The 'adaptive zone' – A concept for assessing discomfort glare throughout daylit spaces

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Abstract

Discomfort glare is an underutilized parameter in contemporary architectural design due to uncertainties about the meaning of existing metrics, how they should be applied and what the benefits of such analysis are. Glare is position and view direction-dependent within a space, rendering it difficult to assess compared to conventional illuminance-based metrics. This paper compares simulation results for five glare metrics under 144 clear sky conditions in three spaces in order to investigate the ability of these metrics to predict the occurrence of discomfort glare and to hence support the design of comfortable spaces. The metrics analyzed are Daylight Glare Index, CIE Glare Index, Visual Comfort Probability, Unified Glare Rating, and Daylight Glare Probability. It is found that Daylight Glare Probability yields the most plausible results. In an attempt to deal with multiple positions and view directions simultaneously, the concept of an 'adaptive zone' is introduced within which building occupants may freely adjust their position and view in order to minimize the effect of glare. The spatial and directional extents of the adaptive zone depend on furniture layout and the freedom of occupants' tasks. It is found that applying the adaptive zone concept to a sidelit office with manually operated venetian blinds reduces the predicted hours of intolerable discomfort glare from 735 to 18 occupied hours per year and increases the annual mean daylight availability from 40 to 72 percent.

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Definition of relevant terms

L_s	luminance of the glare source (cd/m^2)
ω	solid angle of the glare source (sr)
ω_{pos}	the solid angle of the glare source modified for its position in the field of view (sr)
P	weight factor based on position in a viewing hemisphere, the Position index
E_v	total vertical eye illuminance (lux)
Ω	solid angle of a viewing hemisphere subtended by glare sources (sr)
L_b	background luminance determined by taking the average luminance of areas not identified as glare sources (cd/m^2)
L_{adapt}	adaptation luminance (cd/m^2)
$L_{exterior}$	average exterior luminance (cd/m^2)
L_{window}	average window luminance (cd/m^2)
E_d	direct vertical illumination (lux)
E_i	diffuse vertical illumination (lux)

1. Introduction

A desire strongly returning to contemporary architecture is to create comfortable and energy-efficient daylit buildings. Daylight has been shown to improve health, awareness and feelings of well-being in spaces where it is present;[1] however, simply maximizing daylight is potentially undesirable. The suitability of a space for inhabitation can be compromised if glare is experienced in its use. Glare is a measure of the physical discomfort of an occupant caused by excessive light or contrast in a field of view. It is hence dependent on the luminance distribution seen by an observer which may correlate very poorly with work plane illuminance metrics such as the daylight factor or daylight autonomy, especially in toplit spaces.[2] Glare is typically categorized as either disability glare, discomfort glare or veiling glare. Disability glare measurably impairs vision, reducing the contrast of the retinal image by the presence of a very bright light source in the field of view.[3] Discomfort glare, in opposition to disability glare, is merely irritating, though its root cause is the same — a bright, visible light source. As brightness, size, and prominence of a glare source increase, discomfort glare turns into disability glare. Veiling glare has to do with the origin of the glare source and occurs when a bright light source is reflected by a surface, for example when light falling on a monitor display screen obscures the transmitted image.

While many architects have sensibilities for other subjective factors concerning the light within a space such as how ‘pleasing’ a space is or what a ‘good’ view is, they lack an intuition for what amount of glare is acceptable. Discomfort glare is even more difficult to discern than disability and veiling glare, as it does not initially produce observable effects such as the inability to perform a task.[4] To further complicate matters, there is some evidence that suggests that interesting views increase tolerance to glare.[5] To improve our ability deal with glare, there has long been an interest in quantifying glare in buildings using the concept of a ‘glare index’. A glare index is a numerical expression derived from the luminance distribution in the field of view of an observer. As within the context of a glare index, disability and discomfort glare are separated only by the extremes of the brightness of the glare sources, their sizes and their prominence in the field of view. An occupant will always feel discomfort when experiencing disability glare; therefore, preventing against discomfort glare mostly precludes the possibility of experiencing disability glare. This is reflected in most glare metric calculations which predict the probability of experiencing visual discomfort, rather than visual disability, in a space.

With modern buildings’ increased use of glazing, the interest in and need to quantify and avoid discomfort glare have increased in tandem. Historically, there have been more than half a dozen separate attempts to quantitatively predict glare, each developed under varying experimental circumstances and for different purposes. Thus far, there have been only very limited attempts to directly compare predictions from these metrics and to define their ranges of applicability. As a result, it is currently rather difficult for a designer to decide which glare metric to use, if any. For example, green building rating systems, such as the US Green Building Council’s LEED system, avoid the application of glare indices altogether.[6] The only widely implemented glare prevention strategy is to generally keep direct sunlight away from vertical task planes such as computer monitors and horizontal task planes such as desks. This recommendation mainly addresses disability and veiling glare. In order to avoid discomfort within the field of view, the most frequently quoted rule is to avoid luminance ratios larger than 1:3 and 3:1 between the work surface and the near visual field and 1:10 and 10:1 in the far visual field. To the authors’ knowledge, these recommendations are not based on any human subject studies, and there is a general attitude within the design community that they are too stringent for daylit spaces, and thus are applicable only for electrically lit environments. Thereby one is left wondering whether the design community should begin adopting more sophisticated glare analysis methods?

The increased use of three dimensional digital models during building design combined with enhanced availability and usability of validated, physically based daylight simulation engines[7] means many architectural design teams now have access to high dynamic range visualizations of existing and unbuilt spaces. One of the uses of these visualizations is to assess the likelihood of glare in spaces using the above mentioned glare indices. In fact, the Radiance backward raytracer has supported this functionality since 1993 using the 'findglare' program.[8] However, this functionality is rarely used by practitioners, likely due to the above mentioned confusing number of competing metrics available and little advice as to how and for what types of spaces these metrics should be investigated.

On a practical level, a second barrier towards the use of glare metrics in building design is that glare depends not only on the current sky condition but also on the position and view direction of an observer in a space, i.e. on a sunny day one might experience severe glare facing a window but be perfectly comfortable facing towards the inside. A further example is that changing a seating position to be closer to a partition might obscure a luminance source which would otherwise cause glare. In order to introduce glare into rating systems it is hence desirable to summarize the overall glare sensation spatially and over the course of a year.

This paper is therefore an attempt to make recommendations for determining the probability of discomfort glare in daylit spaces based upon simulations or real-world interior scenes. In examining the current state of various glare simulation processes and metrics, the paper compares predictions from five glare indices, Daylight Glare Index (DGI), CIE Glare Index (CGI), Visual Comfort Probability (VCP), Unified Glare Rating (UGR), and Daylight Glare Probability (DGP). Following a review of the five glare metrics, the methodology section describes a large parametric simulation effort to evaluate predictions of these glare metrics in three daylit scenes. By analyzing glare for multiple view-directions and locations, a visualization of spatial comfort analysis which has the capacity to support design decisions is created. Pursuant to reviewing the simulation results, the discussion makes specific recommendations of which metrics are useful under what circumstances. The concept of an 'adaptive zone' which accounts for occupant freedom to change position and view direction is then introduced as a method to predict occupant behavior under daylit conditions in response to discomfort glare and to assess the overall glare sensation throughout a space.

2. Review of existing glare metrics

2.1 Basis of discomfort glare

Glare is typically expressed as the ratio of the size, location and luminance of glare sources in a field of vision when compared to the average luminance not inclusive of the glare source. This can be expressed as a simplified equation,

$$Glare = \sum_{i=1}^{n} \frac{L_{s,i}^{exp} \omega_{s,i}}{L_b^{exp} P_i^{exp}} \tag{1}$$

where exp is a weighting exponent applied to each variable. It can be observed that, in a generalized fashion, larger and brighter glare sources (L_s) increase glare probability, where ω is the solid angle size of a glare source. A brighter average or background luminance (L_b) decreases the probability of glare, and the further away a glare source is from the center of the visual field, the less likely you are to be disturbed by it. The value of P, the position index, grows larger as a glare source approaches your visual periphery with a value of one being perfectly centered in your vision. The position index was originally developed by Guth, and it is a convenient way to weigh a glare source based on its location in a view (Figure 1)[9]. From this basic concept of glare, many different datasets developed through subjective polling of space occupants have led to different equation fits. Therefore, the conditions under which each metric gathered its user data is important in evaluating its applicability to a given situation.

