**White Paper**
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**By: Jeff Shuster**

# Addressing Glare in Solid-State Lighting

**Abstract: Glare is a phenomenon caused by a bright light source that inhibits the ability to view a task or scene, due to an uncomfortable or even blinding effect on the viewer. Although many metrics have been developed attempting to quantify glare, each has limitations and most are difficult to measure in the field. This paper briefly examines several of these methods, provides general recommendations to reduce glare, and assesses an installation of Ephesus Arena lights.**

## Introduction

Glare can be divided into two categories: disability glare and discomfort glare. Disability glare is a reduction in visibility due to scattered light in the eye, and is commonly used in the context of automotive head lamps. It is not necessarily associated with physical discomfort, only reduced visibility. Figure 1 below shows an illustration of how disability glare impacts the eye by scattering light and reducing contrast in an image. Tests for disability glare measure the ability of a subject to detect an object in the presence of a glare source.

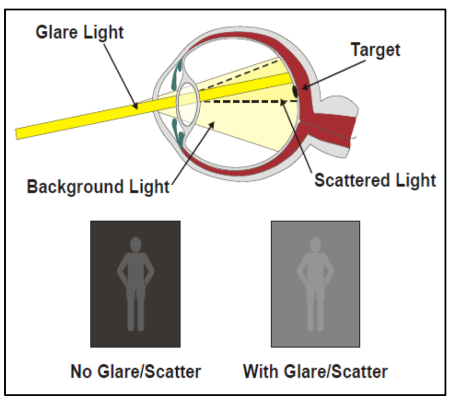


*Figure 1: Mechanism of Disability Glare* [2]

By contrast, discomfort glare is defined as an annoying or painful sensation when exposed to a bright light in the field of view, without necessarily impairing vision. Discussions of glare in sports lighting generally refer to the discomfort type of glare. Unlike disability glare, discomfort glare is subjective and hasn't been directly linked to a physiological cause. There are a number of different models and variables that are used in quantifying discomfort glare. Measurements of glare are based on measurements of light, so it's important to understand some basics of how light is measured before discussing glare further. The strength of a light or light source is quantified in terms of both illuminance and luminance. *Illuminance* is how much light (luminous flux) is incident to a surface or area, basically how much light is going into an area. It is measured in lux (which is a lumen/$m^2$) or foot-candles by a hand-held illuminance meter. These meters are relatively inexpensive (<$100) and commonly used to asses lighting levels. In terms of glare, the illuminance is most often measured incident to the eye.

Where illuminance quantifies the light incident upon an area, luminance by contrast quantifies the light emitted from an area. *Luminance* is a measure of how powerful the light is (luminous intensity) emitted from a particular area within a solid angle. It is measured in units of candela per square meter and typically measured using a hand-held luminance meter, which is more expensive (>$3000) and therefore less common than the illuminance counterpart. It is also limited by the need to have the source subtend the entire field of view of the meter for accurate readings, which means at a certain distance away the measurement is no longer accurate. To bypass this limitation, a digital camera can also be used to measure luminance with the proper settings and calibration[1]. For a Canon G15 digital camera, the field of view of a pixel is 0.017 degrees in the wide angle lens position and 0.0034 degrees in the telephoto position. This is a much finer resolution that the standard 1 degree view of a luminance meter making it a much more versatile for field measurements. In terms of glare, luminance is most often measured directly toward a light source from a given viewing location.

# Methods of Quantifying Glare

The following list provides a brief overview of several methods to quantify disability glare. As a subjective property with no widely accepted measurement standard, there are additional methods not described here, but the methods described below are most readily used to classify a given lighting situation. The methods of UGR and GR are most useful in conjunction with lighting software, and the GR and luminance measures are more practical for measurement in a field application.

- **CIE, Unified Glare Rating (UGR)** – this model was developed by the international commission on illumination, CIE, for applications of interior lighting [*CIE 117-1995 - Discomfort Glare in Interior Lighting*]. UGR is based on a measurement of the luminance of a fixture for a specified direction of line of sight.

