ASHRAE and IBPSA-USA SimBuild 2016
Building Performance Modeling Conference
Salt Lake City, UT
August 8-12, 2016

APPLICABILITY OF DGP AND DGI FOR EVALUATING GLARE IN A BRIGHTLY DAYLIT SPACE

Andrew McNeil[1,2] and Galen Burrell[2]

[1]Independant Consultant, Oakland, CA
[2]Arup, San Francisco, CA

ABSTRACT

This paper describes experience gained attempting to evaluate visual comfort in a brightly lit workspace. Simulation demonstrated that common discomfort glare metrics such as Daylight Glare Probability (DGP) and Daylight Glare Index (DGI) were ineffective for evaluating glare in a brightly illuminated space, and a subsequent mockup confirmed this conclusion. We attempt to explain why the metrics produced unsuitable simulation results.

INTRODUCTION

The project included envelope design for the renovation of an existing historical structure. The existing structure has a very large volume, with clerestory windows facing east and west.

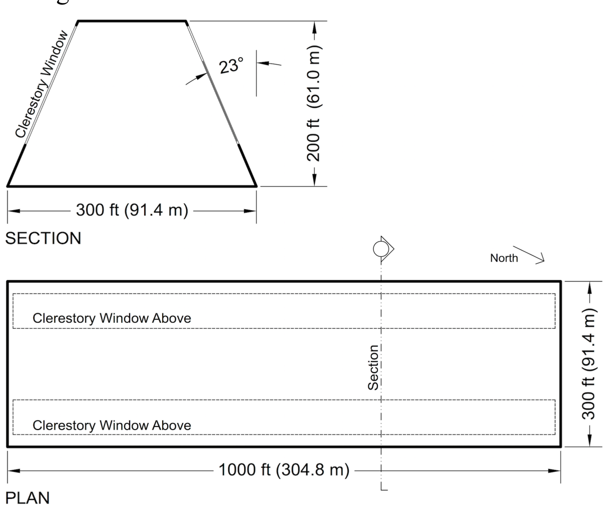

Figure 1 - Section and plan of the repurposed workshop building. The section is shown at a scale 50% larger than the plan.

The structure is being repurposed for a new use, best described as an R&D workshop for assembly-based tasks with some visual display (computer screen) based work. Hazardous material abatement required the removal of existing envelope, which provided the opportunity for the project team to design a new envelope optimized for daylight, thermal, and acoustical performance. The passive thermal strategy for the building, which resides in a mild climate, required high solar gains to the occupied zone in the morning to increase operative temperature. The desire for direct sun on the workshop floor conflicts with a conventional daylight strategy to limit direct sun in the occupied zone. This paper discusses our experience navigating this conflict, specifically with regard to assessment of visual comfort.

In recognition of the flexible nature of a workshop environment, the client allowed the design to adopt a similarly flexible approach to glare mitigation. The design includes localized shading that occupants are able to move and deploy as necessary and uses flexible furniture to allow occupants to change view directions when necessary. This adaptation component played a crucial role in our evaluation of glare given the frequency of direct sunlight for passive heating.

Glare assessment proved difficult for this bright environment where horizontal daylight illuminance is regularly as high as 10,000 lux. The investigation presented in this paper highlights the limitations of DGP and DGI, two commonly used daylight glare metrics, when evaluating glare in brightly daylit spaces. Additionally occupant testing in a mockup demonstrates that DGP isn't currently suited to evaluating glare in brightly daylit spaces.

BACKGROUND

There are two categories of glare, disability and discomfort. When a person experiences disability glare, an inability to clearly see a task prevents them from performing the task. When a person experiences discomfort glare, they are able to perform the task but experience discomfort while doing so.

Disability glare is fairly well understood and can be evaluated objectively. Discomfort glare, on the other hand, is subjective and much more difficult to determine. The two most commonly used metrics for assessing daylight glare are Daylight Glare Index (DGI) and Daylight Glare Probability (DGP).