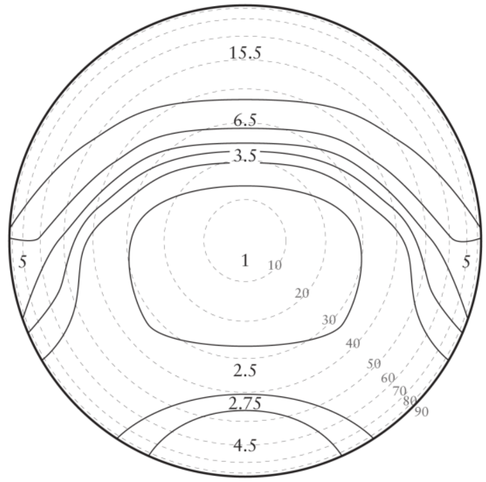


Figure 1 Selected values of the Guth position index plotted on top of a 180 degree hemispheric view projection. The dashed lines indicate the angle between the view center and an object. The solid lines indicate major divisions of values of the Guth index. As an object moves further from the center of the view, its Guth index increases.

2.2 Daylight Glare Index (DGI or Cornell Equation)

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

The Daylight Glare Index metric was originally formulated by Hopkinson in 1972 based upon earlier work he performed at the Building Research Station for small glare sources.[4] DGI considers the possibility of large glare sources, specifically diffuse sky visible through a window. Hopkinson's metric was derived from human subject studies in daylit interiors in which the sky brightness was measured and given a size and position index; however, it is not considered to be reliable when direct light or specular reflections are present in a field of view. This is because Hopkinson's consideration of glare relies only upon visible sky brightness through a window and not interior specular reflections or direct sources of light. DGI correlates the source luminance, size and its position in the field of view against the background luminance and a small percentage of the source luminance which compensates for additional eye adjustment to the visible luminance, resulting in a value where any number greater than 31 corresponds to intolerable glare and a value less than 18 suggests that glare is 'barely perceptible'. Hopkinson also recognized the importance of adding new considerations to his metric by surveying those he asked to make subjective observations of spaces. He listed an evaluation of view and the consideration of interior specular reflections as the two most likely important missing factors in his formula.[4]

2.3 New Daylight Glare Index (DGI_N)

$$DGI_N = 8 \times \log_{10} 0.25 \sum_{i=1}^{n} \frac{L_{exterior,i}^{2} \Omega_{s,i}}{L_{adapt} + 0.07\left(\sum_{i=1}^{n} \omega_{s,i} L_{window,i}^{2}\right)^{0.5}} \qquad (3)$$

The New Daylight Glare Index, developed by Nazzal in 2001,[10] is a modification of Hopkinson's original equation which introduces several new variables into the metric: L_{adapt}, adaptation luminance, the mean luminance of the surroundings; $L_{exterior}$, the mean exterior luminance; and L_{window}, the mean window luminance, treating the window as a uniform glare source. Exacting geometric information on the dimensions of each window and its distance from the viewing location as well as the mean exterior luminance are necessary for its calculation. While this information is often available, it is potentially cumbersome as this data is not inherently available directly from luminance images. DGI_N's results are correlated and validated only against those of the original DGI method; no significant human validation studies have been performed at this time, so DGI_N may contain substantial errors in correlation to discomfort that are unknown.[11] DGI_N specifies exacting measuring techniques utilizing three sensors which measure the shielded window illuminance, total vertical illuminance and the total exterior vertical illuminance which is a great clarifying measure that somewhat allows the consideration of direct sunlight in the scene; however, it is still subject to the same weaknesses as the original DGI, that specular reflections and direct luminance sources are not adequately considered.

2.4 CIE Glare Index (CGI)

$$CGI = C_1 \times \log_{10} C_2 \frac{\left(1 + \frac{E_d}{500}\right)}{E_d + E_i} \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{P^2} \tag{4}$$

Published in 1979, the CIE Glare Index was an attempt by Einhorn to develop a formula that took into account all peer-reviewed glare research in order to be used as a standard glare index adopted by the Commission Internationale de l'Eclairage (CIE).[12] Care was taken that the summation of solid angles of luminance sources (ω) were to an exponent of one for mathematical clarity. Adaptation to glaring sources is a function of the ratios of diffuse and direct vertical eye illuminance which are multiplied by the summation in the equation. CGI has two weighting coefficients C_1 and C_2; for C_1 being 8 and C_2 being 2, factors defined by Einhorn, values greater than 28 are intolerable while those less than 13 are imperceptible, a slightly lower threshold for discomfort as compared to DGI. These values correlate with the later-discussed UGR metric, also adopted by the CIE. There were no user perception studies conducted during the development of the CGI metric; however, correlation studies were performed with other contemporary glare metrics.

2.5 Visual Comfort Probability (VCP)

$$VCP = 279 - 110[\log_{10} \sum_{i=1}^{n} \left[\frac{0.5 L_{s,i}\left(20.4\, \omega_{s,i} + 1.52 \omega_{s,i}^{0.2} - 0.075\right)}{P \times E_{avg}^{0.44}}\right]^{n^{-0.0914}} \tag{5}$$

Visual Comfort Probability expresses "the probability that a normal observer does not experience discomfort when viewing a lighting system under defined conditions."[13] It is defined by the Illuminating Engineering Society of North America (IESNA) as a series of separate equations which are combined via a numerical approximation shown in Equation 5. For ranges of VCP between 20 and 85, Equation 5 is acceptable. VCP essentially weighs the glare source luminance and size against its position in the scene and the average illuminance for a viewing solid angle of five steradian. It is only valid for typically-sized, ceiling-mounted, artificial lighting installations with uniform luminances, as it was derived under these conditions. It is not valid for very small or very large glare sources, and therefore should not be used to evaluate glare from daylight sources nor compact types of luminaires such as halogens.[13] VCP evaluates in a numerical range from 0 to 100, the percentage of people who would feel comfortable under similar lighting circumstances.

2.6 CIE Unified Glare Rating System (UGR)

$$UGR = 8 \times \log_{10} \frac{0.25}{L_b} \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{P^2} \tag{6}$$

The Unified Glare Rating[3] was developed in response to difficulties in calculating direct illuminance required for the earlier CGI metric. Thus, visual adaptation to direct sources of light in the scene is not considered in this metric; however, the CIE technical committee 3-13 created the UGR formula such that its abstraction has "little effect when [...] applied to rooms having illuminances within the usual range recommended for working interiors" which assumes that the background luminance (L_b) will not be bright enough to cause discomfort. In essence, UGR is a simplification of CGI for computational ease; however, with current technologies it is now easy to separate direct and diffuse illuminances so that this simplification is no longer necessary. UGR uses the same numerical scale as CGI. Any value greater than 28 is intolerable while values less than 13 are considered imperceptible. The exact testing and user polling conditions that lead to UGR's derivation are not clearly discussed in the technical report released by the CIE.

2.7 Daylight Glare Probability (DGP)

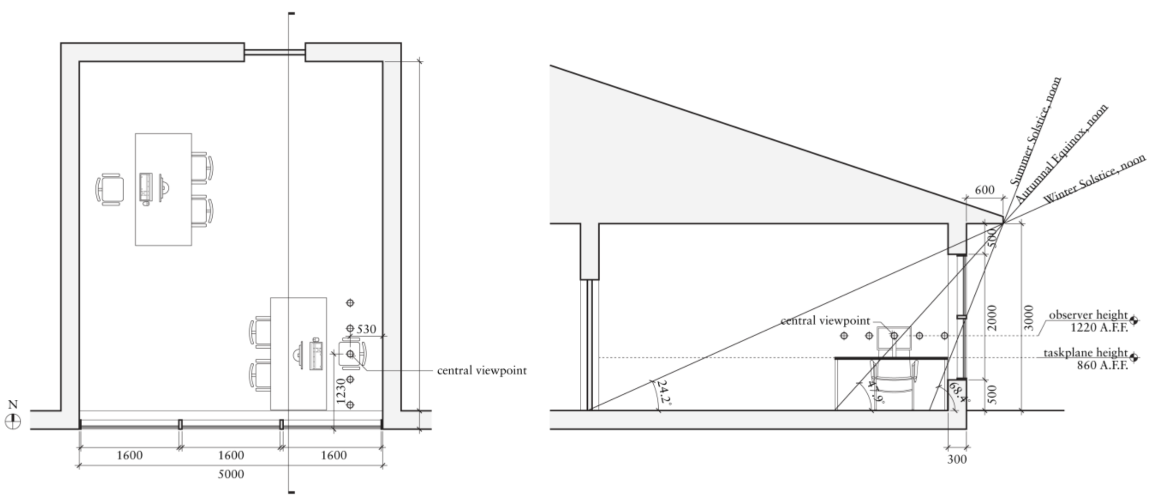
$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-5} \log_{10} 2 \left(1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right) \tag{7}$$