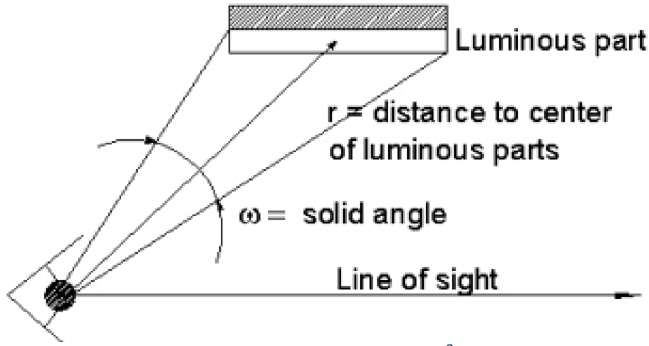


*Figure 2: Unified Glare Rating[3]*

The formula includes terms for background luminance ($L_B$), luminaire luminance (L) summed for all luminaires, the solid angle of the source from the viewer's position in steradians (ω), and the Guth position index (*p*). The Guth position index is based on two angles: α= angle from vertical of the plane containing the source and the line of sight in degrees and β = angle between the line of sight and the line from the observer to the source. The Guth position index is expressed as[9]:

$$P = \exp[\left(35.2 - 0.31889\alpha - 1.22e^{-\frac{2\alpha}{9}}\right)10^{-3}\beta + (21 + 0.26667\alpha - 0.0029663\alpha^2)10^{-5}\beta^2]$$

Based on these terms, the formula for UGR is given as:

$$\mathrm{UGR} = 8\log\left[\frac{.25}{\mathrm{L_B}}\sum\left(\frac{\mathrm{L}^2\omega}{\mathrm{p}^2}\right)\right]$$

This produces values that range from 5 to 40, where anything at 10 or below is negligible and anything above 30 is unacceptably glaring, see table 1. UGR is generally known to only be accurate for small source sizes. It is limited to source sizes between 0.0003 steradians and 0.1 steradians. This corresponds approximately to minimum of a 2-inch source (like a standard incandescent bulb) from about 32 feet away up to maximum fixture 3-feet wide from 10 feet away. This calculation is integrated into many photometric software packages, such as AGI32, based on a specified direction. For this reason, it is a good indicator for glare in an indoor planning situation. Due to the complex interaction of angles and the need to measure each fixture individually, it is difficult to measure in the field.

*Table 1: UGR Criteria [3]*

| UGR | Hopkinson's Criterion |
|---|---|
| 10 | Imperceptible |
| 13 | Just perceptible |
| 16 | Perceptible |
| 19 | Just acceptable |
| 22 | Unacceptable |
| 25 | Just uncomfortable |
| 28 | Uncomfortable |

- **CIE, Glare Rating (GR)** – this model was developed by the international commission on illumination, CIE, for applications in outdoor lighting [CIE document 112-1994]. Glare rating is calculated based on illuminance on the eye when observing each point in an array of points from a single observer position as shown in Figure 2 below.

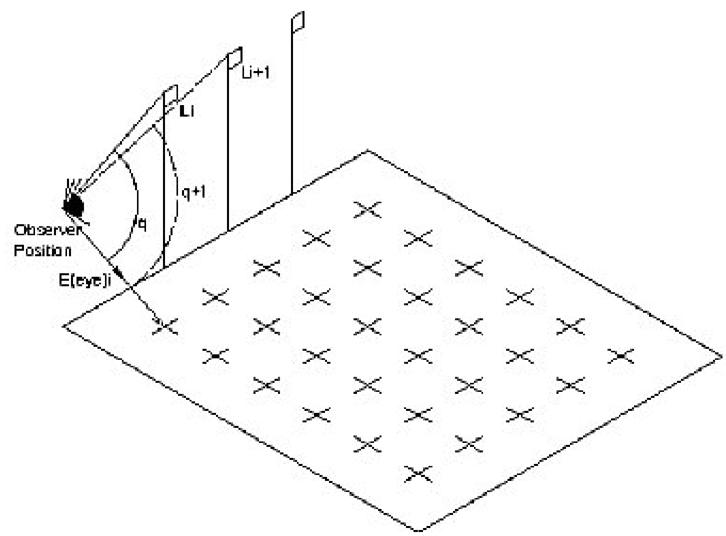


*Figure 3: Glare Rating [4]*

The calculation of Glare Rating includes terms for veiling luminance on the eye ($L_{VL}$) and veiling luminance by the environment ($L_{VE}$). The use of the term luminance here is somewhat misleading because it's calculation relies only on an illuminance measurement. Veiling luminance on the eye is a summation across all luminaires of the illuminance perpendicular to the line of sight ($E_{EYEi}$) and divided by a factor of the angle between the viewer's line of sight and the direction of the light ($q_i$). Veiling luminance by the environment includes the average horizontal illuminance ($E_{HOR,AV}$), the reflectance ($\rho$) and the unity solid angle in steradians ($\Omega$). Glare rating is given as:

