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# ROBUST UNIFIED GLARE RATING EVALUATION FOR REAL LIGHTING INSTALLATIONS

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# ROBUST UNIFIED GLARE RATING EVALUATION FOR REAL LIGHTING INSTALLATIONS

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## Abstract

The unified glare rating (UGR) is a widely accepted measure for discomfort glare of indoor lighting installations. Standards for the lighting of workplaces provide limiting values for the UGR based on the so-called tabular method, like the well-known limit of UGR 19 for office lighting applications. These limiting values are averaged values based on a standardised room layout (rectangular space with rectangular grid of luminaires), indicative of the average discomfort glare to be expected in an actual installation. A direct application of the UGR formula (e.g. using point calculations) to real lighting installations is known to lead to unreliable UGR values that are very sensitive to observer and luminaire positions. These UGR values cannot be directly verified against the limiting values of workplace standards due to the nature of the original determination of the limiting values. An averaging method is proposed that enables a robust UGR calculation for any real indoor lighting installation, i.e. much more flexible than the tabular method that is limited to rectangular spaces with rectangular luminaire layouts of a single type. The method provides UGR values that may be compared to the limiting values of workplace lighting standards.

*Keywords*: Unified glare rating (UGR), tabular method, observer positions

## 1 Introduction: UGR formula and tabular method

In 1995, CIE adopted the unified glare rating (UGR) to evaluate discomfort glare of indoor lighting installations (CIE, 1995). The UGR formula is based on a summation over all glare sources in the field of view, as given by

$$R_{UG} = 8\log\left[\frac{0.25}{L_b}\sum\frac{L_s^2\omega}{p^2}\right] \quad (1)$$

where

- $L_s$ is the source luminance in the direction of the observer;
- $\omega$ is the solid angle subtended by the source at the observer's eye;
- $p$ is the position index;
- $L_b$ is the background luminance.

Meanwhile, the UGR has become an integral part of indoor workplace lighting standards around the world, like the CIE S 008 (CIE 2001), the European standard EN12464-1 (CEN, 2011) and the Chinese standard GB50034 (CABP 2014). These standards employ the so-called tabular method of the UGR to ensure an 'apples to apples' comparison and provide an 'average' UGR value indicative of what one may expect in the actual installation. To achieve this average UGR value, a very high luminaire density is applied (luminaire spacing to height ratio of 0.25, which is typically a spacing of 0.5 m or less) to average out the variation in UGR that can occur. Aside from this averaged UGR value, an indication of the magnitude of these variations with observer position is provided in the bottom part of the UGR table (CIE, 1995).

The very small luminaire spacing, in combination with the large number of boundary conditions of the UGR tabular method (a single type of symmetric luminaires, rectangular luminaire distributions in rectangular spaces with specific room surface reflectance values and specific observer positions and observer viewing directions) have caused many discussions over the years leading to a tendency for designers to look at a ‘point-by-point’ type of calculation as a solution. In these calculations, the UGR formula (1) is applied to any real lighting installation (combinations of different luminaires, arbitrary room shapes) and for any observer position that may be relevant.

While considered cumbersome in 1995, such calculations are increasingly more popular nowadays because software packages (e.g. DIALux, Relux, AGi32) can easily calculate the lighting conditions in any space. A drawback of this method is that the resulting UGR value is very sensitive to observer position and cannot be directly linked to the limiting values of the workplace standards, which are related to the *averaged* UGR values. This sensitivity of the UGR calculation at a single point was already observed by Ashdown (2005), who recommends a calculation of glare ratings from various viewpoints on a dense grid, rather than at a single point.

There is a need to have a UGR calculation methodology for any real lighting installation that produces robust values that are less sensitive to small variations in observer position, such that the outcome may be related to the workplace standards.