A major departure of DGP relative to other metrics summarized in this paper is that glare sources are determined by comparing areas of bright luminance against the total vertical eye illuminance for a viewing hemisphere of 2π sr. [14] Therefore, DGP can evaluate direct sunlight falling on a workplane as a glare source while at the same time a dim visible sky might not be perceived as such. Specular reflections can also be seen as glare sources. A second major change in discomfort glare calculation using DGP is the addition of a novel first-half of the equation, utilizing vertical eye illuminance (E_v) as its sole input. This means that in exceedingly bright scenes, discomfort can be predicted even without significant visual contrast. The latter-half of the equation uses the familiar comparison of the source luminance and size against the scene luminance and the position index of the glare source, an evaluation of visual contrast. In this sense, DGP is the evaluation of glare which considers the most factors that contribute to discomfort. It also resolves some of Hopkinson's original concerns about the DGI metrics' validity by being developed for direct glare sources other than the sky, something which no other metric has done. Similar to VCP, DGP's value scale is intuitive. A glare probability >.45 corresponds to intolerable glare – an estimated 45 percent of people would feel discomfort in such a lighting situation, while a value <.3 is considered imperceptible. DGP's equation is fit to substantial subjective user sampling in both Denmark and Germany under controlled testing conditions. A program, EvalGlare, was developed at the Fraunhofer-Institut für Solare Energiesysteme in Freiburg for the evaluation of DGP and other glare metrics from Radiance RGBE format luminance images and also allows the visualization of contrast-based sources of glare.[15]

3. Methodology

Two differing spaces were analyzed for discomfort glare probability: a sidelit office with an exposed South-facing window and a large, open plan space lit primarily by East-facing clerestory windows. The open plan space is based on Gund Hall, the home building of the Harvard Graduate School of Design. The two spaces were chosen with the intent of observing the applicability of glare metrics in differing spatial conditions; however, it is worth stating that no glare metric has been developed under open plan spaces nor clerestory window lighting. The exact dimensions and locations of view in the two spaces can be seen in Figures 2 and 3. An additional set of calculations were run of the sidelit office space with exterior venetian blinds, the geometric properties of which are summarized in Figure 4. Both spaces are located in Boston, Massachusetts (42°N, 71° W).

Figure 2 Sidelit space geometric properties in plan and section. The sidelit space has one window on the South side, while the occupant views analyzed face West.



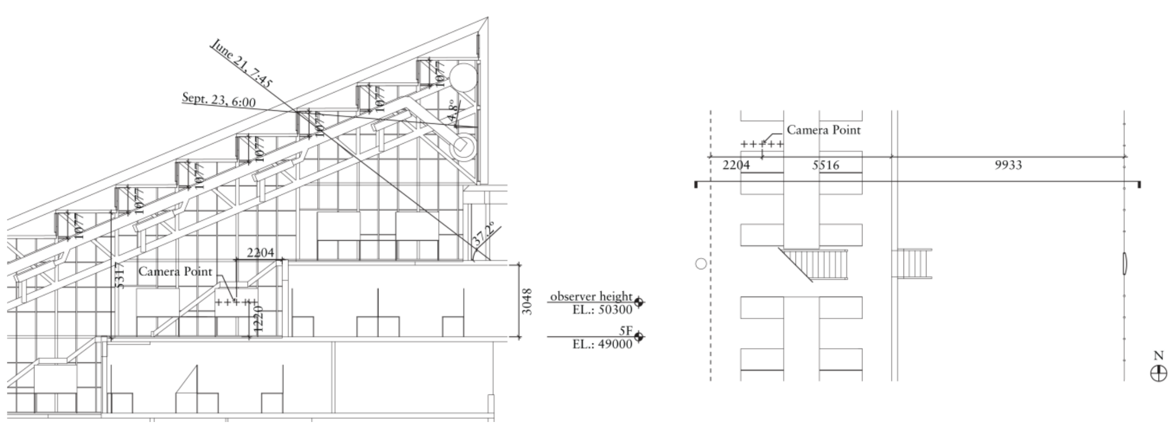


Figure 3 Gund Hall geometric properties in plan and section. The occupant's desk is oriented such that analyzed views face South.

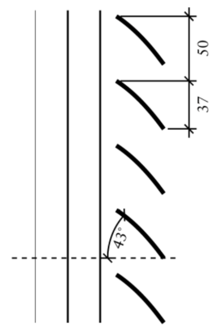


Figure 4 Venetian blind geometric properties in section.

High dynamic range luminance images were generated using the validated Radiance backward raytracer in fifteen minute time intervals for three discrete days during the year: the Winter and Summer solstices occurring on December 21 and June 21 respectively and the Autumnal equinox occurring on September 23. For all three days, simulations were run between the hours of 9am and 9pm local time. Each of the 48 resulting sky conditions were generated by the gensky Radiance program utilizing the +s, CIE clear sky model.[16] The CIE clear sky was chosen because building occupants are likely to experience discomfort from direct sunlight in modern spaces with large window-to-wall ratios. In order to consider occupant adaptation and response, for each sky condition and space, 360 degrees of rotational views were simulated in three degree rotational increments centered about five separate viewpoints, giving the user a degree of rotational and positional freedom as the lighting conditions in the simulated space change. The locations of these viewpoints are illustrated by points in Figures 2 and 3 above for each space. Each luminance image was then used in the calculation of the five previously discussed glare probability metrics: DGI, Daylight Glare Index; CGI, CIE Glare Index; UGR, Unified Glare Index; VCP, Visual Comfort Probability; and DGP, Daylight Glare Probability. DGI_N was not considered due to the geometric complexity involved in its calculation and its lack of significant validation studies. Glare analysis of the resultant images was performed using the EvalGlare program. Glare sources, L_s in Equations 1-7, were identified as any pixel which exceeds five times the mean image luminance. It should be noted that the evaluation of DGP by the EvalGlare program is only valid for vertical eye illuminances greater than or equal to 380 lux. The material properties and Radiance parameters used in the simulations are detailed in Table 1 below.

Table 1 Radiance simulation parameters and material properties utilized in simulations.

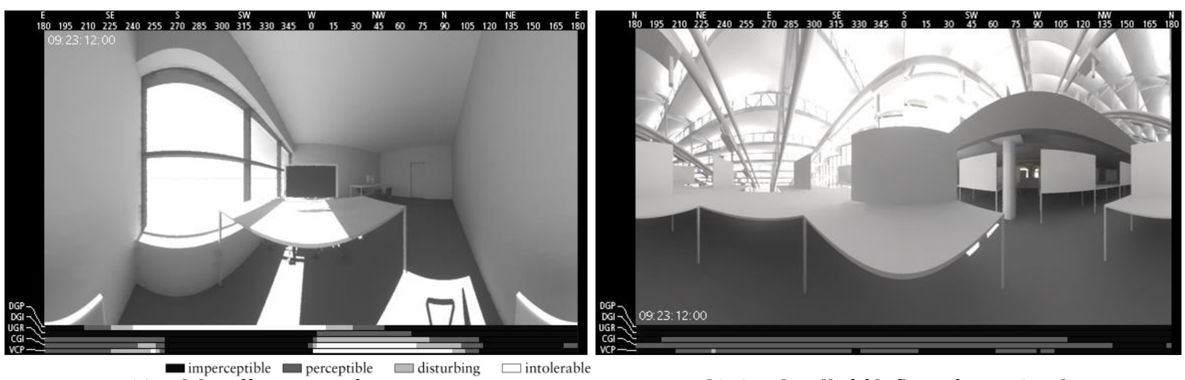
Radiance Simulation Parameters		**Material Properties**	
Ambient bounces (ab)	6	Floors	20% Diffuse Reflectance
Ambient accuracy (aa)	0.15	Walls	50% Diffuse Reflectance
Ambient divisions (ad)	3000	Ceilings	80% Diffuse Reflectance
Ambient super-samples (as)	16	Desk Surfaces	50% Diffuse Reflectance
Ambient resolution (ar)	93	Outside Ground	20% Diffuse Reflectance
		Glazing	72% Transmittance

In order to directly visually compare the results from the various glare metrics, DGI, UGR, VCP and CGI results were normalized to a range between 0 and 1 where 0 corresponds to no likelihood of discomfort and 1 corresponds to 100 percent probability. DGP already evaluates in a range between 0.184 and 1, so no normalization was necessary in that case. DGI was multiplied by a factor of 0.01452, UGR and CGI were multiplied by 0.01607, and VCP was normalized by subtracting its value divided by 100 from 1. The multipliers used in normalization for CGI, UGR and DGI were chosen to correlate the intolerable "white" value ranges with those defined by the DGP metric. Table 2 shows the resulting value ranges in which glare was considered to be ‘imperceptible’, ‘perceptible’, ‘disturbing’ and ‘intolerable’ for the different metrics.

Table 2 Glare prediction value–color assignments used in all visualizations.