Daylight Glare Index

DGI was developed in 1972 by Hopkinson to account for large glare sources such as a window (Hopkinson 1972). The metric is based on subjective ratings from human subjects in a daylit office space. DGI is calculated as the sum of glare contribution of each bright source as follows:

$$DGI = 10 \cdot \log_{10} 0.48 \cdot \sum_{i=1}^{n} \frac{L_{s,i}^{1.6}\ \Omega_{s,i}^{0.8}}{L_b + \left(0.07\omega_{s,i}^{0.5} L_{s,i}\right)} \qquad (2)$$

Table 1 – Relationship between DGI and subjective glare ratings (Jakubiec & Reinhart, 2012)

SUBJECTIVE RATING	DGP RANGE
Imperceptible Glare	< 18
Perceptible Glare	18 – 24
Disturbing Glare	24 – 31
Intolerable Glare	> 31

Equation 2 is similar in form to other glare formulas developed for electric lighting, including the CIE glare index (CGI), CIE unified glare rating system (UGR) and visual comfort probability (VCP). However, because electric lighting generally involves smaller sources compared to windows, these metrics tend to show poor correlation when applied to daylight glare sources.

The background luminance term in the denominator of Equation 1 causes DGI to drop as background luminance increases. Brightly daylit environments will exhibit a high background luminance, which reduces the computed DGI result. Later in this paper we will demonstrate that in a high brightness environment, DGI almost never reports glare. We suspect that this occurs because the background luminance in the denominator dominates.

Daylight Glare Probability

Developed in 2006 by Wienold, DGP is a probability that an occupant will be dissatisfied with the visual environment (Wienold and Christofferson, 2006). The metric was developed using subjective responses from 349 tests in a perimeter office with three window sizes and three shading systems. DGP is perhaps regarded as the best luminance-based metric for assessing discomfort glare from daylight, though it also is known to have shortcomings.

$$DGP = 5.87 \cdot 10^{-5} \cdot E_v \ + \ 9.18 \cdot 10^{-2} \cdot \log\left(1 + \sum_{i=1}^{n} \frac{L_{s,i}^{2}\ \omega_{s,i}}{E_v^{1.87} + P_{s,i}^{2}}\right) + \ 0.16 \qquad (3)$$

Table 2 – Relationship between DGP and subjective glare ratings (Wienold and Christofferson, 2006)

SUBJECTIVE RATING	DGP RANGE
Imperceptible Glare	<0.35
Perceptible Glare	0.35 – 0.40
Disturbing Glare	0.40 – 0.45
Intolerable Glare	>0.45

Equation 3 shows the DGP equation, which contains three terms, the third being a constant. The second term in the DGP equation has a similar form to other glare metrics.

The first term of the DGP equation, which multiplies vertical illuminance by a constant, represents a major difference from other glare metrics. This indicates that, according to DGP, high ambient lighting alone can cause discomfort, even in the absence of a bright glare source. If we set contrast based glare (second term) to zero, we can determine that at a vertical illuminance above 4,100 lux, DGP will always report disturbing glare (DGP>0.4). As a reference, vertical illuminance outside under an overcast sky is typically above 5,000 lux. Figure 1 shows the relationship between vertical illuminance and DGP when excluding the contrast (second) term of the DGP Equation.

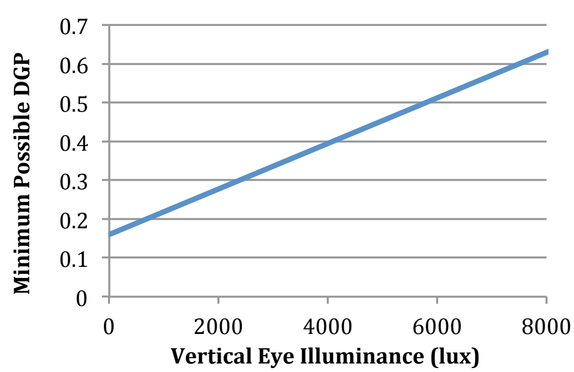

Figure 2 - Graph illustrating DGP resulting from vertical illuminance assuming no contrast-based contribution to discomfort glare.

Wienold provides a valid range for the DGP equation based on range of test cases of DGP between 0.2 and 0.8 and vertical eye illuminance above 380 lux. Wienold does not suggest that there is an upper range of vertical eye illuminance for which DGP is valid. In Wienold's experiments vertical eye illuminance peaked near 10,000 lux. Given the setup of the Wienold's experiment it is likely that the maximum vertical illuminance occurs when direct sun shines near the occupant's face.

Later in this paper we will demonstrate that in a brightly lit environment, using DGP results in almost constant reporting of glare. We suspect this occurs because of the vertical illuminance term in the DGP equation.

Glare Metric Comparisons

Jakubiec and Reinhart published a comparison of several discomfort glare metrics including DGI and DGP for a two-space, a sidelit office (south facing) and a studio with east facing clerestory windows (Jakubiec and Reinhart, 2009). Their study concluded that DGP provided the most predictable results of the glare metrics tested. Jakubiec and Reinhart also noted that DGI fails to report glare in cases when direct sun is in view, partly because source luminance is included in the denominator.

