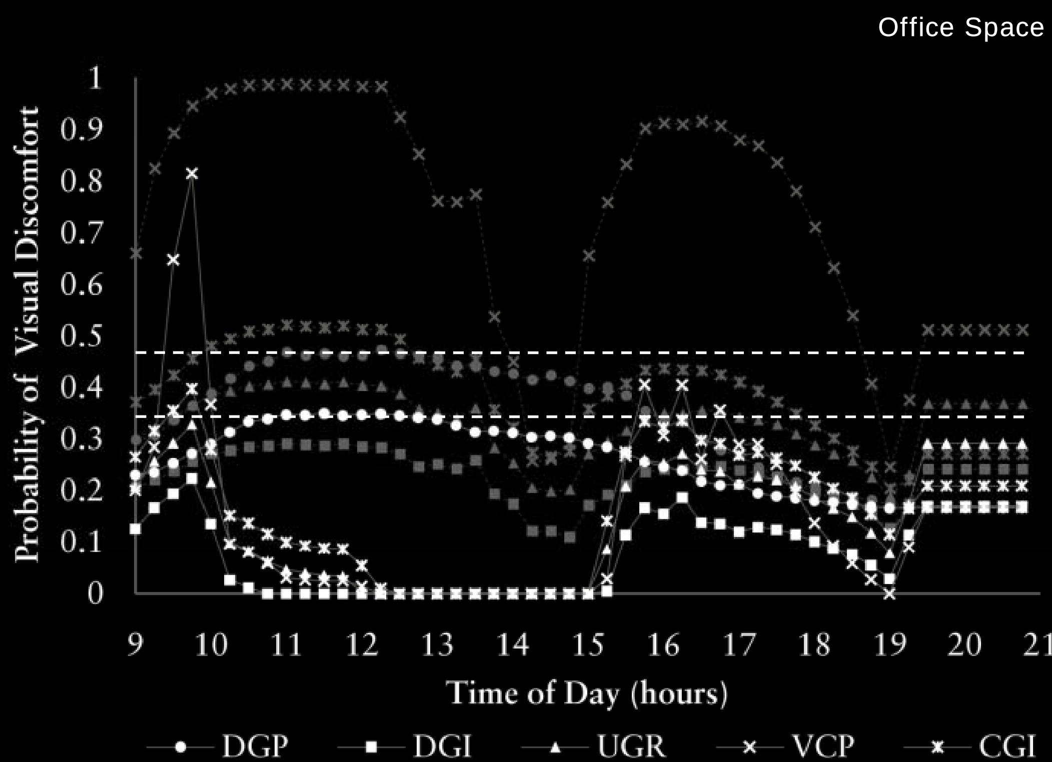
Fixed View Simulation

Range of Glare for 45 degree User Rotational Freedom

Green	Imperceptible Glare
Yellow	Perceptible Glare
Orange	Disturbing Glare
Red	Intolerable Glare

When considering glare, how could flexible use of the space and furniture influence our visual comfort analysis?

Rotational Glare Reduction Potential



September 23 Glare Predictions, +/- 45 degrees of rotational freedom

September 23 Glare Predictions, fixed view

Generating Yearly Glare Profiles

- GenDGPProfile, soon to be released by the Fraunhofer ISE!
- Works by using DAYSIM to predict eye illuminance and rpict with ab 0 for direct solar.
- Planned integration into DAYSIM 3.0 and DIVA.

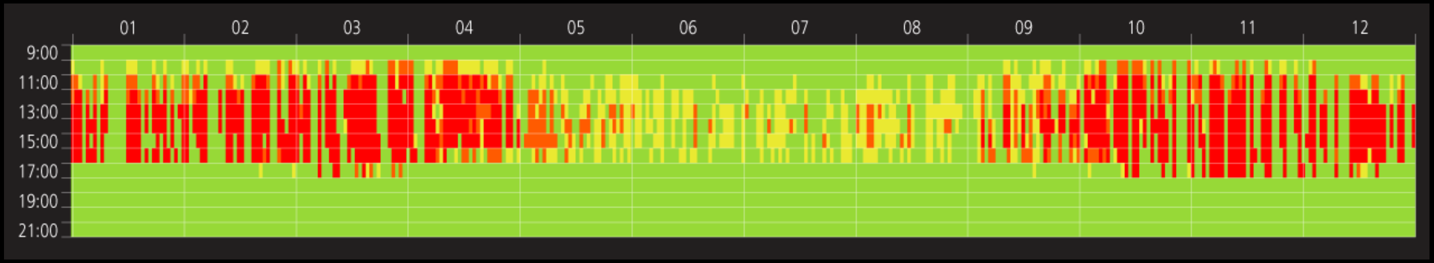
Downsides:

- Currently cannot visualize images and glare sources.