Discomfort classification	Glare range values				
	DGP	DGI	UGR	CGI	VCP
Imperceptible (black)	< .35	< 18	< 13	< 13	80 – 100
Perceptible (dark grey)	.35 – .4	18 – 24	13 – 22	13 – 22	60 – 80
Disturbing (light grey)	.4 – .45	24 – 31	22 – 28	22 – 28	40 – 60
Intolerable (white)	> .45	> 31	> 28	> 28	< 40

A series of time lapse animations was produced from this dataset in 15 minute intervals, mapping the probability of experiencing glare as defined by each metric visualized on top of a 360 degree cylindrical projection from the middle viewpoint of the five view positions. In this way, lighting conditions can be visually correlated to the probability of experiencing discomfort glare in many directions of view in an easily understandable format. Figure 5 shows two typical frames from the output. Falsecolor evaluations of glare metrics are displayed across the bottom of each image with degrees rotation from the center of the view and the corresponding cardinal directions shown at the top. Each frame has a time stamp applied in the format of month : day : hour : minute. For example, in Figure 5 both scenes were rendered on September 23rd at noon under clear CIE sky conditions. The DGP for the sidelit office space (5a) is white, intolerable, for a user facing either straight West (towards the center of the visualization) or towards the window (South to Southwest 240 to 330 degrees). DGI does not predict significant glare for any orientation whereas the other metrics also predict glare for the occupant facing West to Northwest. There is no ‘disturbing’ or ‘intolerable’ glare predicted by any metric for Gund Hall (5b).



(a) sidelit office space, facing West (b) Gund Hall, fifth floor, facing South

Figure 5 View-direction dependent glare evaluations on September 23 at noon. The colored bars across the bottom of each image illustrate predicted levels of discomfort glare in the indicated orientation for each analyzed metric.

While it is not possible to publish the full animation results in this format, they are available in color online from the following URL, http://www.gsd.harvard.edu/research/gsdsquare/GlareRecommendationsForPractice.html

4. Results

Figure 7 illustrates results normalized to a range between zero and one as previously explained for the primary viewing angle (center of the visualization) and occupant position for each sky condition simulated. Simulation results from September 23 were chosen for further analysis, because a variety of lighting conditions in the three model spaces were observed as detailed in Table 3. Areas of interest on September 23rd are marked with vertical dashed lines which will be analyzed in further detail with regards to view rotation and predicted glare reduction. Figure 6 shows typical hemispheric images of the type used in glare evaluation for the three scenes at noon on September 23rd.

Table 3 Lighting conditions observed in simulation models on September 23.

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

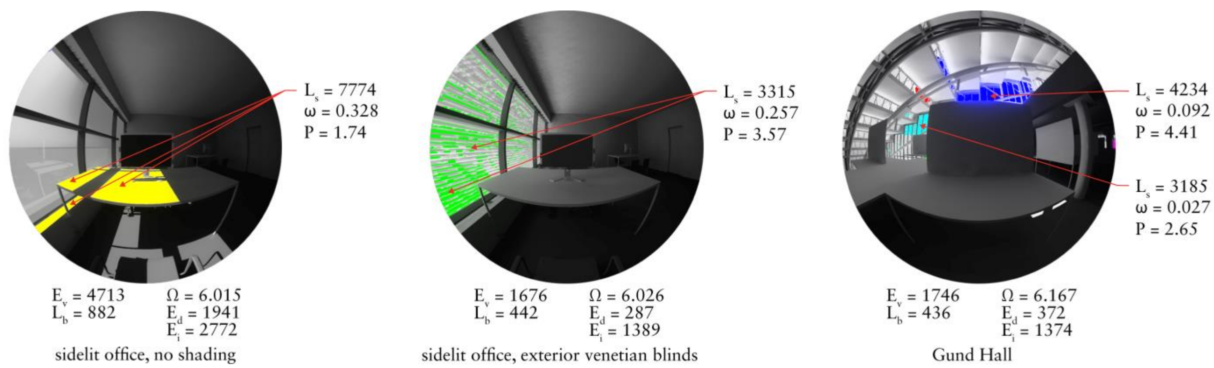


Figure 6 Sample hemispheric views used in glare metric calculations at noon on September 23 with glare sources and associated values identified by EvalGlare.

The direct comparison of the different glare indices over the course of a day in Figure 7 shows that VCP, which is derived for glare originating from electric, typically-sized, ceiling-mounted light sources, often predicts discomfort probabilities much higher than that of the other metrics regardless of whether they were developed for use under electrically lit or daylit conditions. DGI, UGR and CGI correlate strongly, differing most often in their relative intensities. In general it was found in nearly all test cases, during times when the space is daylit, that CGI predicts the highest likelihood of discomfort between the three similarly defined metrics. DGI predicts the lowest values of the three metrics due to its use of a percentage of the source luminance in its denominator. DGP typically evaluates within the upper and lower bounds that DGI, UGR and CGI establish for most lighting conditions for the three simulated days. DGP in general is less sensitive to changes in contrast; this makes sense as its formula is based on two parts which evaluate contrast and total vertical eye illuminance. However, an analysis of these results spatially using many view directions is warranted for further study as the evaluation discomfort glare is effected strongly by both view within a space.

When direct sunlight is present in the scene and the visible sky from the window is very bright, DGP performs better than other existing metrics, predicting a much higher likelihood of discomfort glare. This is the case between 13:15 and 15:15 local time in the sidelit office model with no exterior shading on September and June 21. Under this condition, DGI, UGR, VCP and CGI all predict no likelihood of glare for most view directions when large solid angle luminance sources are in the field of view. Due to DGP's consideration of total vertical eye illuminance as one factor in determining glare, it predicts discomfort when significant contrast does not exist, but excessive luminance is present in the field of view which peaks at around 12000cd/m^2. For the central field of view at 0 degrees rotation, 4515lx falls upon the eye. In this case, DGP's prediction is likely reliable as bright, direct sunlight is generally associated with glare. The discrepancy in prediction with other metrics probably occurs due their purely contrast-based nature. The combined brightness of the window and direct sunlight saturate large portions of the scene except when facing between 30-150 degrees; therefore, significant contrast only exists peripherally in the least-bright directions. This phenomenon is illustrated in Figure 8.

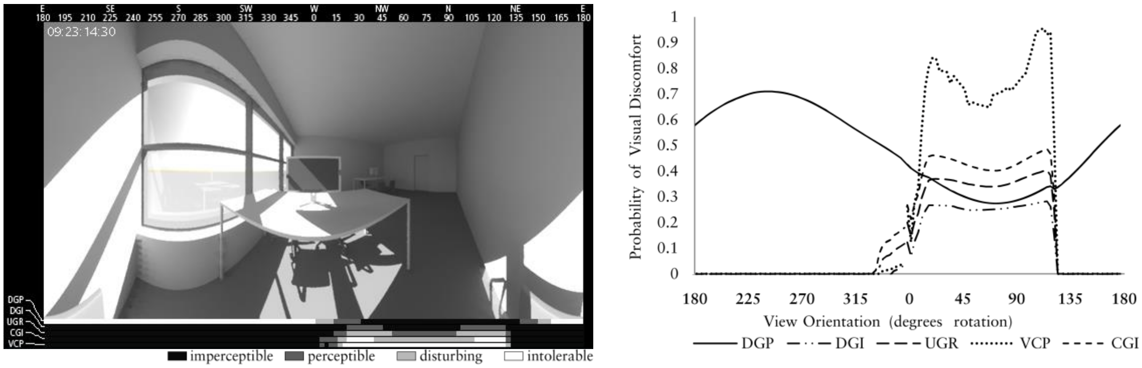


Figure 8 Discomfort glare predictions on September 23rd, 14:30 local time in the sidelit office space.

All metrics appear to make reasonable predictions for the sidelit office space with exterior venetian blinds as long as direct sunlight is prevented from entering the space as is the case in Figure 9. This is expected as DGI, UGR and CGI were developed under presumed conditions of uniformly diffuse windows, although VCP also performs similarly in this lighting scenario. One concern is that our results for venetian blinds experience some seemingly random turbulence. This is most likely due to the ambient accuracy (aa) Radiance simulation parameter used being slightly too high for the complex geometry of the blinds and the ambient divisions (ad) being slightly too low; however, the results should still be reasonably valid as the blinds have no specular material component. In this case, DGP predicts medium levels of discomfort glare (~0.40) when facing the area of bright luminance where the venetian blinds are present due to its evaluation of vertical eye illuminance; however, only VCP predicts significant glare under such lighting conditions.