## 2 Comparison of UGR calculation methods

In this section, we compare several UGR determination methods:

1. The tabular method (averaged value based on a high density of luminaires);
2. The single point calculation method (value of Eq. (1) based on a real luminaire layout);
3. “Naïve” averaging of UGR point calculation values;
4. New method for averaging of UGR point calculation values.

In all determination methods, the commonly used reference space is taken, with recessed luminaires in a ceiling at 3.2 m height, such that they are at H=2.0 m above observer height (1.2 m, eye height of a sitting person). The room dimensions are 4H and 8H, and the reflectance values of ceiling, walls and floor are 70%, 50% and 20% respectively. The maintenance factor is set at 1.

For the comparison, three very different recessed luminaires are selected:

1. A diffuse (Lambertian emission) luminaire tile of 600 mm x 600 mm, 4000 lm output;
2. A square office luminaire of 600 mm x 600 mm, 4000 lm output;
3. A linear office luminaire of 80 mm x 1450 mm, 3100 lm output.

The office luminaires are both designed for low glare by limiting the intensities at high angles with respect to the vertical orientation, see the luminous intensity distributions in Fig. 1.

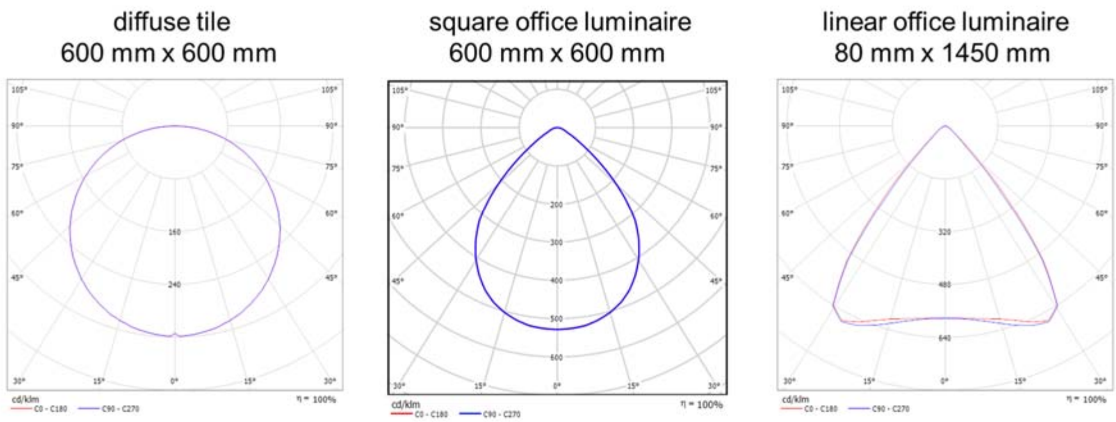


**Figure 1 – Luminous intensity distributions of the three luminaires used in the comparison**

## 2.1 Tabular method

Based on the luminance intensity distributions and luminaire sizes, the UGR according to the tabular method can be calculated. The result is given in Figs. 2, 3 and 4. In these figures, the UGR values that relate to the CEN reference space of 4H x 8H (or 8H x 4H) are indicated by a blue circle. The UGR of the diffuse tile is 22, of the square office lighting luminaire the UGR is 16, and the linear office lighting luminaire has a UGR of 17.The tables also indicate what amount of variation in UGR value may be expected for a luminaire spacing of, for instance, S=1.0H: much less than 1 point for the diffuse tile, about 3 UGR points variation for the square office luminaire and about 10 UGR points for the linear office lighting luminaire.

## 2.2 Single point calculation

Figure 5 gives an impression of the luminaire layout in the room and the illuminance distributions for the three different luminaire types. The layout is chosen such that the average workplane illuminance is about 600 lux.