Van Den Wymelenberg and Inanici created an experimental dataset with 48 human participants. In the experiment participants created "most preferred" and "just uncomfortable" daylight conditions by adjusting motorized window shading (Van Den Wymelenberg and Inanici, 2014). Luminance maps and illuminance data were recorded in an adjacent and identical space. Results showed that DGP exhibited stronger correlation than DGI for their data set, however simpler illuminance based metrics such as vertical illuminance at the monitor and vertical illuminance at the eye outperformed both DGP and DGI at predicting glare with their dataset. Also of note, Van Den Wymelenberg and Inanici found that DGP values were relatively low for their entire study. In 98.5% of the scenes rated as "just uncomfortable" by participants, DGP predicted the same scenes as "imperceptible" or lower. The found a DGP comfort threshold of 0.25 suitable for their dataset, whereas Wienhold's proposed threshold is 0.40.

Adaptive Glare

Jakubiec and Reinhart suggested that occupants tend to adjust their view direction to avoid glare, and introduced the concept of an adaptive zone to account for this phenomenon (Jakubiec and Reinhart 2012). They noted that the amount of adjustment possible depends "on the space type, furniture layout and culture of a space."

PRELIMINARY GLARE SIMULATIONS

Criteria

We started the project by talking with our client about daylight quantity and quality, specifically how more flexible working conditions afford a wider range of occupant acceptance. We then agreed upon four possible types of functional spaces within building, and proposed corresponding design criteria for visual, thermal and acoustic comfort. An adaptive zone, or degree of rotational freedom, was proposed for each space based on client input. Flexible task environments were allowed 360° of rotational freedom, which means occupants can orient themselves in any direction to minimize glare.

Table 3 - Proposed space uses and initial ranges for daylight criteria using DGP for glare assessment.

USE	ILLUMINANCE RANGE	DGP RANGE	ADAPTIVE ZONE
Typ. Office	100-2000 lux	< 0.35	± 45°
Flex. Office	100-2000 lux	< 0.35	± 360°
Workshop	100-10,000 lux	< 0.40	± 360°
Atrium	100-20,000 lux	< 0.45	± 360°

Table 3 shows the space categories and associated ranges for daylight metrics. The client directed us to assume a workshop function and associated daylight metric ranges for the design of the space. Illuminance ranges were chosen based on an informal survey of anecdotal experience of our colleagues. The DGP thresholds are what Wienhold describes for class A (<0.35), class B (<0.40), and class C (<0.45) offices (Wienhold 2009).

We also discussed with our client a layered strategy for daylight mitigation. Specifically, the building skin would provide a base level of mitigation, flexible human-scale shading layers would provide additional mitigation. For example, a wheeled canopy might be used to cover the control station and display screen for a CNC controlled tool. Or an occupant might choose to wear a brimmed hat to reduce glare.

Simulation Methodology

We used the daylight coefficient method in Radiance to generate hourly renderings from a viewpoint facing four directions (north, south, east, and west). The view point was taken in the center of the wokshop. Since we assumed that occupants had 360° rotational flexibility, we reported the lowest of the four DGP values as adaptive DGP for the viewpoint. Hours of operation were 8 AM to 10 PM, but we limited our analysis to daylight hours within this range. Horizontal illuminance was simulated using a daylight coefficient method at

1000 randomly located points over the floor of the workshop. Randomized points were used to reduce bias induced by what would otherwise be a course grid in a large space. Reported horizontal illuminance is an average over the points for a specific time.

Simulation Results

Hourly scatterplots of Adaptive DGP vs. horizontal illuminance were produced to illustrate the daylight signature, or performance, of various facade strategies. Each point in the scatterplot represents conditions for one hour of the year. Boxes that represent the proposed criteria ranges were overlaid on the plots to illustrate how many hours fell within proposed ranges and to indicate which metric caused them to fall outside the acceptable comfort range. Subjective glare ratings are also placed along y-axis at the threshold recommended by Wienohld. Figure 3 shows the scatterplot for one of the façade schemes.