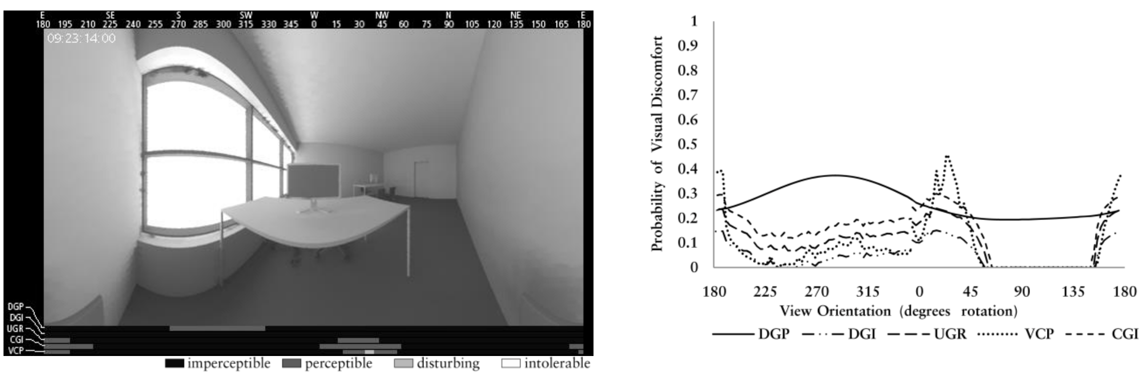


Figure 9 Discomfort glare predictions on September 23rd, 14:00 local time in the sidelit office space with venetian blinds.

The chosen desk location in Gund Hall, with the large partition blocking the Southern view, does not typically experience much direct sunlight on the desk surface. VCP presents results which appear reasonable under these circumstances, though predicted discomfort increases rapidly when the sky behind the large, South-facing window is particularly bright or a glare source (the sun) is located proximate to the center of view (a low Position Index value) as seen in Figure 10. DGI reports comparably low glare probabilities even when the sun is directly visible, a serious weakness for a metric meant for daylight but not unexpected as it was developed under diffuse sky conditions and has a percentage of the source luminance in its denominator. When the sun is not directly visible, DGP, DGI, UGR and CGI correlate strongly, differing primarily in magnitude.

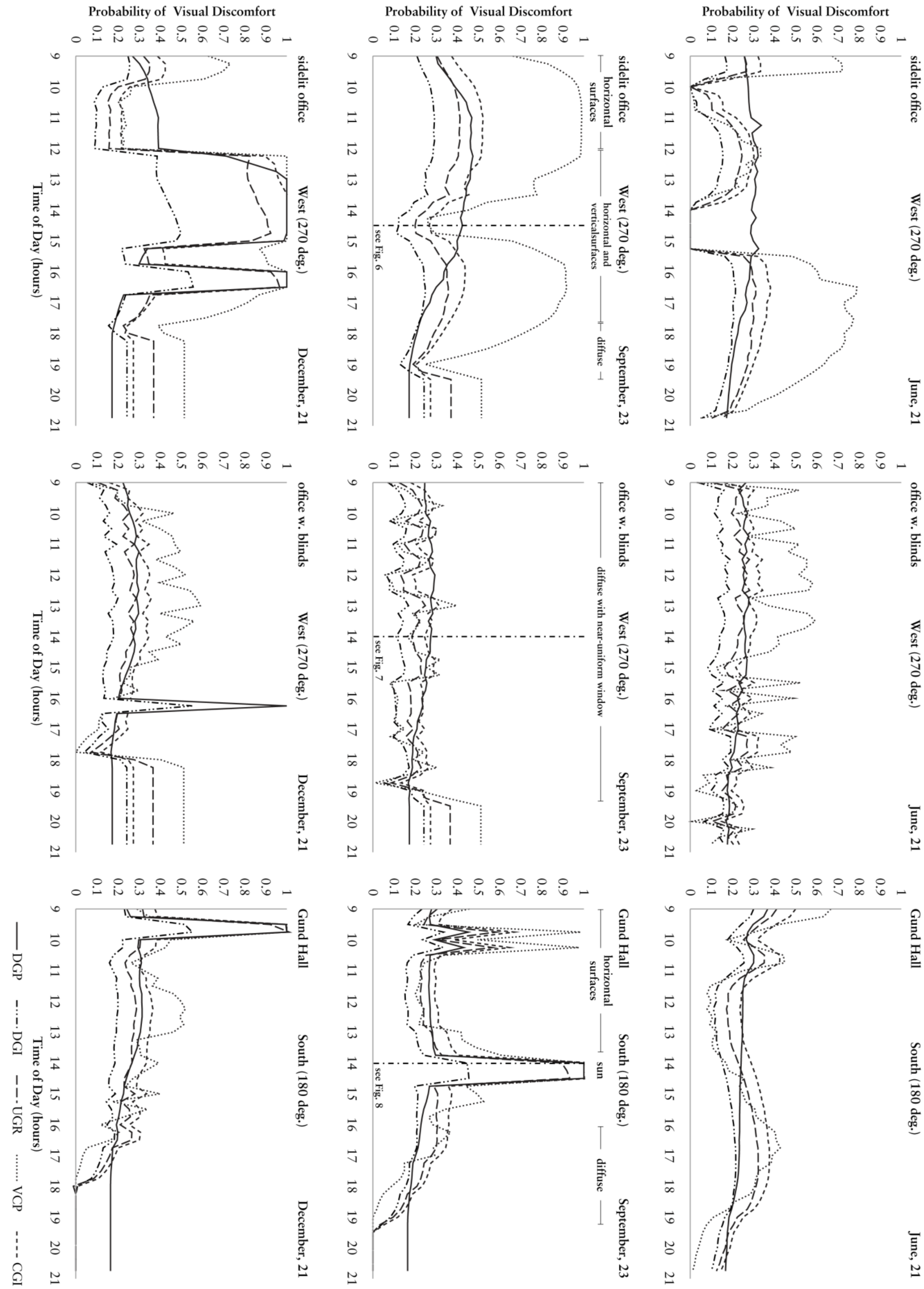


Figure 7 Discomfort glare probabilities for three spatial conditions on July 21, September 23 and December 21.

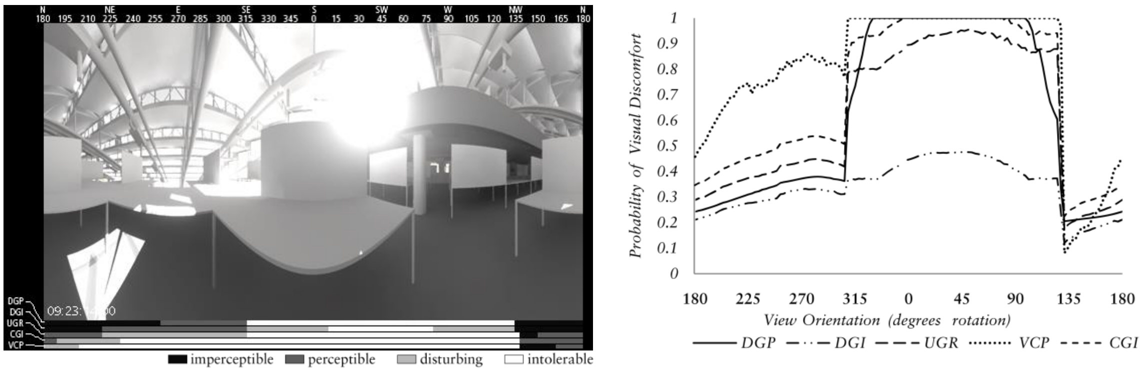


Figure 10 Discomfort glare predictions on September 23rd, 14:00 local time in Gund Hall. The sun is in the direct line of sight of the observer.

5. Discussion

5.1 Appropriate use of metrics

Based on the results from the previous section, the authors generally recommend the following use of the glare metrics investigated. As noted, computational evaluation produces very similar data for the Daylight Glare Index (DGI), CIE Glare Index (CGI) and Unified Glare Rating (UGR). These are useful and valid only under conditions where direct sunlight will not enter the space and where the window can be considered as a medium-sized source of contrast-based glare; however, CGI is the most robust of the three metrics as it consistently predicts a higher likelihood of discomfort, thereby representing a worst-case comfort scenario. As DGI_N requires geometrically complex information and has had no conclusive user validation studies performed, we cannot, at this time, recommend its use; an ideal design analysis workflow is to calculate glare probability from a high definition luminance image without associated geometric and outside sensor data. Under daylit conditions, VCP produces values least in line with other metrics. As it was developed only for very specific, artificially-lit circumstances, we do not recommend its use for daylit scenes. While the five above metrics may be useful under some lighting conditions, our results have shown that they are not applicable under every lighting circumstance that occurred in our simulations (Table 3). In this regard, we have found DGP to be the most robust glare metric. DGP responds predictably to most daylit situations including those with many or large solid angle direct or specular luminance sources. For this reason, the running of many iterative time-step simulations with direct solar ray casting can be achieved and compared with less chance of unreliable or questionable results when using DGP.

5.2 Interpreting glare predictions

The simulation results have shown that cylindrical image projections overlaid with a view direction dependent glare evaluation are an effective way to visually capture the directionality of glare in a single image. These new type of images probably constitute a useful diagram for use in design as they show the perception of discomfort glare under daylit conditions throughout a space in relation to occupant orientation. When compiled as an animation that loops over one or several days of the year, this information helps designers to quickly understand the glare situation within a space over time and in varied directions at least under clear sky conditions.