$$GR = 24 + 27\log\left(\frac{L_{VL}}{{L_{VE}}^{0.9}}\right)$$

$$L_{VL} = 10\sum_{i=1}^{n}\frac{E_{EYEi}}{(q_i)^2}$$

$$L_{VE} = 0.035 * \left[\frac{E_{HOR,AV} * \rho}{(\pi * \Omega)}\right]$$

This results in values ranging from 10 to 90, where 10 and below is unnoticeable and 90 is considered unbearable, see table 2 below[4]. For outdoor sports competition, it's recommended the GR remain below 50. Similar to UGR, this calculation is integrated into photometric software packages, so is useful to apply in a planning situation for an outdoor field. It should also be noted that the calculation of this value is done from a single observer's point within the area being lit, so it's largely dependent on what points are chosen. Due to the difficulty of separately measuring each luminaire, particularly in outdoor sporting venues which have hundreds of lights, this quantity is also very difficult to capture in the field.

*Table 2: Glare Rating Criteria* [4]

| GR | Classification |
|---|---|
| 10 | Unnoticeable |
| 20 | |
| 30 | Noticeable |
| 40 | |
| 50 | Just Admissible |
| 60 | |
| 70 | Disturbing |
| 80 | |
| 90 | Unbearable |

- **LRC, Discomfort Glare (DG)** – The Lighting Research Center (LRC) of Rensselaer Polytechnic Institute, has developed their own empirical model to quantify discomfort glare. Through series of studies in both indoor and outdoor scenarios, they had subjects rate the level of discomfort glare on the DeBoer scale (see table 3) and statistically analyzed the results. It's worth noting that the DeBoer scale works in the opposite direction of the previously mentioned ratings, so the higher the number the less glare is present.

*Table 3: DeBoer Scale*

| DB | Classification |
|---|---|
| 9 | Just Noticeable |
| 8 | |
| 7 | Satisfactory |
| 6 | |
| 5 | Just Permissible |
| 4 | |
| 3 | Disturbing |
| 2 | |
| 1 | Unbearable |

In contrast to the CIE UGR model, the LRC found ratings of discomfort glare were much more strongly correlated to the illuminance, rather than the luminance of the source[5]. However, this effect is limited to a certain source size – when the source was larger within the field of view, subtending more than 0.3 degrees, they found luminance carried a greater influence.  Their model for discomfort glare uses four terms: illuminance from the source ($E_L$), luminance of the source ($L_L$), illuminance from the area surrounding the source ($E_S$) and ambient illuminance ($E_A$) if the glare source and the light system it were part of were not installed. Discomfort glare is then given as[5]:

$$DG = \log(E_L + E_S) + 0.6\log\left(\frac{E_L}{E_S}\right) - 0.5\log(E_A)$$

Note the value for surround illuminance, $E_S$, must be non-zero for this expression to work. In correspondence with the LRC, they listed the surround and ambient illuminance in a black room as 0.01 lux. Additionally, they reported about 0.02 lux for outdoor rural areas, 0.2 lux for suburban areas and 2 lux in urban areas. This value for DG is then converted into a rating on the DeBoer scale using the formula:

$$DB = 6.6 - 6.4\log(DG) + 1.4\log\left(\frac{50{,}000}{L_L}\right)$$

The final term of this equation, containing luminance of the source ($L_L$) is only included if the source size subtends more than 0.3 degrees in the field of view. At 20 feet away, a source of about 1.25 inches or larger would meet this criteria. At 50 feet away, a source of about 3 inches or larger would meet this criteria. This is comparatively a more simple calculation to the CIE methods, because it measures glare from a single source, rather than requiring summing all sources. For field measurement of an isolated single source, this is a valuable method. However, in certain types of lighting systems where there is a bank or cluster of lights it may be impractical to turn a single light on or off to take these measurements independent of the other lights.

- **Luminance Criteria –** Although the aforementioned methods provide a repeatable, independent measurement of glare, they leave something to be desired when a simple comparative measurement is all that's required. In some cases of LED installations, it's enough to know if glare will be better or worse than the current lighting. To this end, there are a number of criteria that use luminance measurements as an indication of glare. Some take a ratio approach, measuring luminance between the task being viewed and the glare source. These have proposed various ranges of acceptable luminance ratios from 100:1 down to 10:1, but found limited degrees of applicability based on individual perception[6].