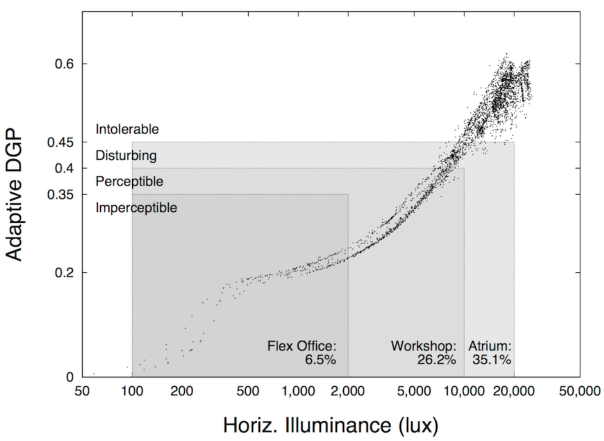

Figure 3 - Annual scatterplot of hourly adaptive DGP vs. horizontal illuminance. Shaded boxes show proposed range for each use with percent of hours within range depicted in the plot.

Immediately visible in Figure 3 is a strong apparent correlation between horizontal illuminance and DGP. Figure 4 is similar to Figure 3 except that DGP is plotted for all four directions instead of just the direction with lowest DGP.

The range of DGP values expand, but the apparent correlation persists. According to these results it is not possible to have a situation where horizontal illuminance is 10,000 lux and visual comfort according to DGP is less than disturbing. Anecdotal experience indicates that conditions outside under a 10,000 lux overcast sky can be visually comfortable. The results of simulations using DGP led us to question the validity of the metric for our situation. Specifically the absolute, vertical illuminance based term causes results is high reporting of glare for a brightly daylit space.

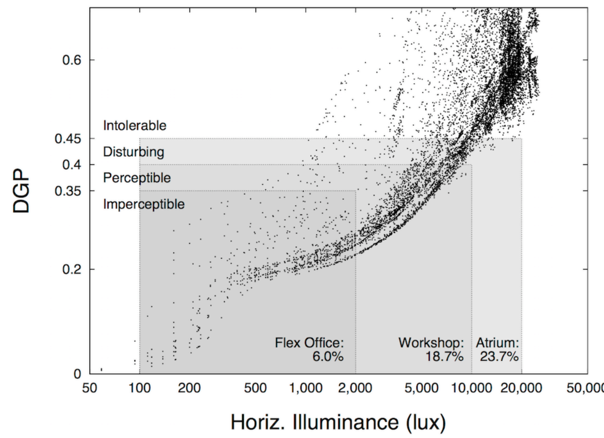

Figure 4 - Annual scatterplot of hourly DGP for all four view directions vs. horizontal illuminance. Shaded boxes show proposed range for each use with percent of hours within range depicted in the plot.

Unsatisfied with DGP, we re-analyzed the simulation results using DGI as the glare metric. Table 4 contains the revised ranges for each functional use.

Table 4 - Proposed space uses and revised ranges for daylight criteria using DGI for glare assessment.

USE	ILLUMINANCE RANGE	DGI RANGE	ADAPTIVE ZONE
Typ. Office	100-2000 lux	< 20	± 45°
Flex. Office	100-2000 lux	< 20	± 360°
Workshop	100-10,000 lux	< 24	± 360°
Atrium	100-20,000 lux	< 28	± 360°

The previously simulated hourly renderings were reprocessed using DGI to evaluate glare. The adaptive component remained the same, so we reported the lowest DGI of the four view directions as adaptive DGI.

Figure 5 is the annual scatterplot using adaptive DGI to evaluate glare. Interestingly this metric has no obvious apparent correlation with horizontal illuminance. Also, adaptive DGI indicates that occupants will always be able to face a direction where they will experience imperceptible glare.

The scatterplot in Figure 6 contains data points for all four views directions. Again, no apparent correlation between horizontal illuminance and DGI is obvious.

The project's climate is known to exhibit relatively abundant sunshine, and anytime the sun is shining it would be visible in two of four view directions. Interestingly only 13.5% of values have a DGI above 24 (disturbing glare), which indicates that there are numerous instances where the sun is in view, and glare is rated only perceptible or imperceptible. Recall that Jakubiec and Reinhart demonstrated that DGI fails to report glare in cases when direct sun is in view (Jakubiec and Reinhart 2012).

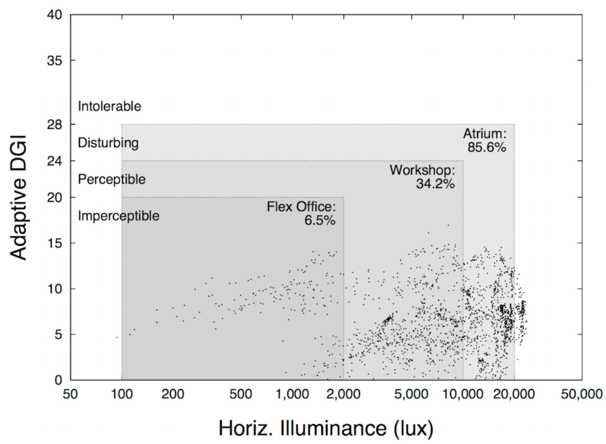

Figure 5 - Annual scatterplot of hourly adaptive DGI vs. horizontal illuminance. Shaded boxes show proposed ranges for each use with percent of hours within range depicted in the plot.