A limitation of this approach is that it does not yet take actual climate data into account as, for example in the Boston climate, clear sky conditions in December might be rare. Another limitation is the difficulty in correlating visual comfort data to the illuminance availability in a space as the former is perceptual and view dependent while the latter is a measured minimum distribution of light in a space.[17] One aspect that requires further inquiry is how a designer should actually interpret the result that an occupant might experience glare at a certain point in time when facing in one direction but not if facing in another, i.e. is the glare at a particular location in a building acceptable if an occupant is likely to experience severe glare looking in one direction and less or no glare facing another direction? The answer depends on the space type, furniture layout and culture of a space. A typical response to visual discomfort from the students in Gund Hall is to change their viewing position as to obscure the glare source or move it further from the center of view. The design students who inhabit the space also often construct their own makeshift shading devices which further serve to illustrate how important user interaction and behavior can be in determining visual comfort. The authors therefore propose the new concept of an ‘adaptive zone’ within which an occupant can change position and view direction in order to adapt to the visual environment for a particular workplace and minimize the occurrence of glare. In the sidelit space from Figure 8 with a simple rectangular desk, the range of such an ‘adaptive zone’ would be from about 315 to 45 degrees, a +/-45 degree rotational freedom while also allowing the occupant to move their chair about 0.75m to the left or right. Assuming that an occupant is going to select the least disruptive position within the adaptive zone, the designer may pick for each time step the lowest glare prediction in either of these directions (or positions if applicable). The key advantage of this interpretation is that glare relative to occupant orientation and position can be considered by a single number for each moment in time. The resulting reduced daily glare profile, $DGP_{adaptive}$, is shown in Figure 11 on September 23rd plotted against the original fixed view glare results (DGP). In the case of the sidelit office, the fixed-view DGP profile results mostly in intolerable discomfort glare for the occupant; however, adjusting to glare allows the occupant to avoid any significant discomfort. The same results can be seen in Gund Hall where the occupant is successfully able to avoid a direct view of the sun within the adaptive zone between 13:45 and 14:45.

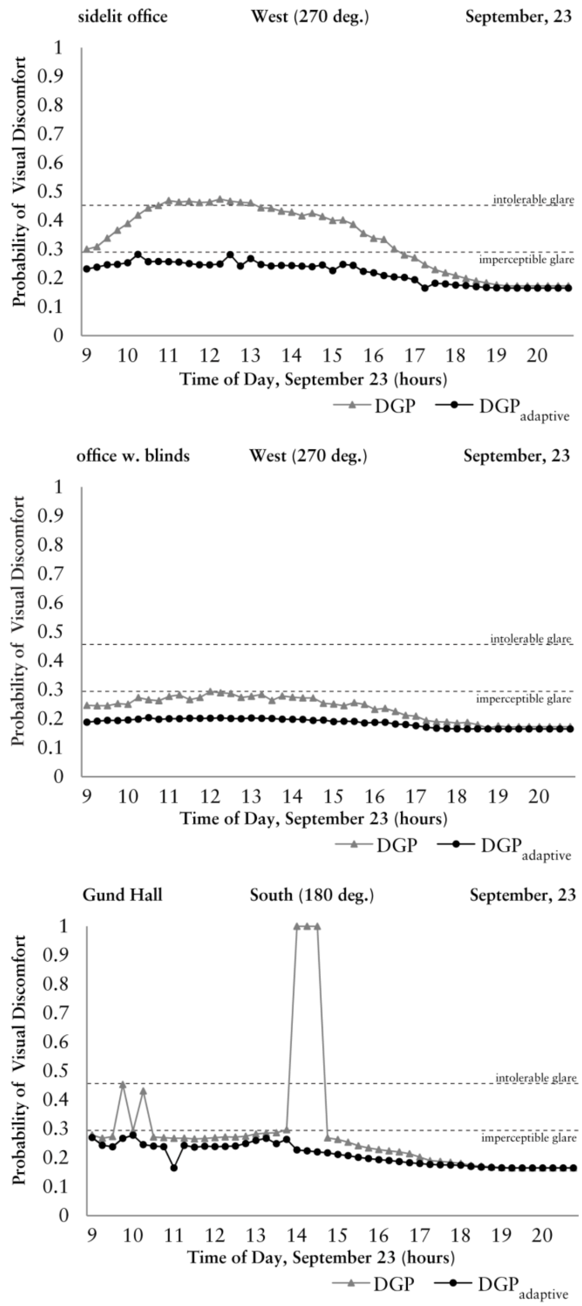


Figure 11 DGP and $DGP_{adaptive}$ timelapse plots for three simulated spaces on September 23rd.

What is the effect of allowing occupants to adjust their orientation within a certain range? Allowing occupants to avoid glare obviously reduces the predicted glare. The larger the adaptive zone, the greater on average will be this reduction. Table 4 shows the mean and maximum reduction of predicted glare for all 144 simulated sky conditions across the three simulated days in all seating positions and for various degrees rotational freedom with respect to an occupant that is only allowed to face forward from a central, fixed position as the reference value.

The mean and maximum values were taken from the rotational ranges of +/- 15, +/- 30, +/- 45, +/- 90, and +/- 180 degrees across the five seating positions. For the typical, sidelit space it becomes apparent that giving occupants, via furniture layout, the ability to adjust themselves substantially reduces predicted glare within a space. For DGP this amounts to a mean reduction of 10% in the case of a workplace which allows the rotation from -45 to +45 degrees from the center. As the difference between the tolerance for 'perceptible' and 'intolerable' glare in the DGP metric is only 15%, a 10% reduction in predicted discomfort glare is significant. Maximum glare reduction probabilities show that simple changes in view position and orientation can have even larger user comfort effects. The reductions for the sidelit space with blinds and the Gund Hall workspace are smaller, because the glare indices are lower in these situations than for the sidelit office without blinds. Table 4 is therefore an effective argument to providing occupants with flexible workspace options. A caveat within this analysis is that VDTs tend to be fixed in most workspaces. Unless the occupants work on laptops, it is necessary that they are able to move their chairs or VDTs in order to adjust their view.

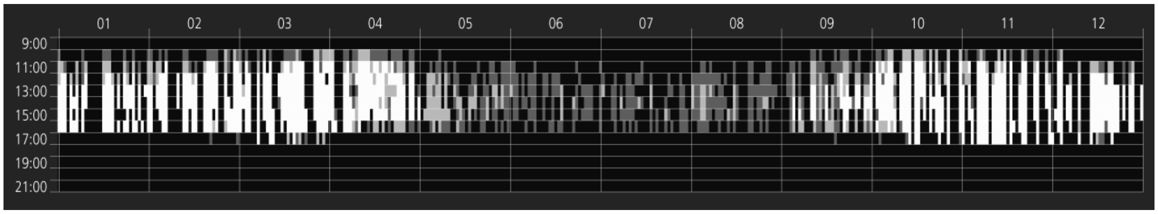
Table 4 Yearly mean and maximum discomfort glare reduction probability with user freedom of adaptation. Simulated users were allowed to move their chairs in front of desks and given degrees of rotational freedom from 15 to 180 degrees in order to reduce discomfort.

		User Rotational Freedom				
Simulated Space	**Result**	**+/- 15**	**+/- 30**	**+/- 45**	**+/- 90**	**+/- 180**
sidelit office	mean reduction	0.11	0.13	0.14	0.16	0.16
	maximum reduction	0.77	0.78	0.79	0.79	0.79
sidelit office w. venetian blinds	mean reduction	0.04	0.05	0.05	0.06	0.06
	maximum reduction	0.82	0.82	0.82	0.82	0.82
Gund Hall	mean reduction	0.04	0.05	0.05	0.06	0.07
	maximum reduction	0.76	0.77	0.78	0.80	0.81

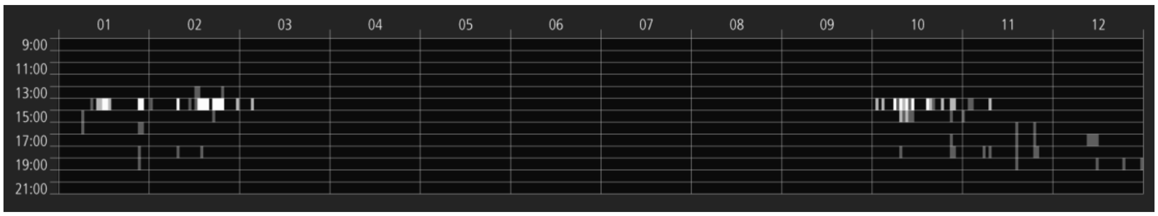
5.3 Yearly hour-by-hour discomfort glare simulation with DAYSIM and enhanced simplified DGP