  Another study of office environments suggested any luminance above 1500 cd/m$^2$ was likely to be a source of glare[7]. It's important to acknowledge the lighting requirements in sporting venues are often up to eight times higher than those of a standard office environment, so this luminance threshold may be overly conservative when applied to a sporting venue due to the high surround illuminance. Luminance measurements taken from an off-angle, outside the target area of the source, can provide an indication of the level of light spillage. Research is ongoing to determine an appropriate comparison threshold for sporting venues and similar lighting systems. Some combination of source luminance and illuminance at the eye may be the most appropriate for a comparative field measurement. At any rate, these measurements provide a more straightforward way to quickly assess glare in a field application.

# Considerations to Reduce Glare

Reducing the effects of glare involves two primary considerations: light spillage and fixture position. Light spillage is a property of the luminaire design and is related to how well the luminaire limits projected light to the intended area. Figure 4 below shows an implementation of four different designs as the manufacturer worked to improve the fixture design [8]. Often shades, reflectors or special lensing can be incorporated into a design to reduce light projection in an unintended direction, thereby reducing glare. Spillage is typically most concerning when lights aimed vertically emit unintended light in the horizontal plane, causing a bright source in a viewer's eyes.

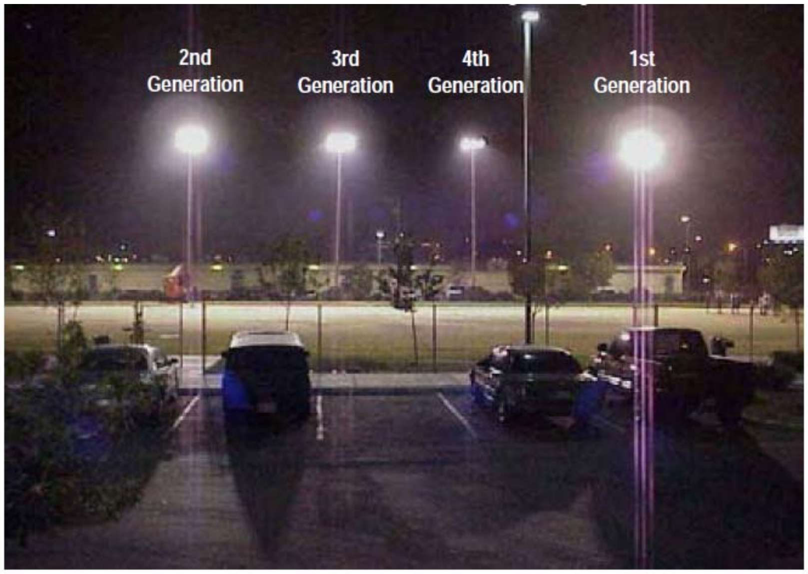


*Figure 4: Light Spillage as a result of Luminaire Design*

The other property which influences the amount of glare is the fixture position. In general fixtures positioned higher from the target area and more directly overhead result in less discomfort glare than fixtures that are lower and further off-center from the targeted area. Figure 5 illustrates this effect for a sports field installation shown with a 50 foot mounting height and a 90 foot mounting height[8]. The higher pole shown in the bottom half of the figure allows for better cutoff of light and eliminates spillage into the sky. If the mounting position of the luminaire cannot be changed, aiming the center point of the luminaire closer to the mounting location can also help to reduce glare. In many cases, this is a competing requirement with supplying adequate light levels to the target area, so requirements must be prioritized.