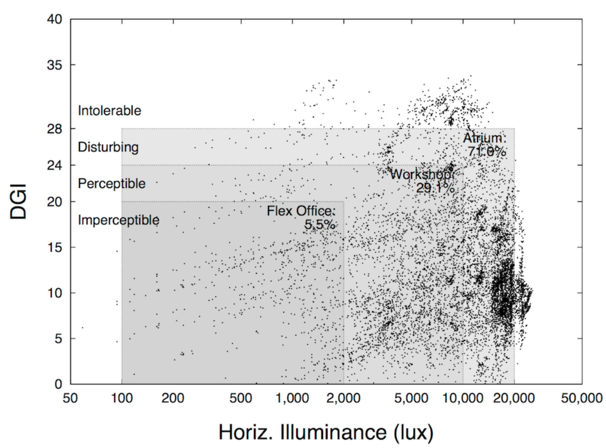

Figure 6 - Annual scatterplot of hourly DGI for all four view directions vs. horizontal illuminance. Shaded boxes show proposed ranges for each use with percent of hours within range depicted in the plot.

In summary, for our brightly lit workspace, Daylight Glare Probability (DGP) nearly always reported intolerable glare regardless of view direction because DGP is weighted so heavily on vertical illuminance. Conversely, Daylight Glare Index (DGI) nearly always reported less than imperceptible glare, even when facing direct sun, because of the average luminance term in the denominator of the DGI equation. We didn't have confidence in either DGP or DGI for this project.

GLARE TESTING IN A MOCKUP

To facilitate early stage evaluation of several skin options, the client built a scale mockup of the workshop. Given our difficulty finding a suitable glare metric we arranged to use the mockup for glare testing, by means of both subjective evaluation and measurement.

The mockup measured approximately 30 ft by 40 ft and was divided into four 30 ft by 10 ft bays using a grey fabric curtain that extended from floor-to-ceiling and wall-to-wall.

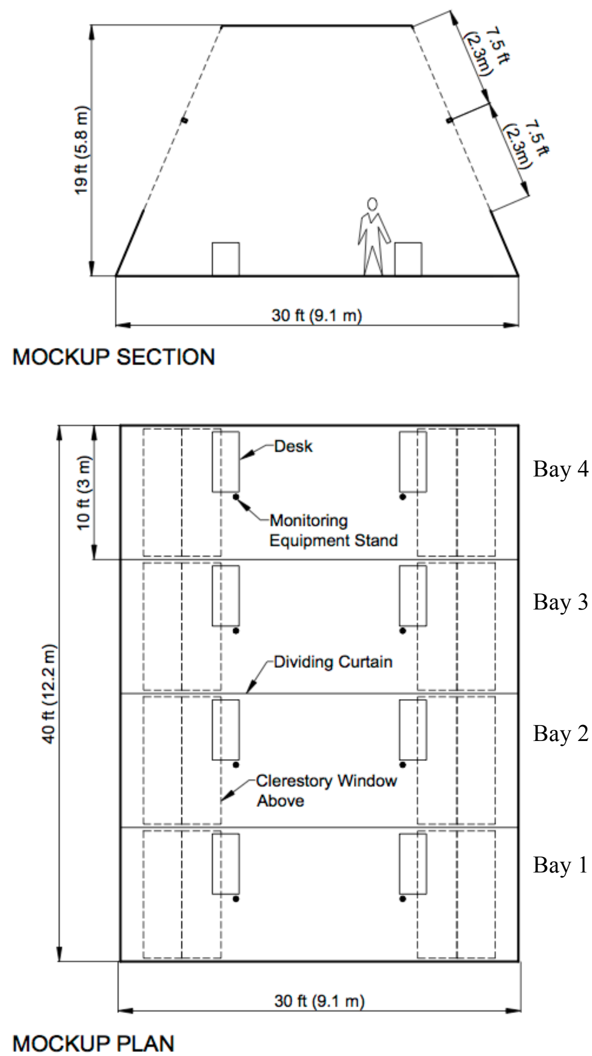

Figure 7 - Section and plan of the mockup.