As mentioned above, the forgoing glare analysis did not take actual climate data into account but assumed clear sky conditions throughout the year. Recent advances in daylight simulations have allowed hour-by-hour illuminance predictions across an entire year based on typical meteorological year weather data. One program which enables such predictions is DAYSIM; DAYSIM is a validated daylighting analysis software which predicts yearly illuminance levels by using one raytracing operation to a sky dome consisting of 144 sky segments and around 65 direct solar positions.[18] Each sky segment is weighted relative to its illuminance contributions in the scene. In this way, illuminance can be predicted across an entire year in any incremental time step without running thousands of separate raytrace simulations directly in Radiance.[19] Because DGP is defined by a two-part formula of total vertical eye illuminance and contrast, one-half of the formula can be satisfied by data generated from DAYSIM alone. By combining fast Radiance simulations showing direct sunlight only by using zero ambient bounces (ab) for each hour of the year with the results of a yearly DAYSIM illuminance simulation, enhanced simplified DGP (eDGPs), developed by Jan Wienold, is a validated method of predicting glare across an entire year using minimal computational resources.[20]

The enhanced simplified DGP method was used to predict discomfort glare in the sidelit office space, and the results were visualized using a falsecolor temporal map between the hours of 9:00 to 21:00 for each day of the year. On the temporal map, the vertical axis describes the time of day, whereas the horizontal axis corresponds to the day of the year. The color scale corresponds to the same values as defined in Table 2. 155 eDGPs simulations were run in three degree rotational increments for each of five seating positions to cover a visual range of plus or minus 45 degrees rotation as in earlier non-dynamic simulation methods. Visually comparing the results of a simulation without (12a) and with adaptation (12b) dramatically underscores the potential importance of office furniture, flexibility and user behavior in the use of a daylit spaces as seen in Figure 12. For the adaptive DGP predictions, glare basically ceases to be a problem in the sidelit space from March to September. Table 5 contains the percentage of annual occupied hours when discomfort is predicted using $DGP_{adaptive}$ versus DGP.



(a) Annual DGP distribution, fixed view facing forward only



(b) Annual adaptive DGP distribution (+/- 45 degrees rotational freedom)

imperceptible perceptible disturbing intolerable

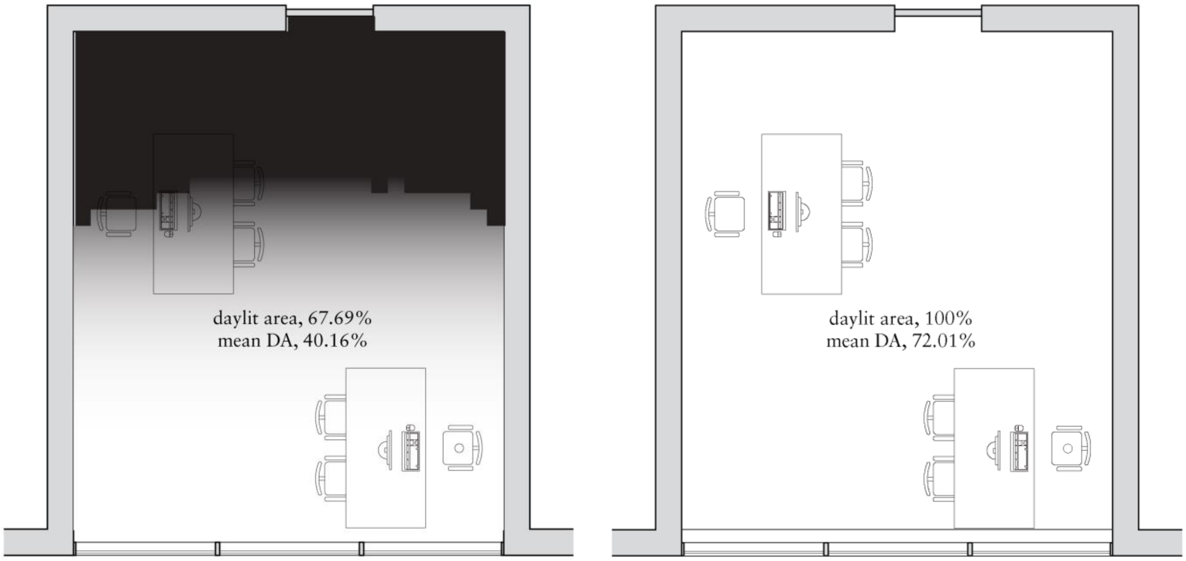
Figure 12 Falsecolor visualizations of yearly glare predictions for the sidelit office space. The horizontal axis indicates the day with the numbers across the top representing the twelve months. The vertical axis illustrates the time of day each prediction was experienced.

Table 5 Yearly percentage of predicted discomfort glare during occupied hours for the sidelit office space.

Metric	**Percent of Occupied Hours**			
	Imperceptible	Perceptible	Disturbing	Intolerable
DGP	70.1 %	9.3%	5.2%	15.4%
$DGP_{adaptive}$	98.4%	0.9%	0.3%	0.4%

5.4 Considering user blind behavior

Glare predictions can be combined with an occupant behavior model in order to determine how a shading device is manually operated over the course of the year. Annual daylight glare probability predictions have already been used for this purpose as an extension to the Lightswitch behavioral model.[21] The Lightswitch model supports two types of users, an active user who opens the blinds in the morning and after a lunch break and closes them either when direct sunlight is incident on the workplace or the predicted DGP becomes disturbing (greater than 0.45) and a passive user who leaves blinds closed for days on end.[22,23,24] The setting of the venetian blinds throughout the year has an obvious effect on both the glare experienced by the occupant, the amount of daylight available and electric lighting use within a space. As freedom of rotation and seating position is introduced, the blinds are lowered less often as the occupant manages to avoid glare; however, this model operates under the assumption that the benefits of view are greater than the annoyance of changing position, and some users may opt to close blinds even in the presence of a flexible workspace. The effect of the behavioral model is shown in Figure 13 for the sidelit space with and without freedom of adaptation. Blinds are opened by a conscientious (active) user seated near the window each day in the morning and at a noon lunch break. If the same user experiences a DGP value of 0.45 or greater, the blinds are lowered until the end of the lunch break or until the next morning. The annual predicted illuminance resulting from this behavior model is used to determine the daylight autonomy (DA) distribution in the space at a minimum illuminance level of 500lx via DAYSIM simulations and the aforementioned behavior model. Daylight autonomy is the percentage of occupied hours in a year where lighting requirements can be met with daylight alone. We further define the daylit area of a space as those which achieve half of the maximum DA value measured inside, indicated in Figure 13. When blind behavior in the simulation is controlled by a fixed-view DGP threshold (13a), the mean daylight autonomy in the space is 40.16% while the daylit area is 67.69% of the floor area. In contrast, when the prediction of $DGP_{adaptive}$ controls blind behavior in the model (13b), the mean daylight autonomy is 72.01% and the daylit area 100% – a substantial difference. Notice that the daylit area using flexible workspaces and $DGP_{adaptive}$ includes the entire room while a prediction using DGP alone leaves the rear portion of the room requiring electric lighting more often than not. The increase of the daylight autonomy and daylit area thus suggest a correlate decrease in predicted lighting energy use and internal heat gains from electric lighting.[25]



(a) DGP control of user blind behavior (b) $DGP_{adaptive}$ control of user blind behavior

Figure 13 Daylight autonomy distributions with occupant controlled blinds relative to predicted glare.

5.5 Required simulation effort

The method discussed above provides an effective way to visualize the likelihood of glare within a daylit space under selected days of the year as well as to take the effect of user adaptation into account. The latter extension of glare analysis can be directly integrated into holistic evaluations of daylight spaces concerning daylight availability, glare and energy use.[26] One question that is likely on the reader's mind now is, "how much effort is required for such an analysis?"

Increasing the simulation domain for variable user orientations versus a single orientation requires no additional simulation input from the user and minimal additional computational effort since global illumination information can be stored, maintaining associated luminance data for each lighting condition. For our Radiance parameters, model complexities and simulated skies, once an initial fisheye view had been calculated, each additional, rotational view took a fraction of the initial simulation time. The overall simulation time to generate a daily glare animation varies by model complexity, the number of time steps associated with that day and the number of occupant positions chosen; simulation times for one sky condition and position in each of the three spaces range from about 3.5 hours for the sidelit office space without blinds to 15.5 hours for the Gund Hall space on a standard laptop computer using a single-core 2.4 GHz processor and high-quality Radiance image parameters.

The annual enhanced simplified DGP simulations were performed using the new gen_dgp_profile subprogram developed by Jan Wienold that has been implemented into DAYSIM 3.1.[27] The time involved in simulating a single yearly eDGPs profile using DAYSIM was comparable to the time required to generate one day's worth of cylindrical projection glare overlay data using static Radiance simulations.

In summation, the analysis procedure presented here can be largely automated since additional simulation input required by the user is negligible. The required simulation time on the other hand is substantial and requires the use of a dedicated calculation engine (ideally a simulation cluster) or overnight calculations.