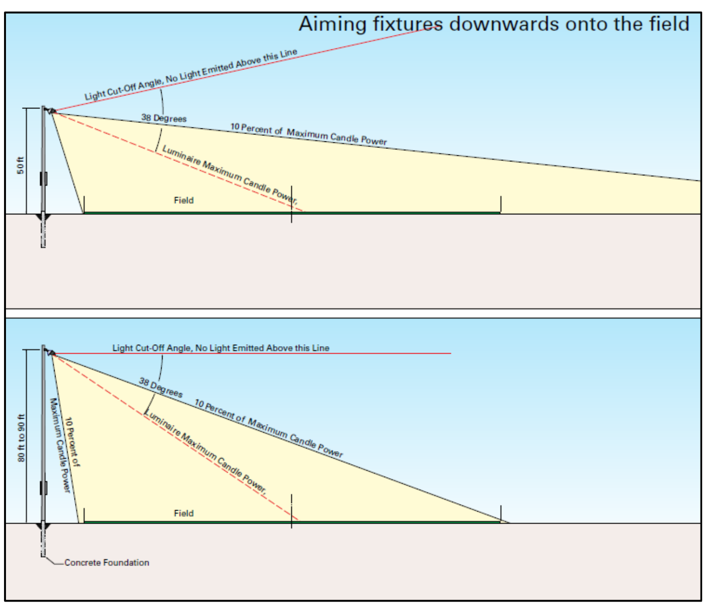


*Figure 5: The Importance of Light Position to Reduce Glare*

# Assessment of Glare in an Ephesus Installation

This section applies the UGR and luminance criteria methods for quantifying glare discussed earlier to an installation of Ephesus Arena LED luminaires at Ricoh Coliseum in Toronto, Canada. As shown in Figure 6, this installation includes a mixture of overhead lights pointed directly downward and a row of side lights angled in toward the ice.

*Figure 6: Ephesus Arena Lighting in Ricoh Coliseum, Toronto*

It's expected that the lights angled in from the side will contribute most significantly as a glare source, since they are lower and more likely to cross a viewer's line of sight. The first evaluation uses a 3D model of the Ricoh Coliseum and calculates the UGR along a 10 x 10 horizontal grid, 4 feet above the surface of the ice. AGI32 software was used to perform this analysis. Calculation of UGR is based on a specified direction for line of sight, so evaluation was performed looking both from the left to the right along the length of the ice and from the bottom to the top across the width of the ice. Figure 7 below shows the UGR looking down the length of the ice. The maximum values are around 20 which is within the acceptable range listed in Table 1. This viewing angle allows glare to be assessed with minimal contributions from the side lights. This acceptable result indicates no unintended spillage from the overhead lights is causing glare.

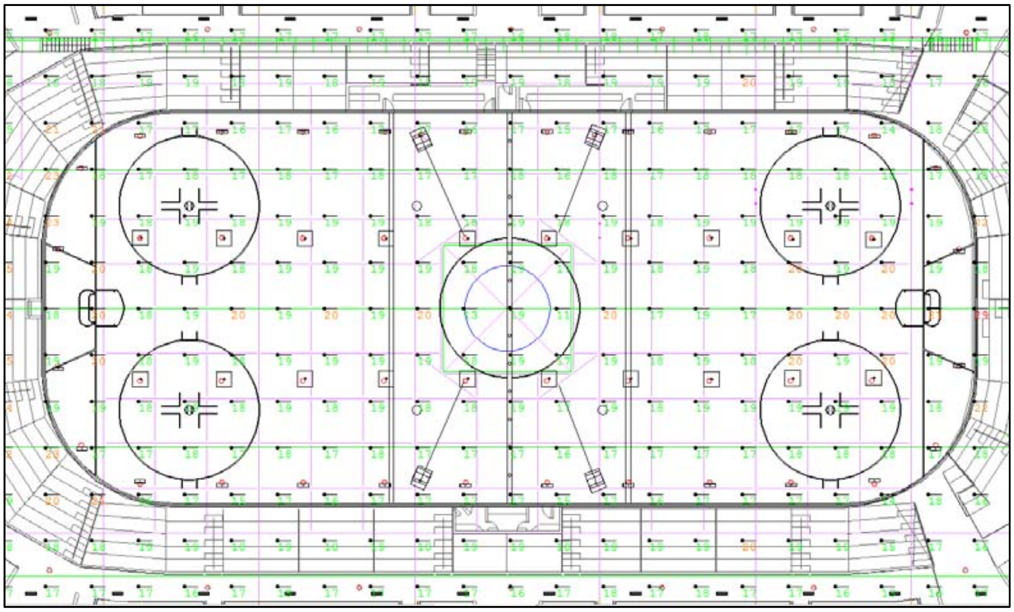

*Figure 7: Evaluation of UGR at Ricoh, Left to Right*

Figure 8 shows the UGR with the line of sight rotated 90 degrees, looking across the width of the ice. Now the contribution of the angled side lights is worst case and a number of points across the snapshot are in the uncomfortable range (28 or higher). Although resulting in some glare, these sidelights provide several important functions by eliminating shadows along the inside edges of the boards and greatly increasing the vertical illuminance. Vertical illuminance is essential for quality television broadcasting. Additionally, the high overall lighting levels of the arena help to minimize the potentially uncomfortable effect, because the lights aren't in stark contrast to a dark surrounding.