The initial evaluation was performed with a different clerestory skin in each bay. Three bays had clear ETFE in the clerestory with varying density of opaque frit to represent a wide range of visible light transmission. The fourth bay had a diffusing ETFE covering for the clerestory.

Table 5 – ETFE Transmission Characteristics

BAY	ETFE COLOR	FRIT COLOR	FRIT COVER	VLT (%)
1	Clear	White	50%	70%
2	Clear	Silver	63%	59%
3	Clear	Dark Grey	46%	58%
4	White/Opaque	Silver	46%	5%

We set up eight desks, two in each bay, one facing the east clerestory and one facing the west clerestory. At the time of testing there was no shading in the clerestory windows or local to the occupant's desk. At each desk a Raspberry Pi camera system with fisheye lens recorded HDR images every five minutes. HDR images were processed for glare metrics using Wienold's evalglare, with default settings. Figure 8 contain an example of an HDR image along with a falsecolor representation. Also a photometer at each desk measured horizontal illuminance, recorded every minute. A sunshine pyranometer on the roof recorded diffuse and global exterior irradiance every minute.

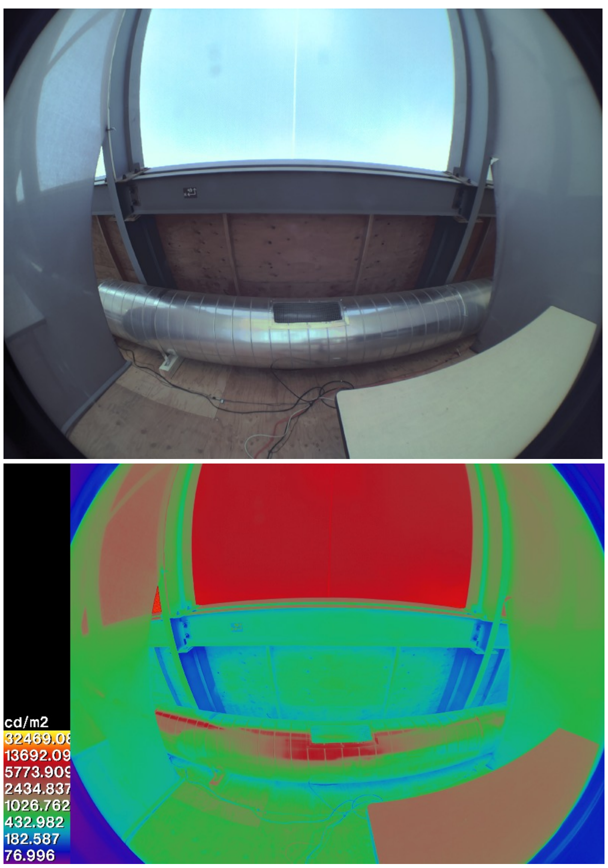

Figure 8 - Tone mapped HDR image and false color image generated by the Raspberry Pi camera at 11:00 daylight savings time on March 15th. This desk is in bay 3 and faces west.

Figure 9 – A photo of a test subject in one bay of the mockup. The equipment stand at the corner of the desk holds the raspberry pi camera and horizontal illuminance sensor.

The survey included the following four questions:

1. At which desk are you currently sitting?
2. Does your laptop have a glossy or matte screen?
3. Please rate the glare you experience working on your laptop.
   (1) Imperceptible Glare - You don't notice any glare.
   (2) Perceptible Glare - Minor glare, which does not impact your ability to work.
   (3) Disturbing Glare - You would lower a shade or move if you could. You can still work, but your productivity is reduced.
   (4) Intolerable Glare - The glare is so bad you can't work no matter how hard you try.
4. Please rate the lighting condition as comfortable or uncomfortable for working on your laptop.

There was also a free response section for subjects to enter comments.

Test subjects consisted of project team members including architects, engineers, construction managers and client representatives involved with the project. There were 16 test participants, and the test procedure was completed 21 times. Some participants completed the testing more than once, under a different sky condition or different time of day from their first participation. There were a total of 156 survey responses. There are fewer than the expected 168 responses because the camera at one desk was not operational for a period of time during testing, so the desk was skipped.

Testing occurred between the hours of 7:00 AM and 3:00 PM, during the first two weeks of March. Sky conditions included overcast, clear and partly cloudy.

Mockup Results

DGP values recorded during occupied testing ranged from 0.195 to 1.0, DGI values ranged from -20.0 to 24.4 (surprisingly, negative DGI values are technically possible), and horizontal illuminance ranged from 360 lux to 45,700 lux. Figure 10 shows the distribution of glare ratings provided by test subjects at all eight desks.