Figure 6 illustrates the result of the UGR point calculations in the rooms as depicted in Fig. 5. The top row of images shows the UGR point value in grey scale for a viewing direction along the long side of the room. The bottom row shows the UGR point values for a viewing direction along the short side of the room (note that the grey scales are different for the different images). The positions and viewing directions of the standard observers are indicated in red, together with the corresponding UGR value. For the diffuse tile, the UGR point calculation agrees well with the data in the UGR tables: the UGR is 22 for the observer standing against the shortest wall and it is 21 for the observer at the long wall. For the luminaires with an intensity cut-off, the situation is different. For the square office luminaire, the tabular method results in a value of 16 for both observers, while the point method results in differences in both directions (13 vs 19). For the linear office luminaire, the tabular method gives a UGR value of 17, while the point method gives values of 10 and 20.

Diffuse tile UGR 22

**Glare Evaluation According to UGR**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ρ Ceiling | | 70 | 70 | 50 | 50 | 30 | 70 | 70 | 50 | 50 | 30 |
| ρ Walls | | 50 | 30 | 50 | 30 | 30 | 50 | 30 | 50 | 30 | 30 |
| ρ Floor | | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Room Size X | Y | Viewing direction at right angles to lamp axis | | | | | Viewing direction parallel to lamp axis | | | | |
| 2H | 2H | 17.1 | 18.5 | 17.4 | 18.7 | 18.9 | 17.1 | 18.5 | 17.4 | 18.7 | 18.9 |
| | 3H | 18.9 | 20.2 | 19.3 | 20.5 | 20.7 | 18.9 | 20.2 | 19.3 | 20.5 | 20.7 |
| | 4H | 19.7 | 20.9 | 20.1 | 21.2 | 21.5 | 19.7 | 20.9 | 20.1 | 21.2 | 21.5 |
| | 6H | 20.4 | 21.5 | 20.8 | 21.8 | 22.2 | 20.4 | 21.5 | 20.8 | 21.8 | 22.2 |
| | 8H | 20.7 | 21.8 | 21.1 | 22.1 | 22.4 | 20.7 | 21.8 | 21.1 | 22.1 | 22.4 |
| | 12H | 20.9 | 21.9 | 21.3 | 22.2 | 22.6 | 20.9 | 21.9 | 21.3 | 22.2 | 22.6 |
| 4H | 2H | 17.9 | 19.0 | 18.2 | 19.3 | 19.6 | 17.9 | 19.0 | 18.2 | 19.3 | 19.6 |
| | 3H | 19.9 | 20.9 | 20.3 | 21.2 | 21.6 | 19.9 | 20.9 | 20.3 | 21.2 | 21.6 |
| | 4H | 20.9 | 21.8 | 21.3 | 22.1 | 22.5 | 20.9 | 21.8 | 21.3 | 22.1 | 22.5 |
| | 6H | 21.7 | 22.5 | 22.1 | 22.9 | 23.3 | 21.7 | 22.5 | 22.1 | 22.9 | 23.3 |
| | 8H | 22.0 | 22.8 | 22.5 | 23.2 | 23.6 | 22.0 | 22.8 | 22.5 | 23.2 | 23.6 |
| | 12H | 22.3 | 23.0 | 22.7 | 23.4 | 23.8 | 22.3 | 23.0 | 22.7 | 23.4 | 23.8 |
| 8H | 4H | 21.3 | 22.0 | 21.7 | 22.4 | 22.8 | 21.3 | 22.0 | 21.7 | 22.4 | 22.8 |
| | 6H | 22.3 | 22.9 | 22.7 | 23.3 | 23.8 | 22.3 | 22.9 | 22.7 | 23.3 | 23.8 |
| | 8H | 22.7 | 23.3 | 23.2 | 23.7 | 24.2 | 22.7 | 23.3 | 23.2 | 23.7 | 24.2 |
| | 12H | 23.1 | 23.5 | 23.6 | 24.0 | 24.5 | 23.1 | 23.5 | 23.6 | 24.0 | 24.5 |
| 12H | 4H | 21.3 | 22.0 | 21.8 | 22.4 | 22.8 | 21.3 | 22.0 | 21.8 | 22.4 | 22.8 |
| | 6H | 22.4 | 22.9 | 22.9 | 23.4 | 23.9 | 22.4 | 22.9 | 22.9 | 23.4 | 23.9 |
| | 8H | 22.9 | 23.3 | 23.4 | 23.8 | 24.3 | 22.9 | 23.3 | 23.4 | 23.8 | 24.3 |
| Variation of the observer position for the luminaire distances S | | | | | | | | | | | |
| S = 1.0H | | +0.1 / -0.1 | | | | | +0.1 / -0.1 | | | | |
| S = 1.5H | | +0.2 / -0.3 | | | | | +0.2 / -0.3 | | | | |
| S = 2.0H | | +0.3 / -0.5 | | | | | +0.3 / -0.5 | | | | |
| Standard table | | BK07 | | | | | BK07 | | | | |
| Correction Summand | | 5.6 | | | | | 5.6 | | | | |
| Corrected Glare Indices referring to 4000lm Total Luminous Flux | | | | | | | | | | | |