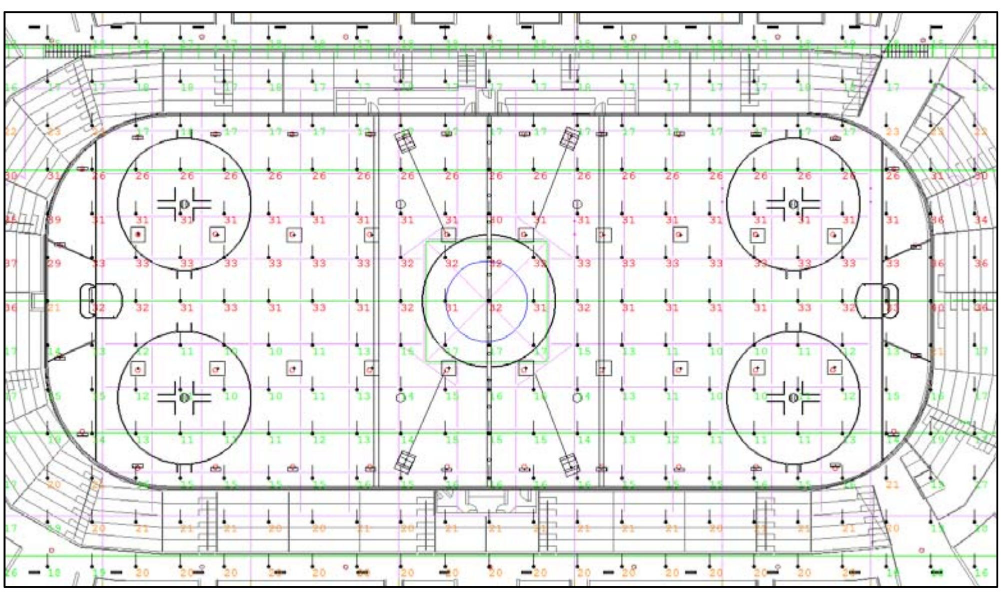

*Figure 8: Evaluation of UGR at Ricoh, Bottom to Top*

A third party evaluation of the Ricoh Coliseum based on luminance criteria was performed by Peter Hiscocks, of Syscomp Electronic Design Limited. Based on the glare criteria of 1500 cd/m$^2$ mentioned previously, he assessed luminance from ten positions in the Ricoh Center, both from the ice and in the viewing stands. Using a calibrated digital camera with appropriate filters, he was able to capture multiple fixtures in each frame and report luminance values from each light fixture. A few sample figures from the analysis are copied in Figure 9 below.

(a) Ice-level-by-team-box-slight-elevation

(b) Ice-level-by-team-box-horizontal

(c) On-ice-in-corner-near-section-116

(d) On-ice-near-non-rogers-goal

*Figure 9: Ricoh Luminance Assessment*

It was found the fixtures that were aimed vertically had well controlled spillage and were not a source of glare, like the fixtures in the far left of (a) in Figure 9. The fixtures aimed in at sides of the rink produced luminance readings an order of magnitude higher than the threshold of 1500 cd/m$^2$, such as those in the center of (b) and (c) in Figure 9. This agrees with the results from the UGR analysis that these side lights are the most likely culprits for glare in this installation. As viewed down the length of the ice, from behind the goal, luminance values were all below the glare threshold, shown in (d) of Figure 9. Keeping in mind this threshold was suggested primarily for office environments, where typical horizontal illuminance values are 30-40 foot-candles versus 150 foot-candles at the Ricoh Center, this is a remarkable result.

# Conclusion

There are many approaches to quantifying discomfort glare, but with any approach it remains a subjective measurement. CIE methods of Unified Glare Rating (UGR) and Glare Rating (GR) are helpful in planning situations, where software can complete the complex calculations. The LRC's method of Discomfort Glare (DG) provides a robust empirical model, but requires measurements of a single light at a time, which may be impractical for field measurements in a large installation like a sporting venue. Lastly, the luminance criteria method provides a practical field measurement, but lacks the inclusion of other potential contributing factors, most noticeably illuminance at the eye.

Glare results from a combination of both luminaire design, and position. Even the best designs can produce glare if positioned a certain way. Measuring the Ephesus Arena installation with both the analytical method of UGR and the more simplistic luminance criteria indicates the general spillage control of the fixture is very good. This means the element of glare associated with fixture design is adequate. The greatest likelihood of glare with an Ephesus fixture is related simply to its aiming position.

# References


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