Rotational Glare Reduction Potential

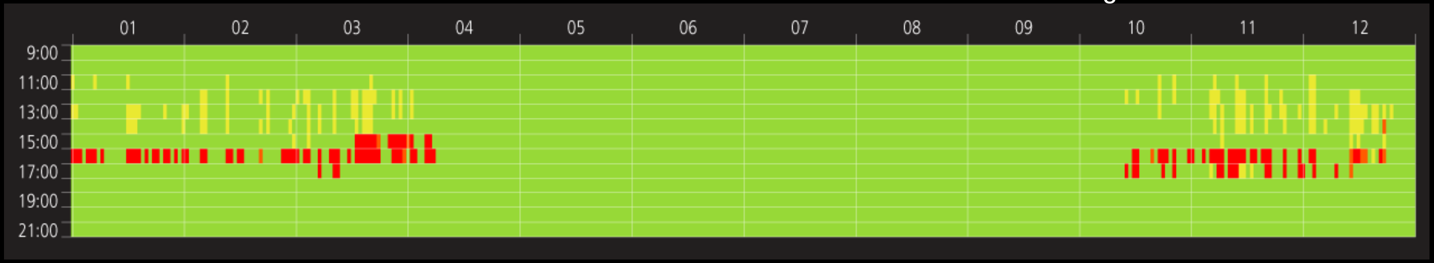
Unshaded Office Space Yearly Simulation Using Enhanced Simplified DGP Method

Yearly Falsecolor Glare Profile
No User View Freedom



	Imperceptible	Perceptible	Disturbing	Intolerable
Daylit Hours	3326	439	245	735
Percent	70.1%	9.3%	5.2%	15.4%

Yearly Falsecolor Minimum Glare Profile
+/- 45 Degrees Freedom of View



	Imperceptible	Perceptible	Disturbing	Intolerable
Daylit Hours	4476	142	11	116
Percent	94.3%	3.1%	.2%	2.4%

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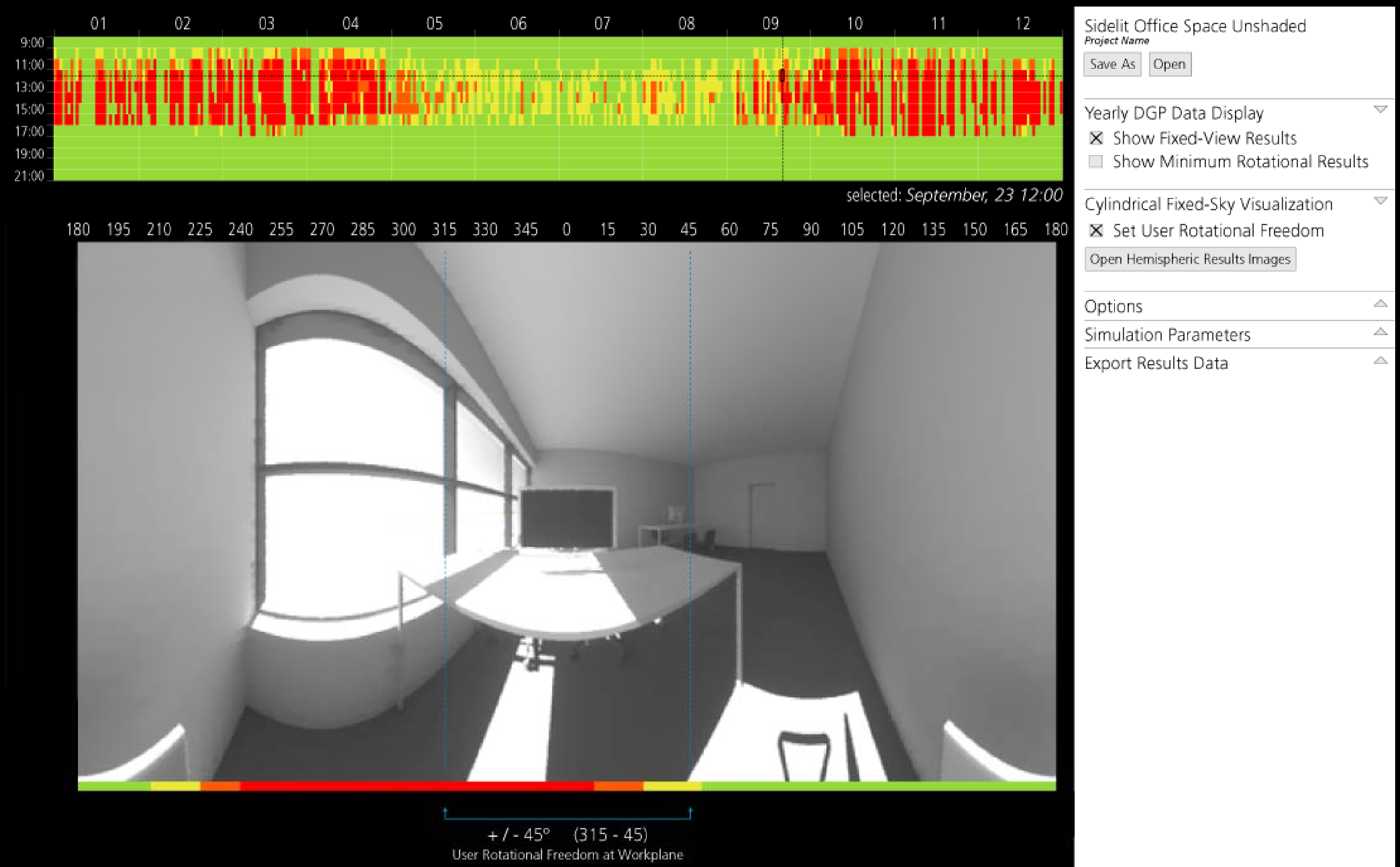
Rotational Glare Reduction Potential



- In the future, complete automation of yearly glare profiles and cylindrical glare images.

Thank you.

Questions?

Links to tools used:

- DIVA: http://www.diva-for-rhino.com/ (DAYSIM / Radiance)
- EvalGlare: http://www.ise.fraunhofer.de/downloads/software/evalglare-v0.9/view/