**Figure 2 – UGR table of the diffuse luminaire**

## Office luminaire UGR 16

**Glare Evaluation According to UGR**

| ρ Ceiling | | 70 | 70 | 50 | 50 | 30 | 70 | 70 | 50 | 50 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ρ Walls | | 50 | 30 | 50 | 30 | 30 | 50 | 30 | 50 | 30 | 30 |
| ρ Floor | | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Room Size X | Y | Viewing direction at right angles to lamp axis | | | | | Viewing direction parallel to lamp axis | | | | |
| 2H | 2H | 15.8 | 16.8 | 16.1 | 17.0 | 17.3 | 15.8 | 16.8 | 16.1 | 17.0 | 17.3 |
| | 3H | 15.8 | 16.8 | 16.1 | 17.0 | 17.3 | 15.8 | 16.8 | 16.1 | 17.0 | 17.3 |
| | 4H | 15.9 | 16.7 | 16.2 | 17.0 | 17.3 | 15.9 | 16.7 | 16.2 | 17.0 | 17.3 |
| | 6H | 15.9 | 16.7 | 16.2 | 16.9 | 17.2 | 15.9 | 16.7 | 16.2 | 17.0 | 17.2 |
| | 8H | 15.9 | 16.6 | 16.2 | 16.9 | 17.2 | 15.9 | 16.6 | 16.2 | 16.9 | 17.2 |
| | 12H | 15.8 | 16.6 | 16.2 | 16.9 | 17.2 | 15.9 | 16.6 | 16.2 | 16.9 | 17.2 |
| 4H | 2H | 15.9 | 16.7 | 16.2 | 17.0 | 17.3 | 15.9 | 16.7 | 16.2 | 17.0 | 17.3 |
| | 3H | 16.0 | 16.7 | 16.4 | 17.0 | 17.3 | 16.0 | 16.7 | 16.4 | 17.0 | 17.4 |
| | 4H | 16.1 | 16.7 | 16.5 | 17.0 | 17.4 | 16.1 | 16.7 | 16.5 | 17.0 | 17.4 |
| | 6H | ~~16.1~~ | 16.7 | 16.5 | 17.0 | 17.4 | ~~16.1~~ | 16.7 | 16.5 | 17.0 | 17.4 |
| | 8H | 16.1 | 16.6 | 16.6 | 17.0 | 17.4 | 16.1 | 16.6 | 16.6 | 17.0 | 17.4 |
| | 12H | ~~16.1~~ | 16.6 | 16.6 | 17.0 | 17.4 | ~~16.1~~ | 16.6 | 16.6 | 17.0 | 17.4 |
| 8H | 4H | 16.0 | 16.5 | 16.5 | 16.9 | 17.3 | 16.0 | 16.5 | 16.5 | 16.9 | 17.3 |
| | 6H | ~~16.1~~ | 16.5 | 16.6 | 17.0 | 17.4 | ~~16.1~~ | 16.5 | 16.6 | 17.0 | 17.4 |
| | 8H | 16.2 | 16.5 | 16.6 | 17.0 | 17.4 | 16.2 | 16.5 | 16.7 | 17.0 | 17.4 |
| | 12H | 16.2 | 16.5 | 16.7 | 17.0 | 17.4 | 16.2 | 16.5 | 16.7 | 17.0 | 17.5 |
| 12H | 4H | 16.0 | 16.5 | 16.5 | 16.9 | 17.3 | 16.0 | 16.5 | 16.5 | 16.9 | 17.3 |
| | 6H | 16.1 | 16.5 | 16.6 | 16.9 | 17.4 | 16.1 | 16.5 | 16.6 | 16.9 | 17.4 |
| | 8H | 16.2 | 16.5 | 16.7 | 16.9 | 17.4 | 16.2 | 16.5 | 16.7 | 16.9 | 17.4 |
| Variation of the observer position for the luminaire distances S | | | | | | | | | | | |
| S = 1.0H | | +1.2 / -1.9 | | | | | +1.2 / -1.9 | | | | |
| S = 1.5H | | +2.1 / -4.0 | | | | | +2.1 / -4.0 | | | | |
| S = 2.0H | | +3.5 / -5.0 | | | | | +3.5 / -5.0 | | | | |
| Standard table | | BK01 | | | | | BK01 | | | | |
| Correction Summand | | -1.9 | | | | | -1.9 | | | | |
| Corrected Glare Indices referring to 4000lm Total Luminous Flux | | | | | | | | | | | |