6. Conclusion

Experimental results in three spaces utilizing individual Radiance simulations for each sky condition and space showed that of five tested glare metrics DGP, daylight glare probability, is the most robust metric and least prone to produce misleading or inaccurate glare predictions under a wide variety of analyzed solar conditions. It seems sensible at this time to recommend the use of DGP to quantitatively predict discomfort from glare in daylit scenes during design and afterwards using HDRI photography.[28]

The enhanced simplified DGP method allows a more comprehensive analysis of yearly comfort data for a specific space, requiring a much smaller computational effort than performing thousands of Radiance simulations for sky conditions across the entire year; however, to perform the simulation still takes a substantial amount of time and thus should only be attempted once basic performance and reasonableness have been established using luminance images from discrete time simulations. For example, it is prudent to check for glare and direct sunlight over several hours on the solstices and an equinox before investigating the annual presence of discomfort glare using climate-based daylight simulations.

We find the newly created cylindrical images with glare prediction data overlaid to be an effective tool for design and presentation, illustrating lighting quality, distribution, and comfort in one image. As rendering is already a key element in the architectural design process, generating a set of these images lends additional value beyond environmental simulation such as for daylight animations and client presentations. The adaptive zone glare analysis described in this paper can be performed on a yearly basis using the enhanced simplified DGP method and then be combined with a set of medium-quality cylindrical projections. At that time, a designer could navigate glare predictions and their visual correlates for an entire year using a simple program interface, such as the conceptual one shown in Figure 14.

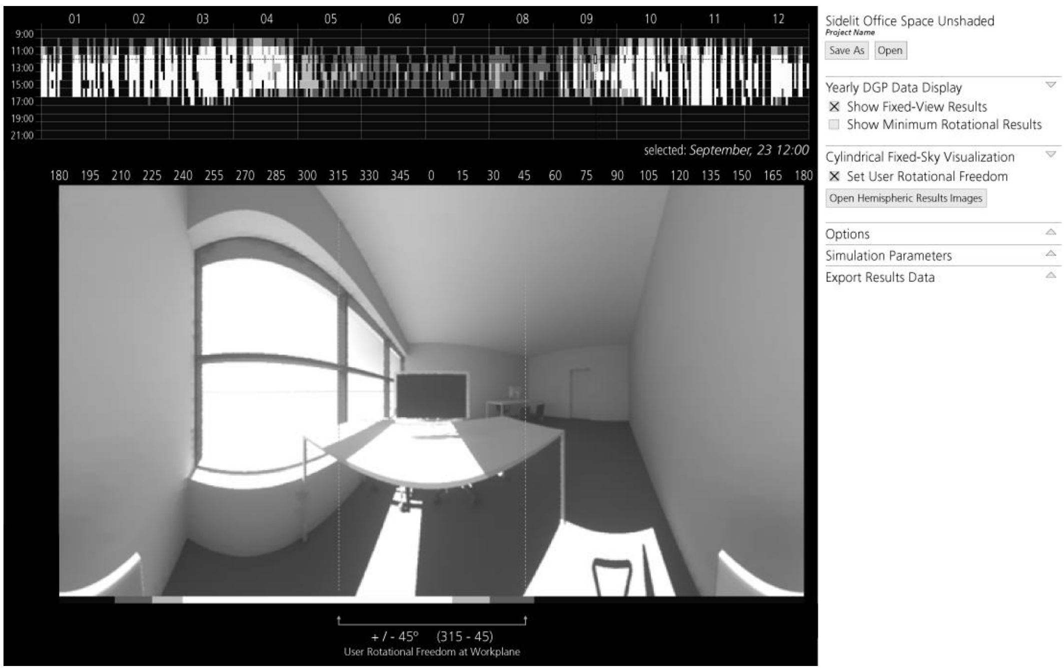


Figure 14 Proposed computer program showing spatial, lighting and glare properties of a space.

This comprehensive study of popular glare metrics attempts to clarify which are meaningful for architectural design and under what conditions they remain reasonable predictors of comfort. Such information should clear the air of ambiguities surrounding glare metrics and allow them to be used as a design parameter for buildings. By expanding glare simulations to multiple view directions and observer positions, it can further be shown that the design of flexibility into interior space layouts can have very positive effects on improving the comfort experienced in a space. Furthermore, this information can be presented in an easily communicable format which adds value beyond a single number which represents visual comfort. Instead, the comfort probability is displayed spatially from the view of the occupant.

In closing it should be noted that while the plausibility tests and adaptive zone concept presented in this study are exclusively based on simulations, the authors are currently validating the adaptive zone concept based on a human subject survey conducted in the Gund Hall studio space from Figure 3.

References

1 Rangi K, Osterhaus W. Windowless environments: are they affecting our health? Proceedings of LIGHTING'99–Then, Now & Beyond, 44th Annual Convention of the Illuminating Engineering Society of Australia and New Zealand; 1999.

2 Reinhart CF, Mardaljevic J, Rogers Z. Dynamic daylight performance metrics for sustainable building design. Leukos 2006; 3,1: 7-31.

3 Commission Internationale de l'Eclairage, CIE Technical Committee 3-13. Discomfort Glare in Interior Lighting. CIE Publication 117, Vienna: CIE 1995.

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

5 Tuaycharoen N, Tregenza PR. View and discomfort glare from windows. Lighting Research & Technology 2007; 39,2: 185-200.

6 USGBC. LEED 2009 for New Construction and Major Renovations Rating System. US Green Building Council. Retrieved November 2010, from http://www.usgbc.org/ShowFile.aspx?DocumentID=7244

7 Reinhart C, Breton P. Experimental Validation of Autodesk® 3ds Max® Design 2009 and Daysim 3.0. Leukos 2009; 6: 1.

8 Larson GW, Shakespeare R. Rendering with radiance: the art and science of lighting visualization. Morgan Kaufmann Publishers Inc. San Francisco, CA, USA; 1998.

9 Luckiesh M, Guth SK. Brightness in visual field at borderline between comfort and discomfort (BCD). Illuminating Engineering 1949; 44: 650-670.

10 Nazzal A. A new daylight glare evaluation method: Introduction of the monitoring protocol and calculation method. Energy and Buildings 2001; 33: 257-265.

11 Nazzal A, Onaygil S, Güler Ö. Subjective experience of discomfort glare in a daylit computerized office in Istanbul and its mathematical prediction with the DGI_N method. The Bulletin of the Istanbul Technical University, Interdisciplinary Journal of Physical and Engineering Science 2005; 54(3).

12 Einhorn H. Discomfort glare: a formula to bridge differences. Lighting Research & Technology 1979; 11,2: 90-94.

13 Harrold R. IESNA lighting ready reference: a compendium of materials from the IESNA. Illuminating Engineering Society of North America. New York, NY: Illuminating Engineering Society of North America; 2003.

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

15 Wienold J, Evalglare version 0.9f. Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany. Retrieved March 2010, from www.ise.fraunhofer.de/radiance

16 Commission Internationale de l'Eclairage. Spatial Distribution of Daylight - CIE Standard Overcast Sky and Clear Sky. CIE Publication S003, Vienna: CIE 1996.

17 Ochoa CE, Capeluto IG. Evaluating visual comfort and performance of three natural lighting systems for deep office buildings in highly luminous climates. Building and Environment 2006; 41: 1128-1135.

18 Reinhart CF, Walkenhorst O. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. Energy and Buildings 2001; 33: 683-697.

19 Walkenhorst O, Luther J, Reinhart CF, Timmer J. Dynamic annual daylight simulations based on one-hour and one-minute means of irradiance data. Solar Energy 2002; 72: 385-395.

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

21 Reinhart CF. Lightswitch-2002: a model for manual and automated control of electric lighting and blinds. Solar Energy 2004; 77: 15-28.

22 Wienold J. Dynamic simulation of blind control strategies for visual comfort and energy balance analysis. Proceedings of Building Simulation; 2007.

23 Rubin AI, Collins BL, Tibbott RL. Window blinds as a potential energy saver: A case study. NSB Building Science Series 112, National Bureau of Standards. Washington, USA; 1978.

24 Lindsay C, Littlefair P. Occupant use of Venetian blinds in offices. Watford, Building Research Establishment. PD 1993; 233: 92.

25 Bodart M, De Herde A. Global energy savings in office buildings by the use of daylight. Energy and Buildings 2002; 34: 421-429.

26 Reinhart CF, Wienold J. The Daylighting Dashboard-A Simulation-Based Design Analysis for Daylit Spaces. Building and Environment. 2011; 46: 386-296.

27 Reinhart CF. DAYSIM version 3.1b. Retrieved November 2010 from http://daysim.com/download.html

28 Inanici M, Galvin J. Evaluation of high dynamic range photography as a luminance mapping technique. Lighting Research & Technology 2006; 38,2: 123-134.