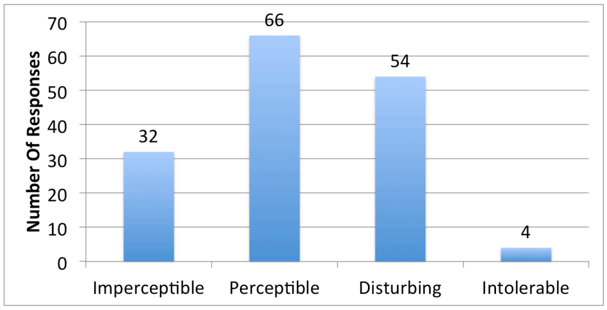

Figure 10 - Distribution of glare rating responses.

Figure 11 contains a scatterplot of DGP versus horizontal illuminance for all eight desks. The apparent correlation between illuminance and DGP is similar to that in the simulation results.

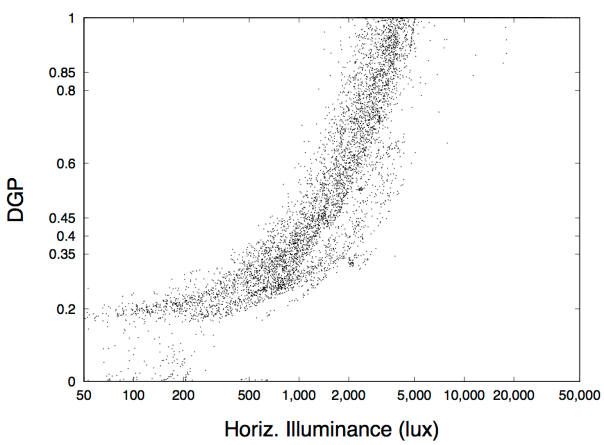

Figure 11 - Scatter plot of DGP vs. horizontal illuminance measured in the mockup (similar to the plots of simulation results in the previous section).

Figure 12 shows a plot of recorded DGP versus subjective glare rating for data collected in our mockup. The linear fit has an r-squared value of 0.36.

Our data suggests a DGP threshold of 0.85 suitable for determining distinguishing between comfort and discomfort in a brightly daylit space such as ours. 91% of data where DGP was below 0.85 subjects reported as either imperceptible or perceptible. When DGP was above 0.85, subjects rated glare as disturbing or intolerable 57% of the time.

Figure 13 contains a scatterplot of DGI vs. glare rating. Our data showed no correlation between DGI and glare rated by test subjects. In fact, only once did we record a DGI above the recommended comfort threshold during occupant testing, and the test subject rated the glare as simply ‘perceptible’.

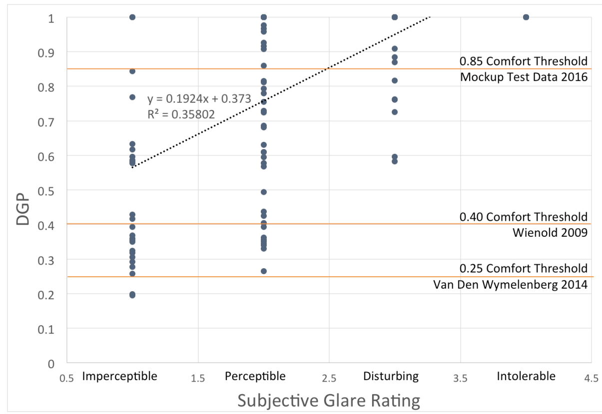

Figure 12 - Scatterplot of recorded DGP vs. glare rated by test subjects with linear fit.

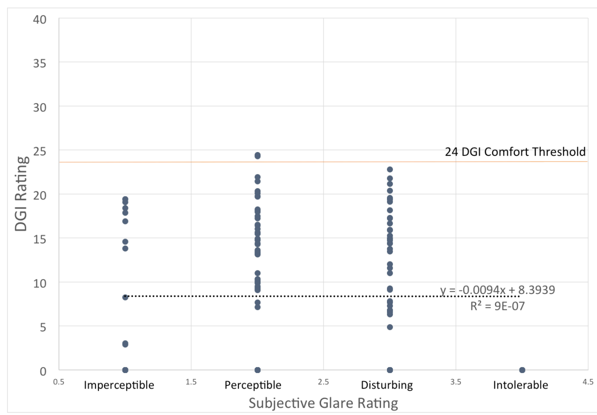

Figure 13 - Scatterplot of recorded DGI vs. glare rated by test subjects with linear fit.

DISCUSSION

Readers may notice deficiencies in our methodology. For example, using project team members as test subjects is problematic and the Raspberry Pi fisheye lens did not provide a full 180 fisheye image. However, the mockup results give credibility to the simulation procedure. Further, our opinion is that the mockup results raise serious questions about the applicability of existing glare metrics for wide-ranging spaces.

Comparing results to other experimental studies

Ours is the third experimental study (of which we are aware) that found a reasonably strong correlation between DGP and subjective glare assessment.

Wienold's formative experiment exhibitied an r-squared value of 0.94 (which is only so high because it is the data used to create the DGP equation). Van Den Wymelenberg and Inanici found an correlation between DGP and glare ranting with an r-squared value of 0.22 in their (the strongest correlation in their study was 0.260). Our correlation with a r-squared of 0.36 if fairly strong for this type of study, though might have been helped by using a four-point scale for assessment.

In comparison to our derived DGP threshold of 0.85, Wienold recommended a threshold of 0.4 based on his formative data, and Wymelenberg and Inanici found a threshold of 0.25 suitable for their experimental data. Wienhold provides validity range for DGP between 0.2 and 0.8. The three thresholds span nearly the entire range of validity. Further, our threshold lies outside of the range of validity. We question whether any DGP comfort threshold is universally applicable.

It seems to us that DGP needs to be reformulated to address a wider range of conditions. Perhaps the vertical illuminance term, specifically, should be revisited.

Our results show no correlation between DGI and subjective glare assessment. Thus, we have no confidence in DGI as a metric for assessing glare.

Discussion of implications specific to this project

For our project, we need a metric to evaluate glare as the design develops. Since we found a correlation between DGP and subjective glare rating, it is tempting to use DGP with our mockup-specific threshold of 0.85. However, given the wide-ranging thresholds found in just three experimental studies we don't have confidence that the threshold we found is sufficiently robust to be valid as the design changes.

Without confidence in DGI or DGP, we are looking into contrast-based disability glare metrics to evaluate glare in our brightly daylit space. We are drawing inspiration from veiling luminance, veiling reflections and monitor contrast ratios, though none of these are sufficiently developed to share at the moment. Luckily for this project we have the luxury of a mockup that will be updated as the design of the building evolves.

CONCLUSION

Simulations indicated that DGI and DGP weren't well suited for assessing glare in a bright daylit workshop space. Occupant testing in a mockup corroborated our simulation findings. The design of the workshop facility will progress using both simulations and the experimental mockup to test and validate glare assessment methods.

ACKNOWLEDGMENTS

We are grateful for assistance from colleagues at Arup, including Felix Weber, Cole Roberts, Sandra Fiz, Ingrid Chaires, and Alexej Goehring. The rest of the project team, including individuals representing the architect, contractor, and owner must remain anonymous to protect project confidentiality, though we are grateful for the significant contributions made by these anonymous individuals.

NOMENCLATURE

E_v = Vertical illuminance at the eye

L_b = Average background luminance in the field of view

$L_{s,i}$ = Luminance for source i

$P_{s,i}$ = Position index

$\omega_{s,i}$ = Solid angle for source i

$\Omega_{s,i}$ = Solid angle for source i modified by a position factor for the source

REFERENCES

Hopkinson R. 1972. Glare from daylighting in buildings. Applied Ergonomics 3,4: 206-215.

Jakubiec, J.A., Reinhart, C.F. 2012. The 'adaptive zone' – A concept for assessing discomfort glare throughout daylit spaces. Lighting Research & Technology 44 (2) 149-70.

Jakubiec, J.A., Reinhart, C.F. Van Den Wymelenberg, K. 2015. Towards an integrated framework for preicting visual comfort conditions from luminance-based metrics in perimeter daylit spaces. Building Simulation 2015. Hyderabad, India

Van Den Wymelenberg, K.G., Inanici M.N. 2014.A Critical Investigation of Common Lighting Design Metrics for Predicting Human Visual Comfort in Offices with Daylight. Leukos10:145-164

Wienold, J., REETZ, C. and KUHN, T., 2004. Evalglare: a new RADIANCE-based tool to evaluate glare in office spaces. In 3rd International Radiance Workshop.

Wienold, J. and Christoffersen, J., 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Buildings, 38(7): 743-757.

Wienold, J. 2009. Dynamic Daylight Glare Evaluation. Proceedings of Building Simulation 2009, Glasgow.