**Figure 3 – UGR table of the square office luminaire**

## Linear luminaire UGR 17

**Glare Evaluation According to UGR**

| ρ Ceiling | | 70 | 70 | 50 | 50 | 30 | 70 | 70 | 50 | 50 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ρ Walls | | 50 | 30 | 50 | 30 | 30 | 50 | 30 | 50 | 30 | 30 |
| ρ Floor | | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Room Size X | Y | Viewing direction at right angles to lamp axis | | | | | Viewing direction parallel to lamp axis | | | | |
| 2H | 2H | 16.9 | 17.7 | 17.2 | 17.9 | 18.1 | 16.7 | 17.5 | 16.9 | 17.6 | 17.8 |
| | 3H | 16.9 | 17.6 | 17.1 | 17.8 | 18.0 | 16.6 | 17.3 | 16.9 | 17.6 | 17.8 |
| | 4H | 16.8 | 17.5 | 17.1 | 17.7 | 18.0 | 16.6 | 17.3 | 16.9 | 17.5 | 17.8 |
| | 6H | 16.8 | 17.4 | 17.1 | 17.6 | 17.9 | 16.6 | 17.2 | 16.9 | 17.5 | 17.8 |
| | 8H | 16.7 | 17.3 | 17.1 | 17.6 | 17.9 | 16.6 | 17.1 | 16.9 | 17.4 | 17.7 |
| | 12H | 16.7 | 17.2 | 17.0 | 17.5 | 17.9 | 16.5 | 17.1 | 16.9 | 17.4 | 17.7 |
| 4H | 2H | 16.8 | 17.4 | 17.1 | 17.7 | 17.9 | 16.5 | 17.2 | 16.8 | 17.4 | 17.7 |
| | 3H | 16.7 | 17.2 | 17.0 | 17.5 | 17.9 | 16.5 | 17.0 | 16.9 | 17.4 | 17.7 |
| | 4H | 16.7 | 17.1 | 17.0 | 17.5 | 17.8 | 16.5 | 17.0 | 16.9 | 17.3 | 17.7 |
| | 6H | ~~16.6~~ | 17.0 | 17.0 | 17.4 | 17.8 | ~~16.5~~ | 16.9 | 16.9 | 17.3 | 17.6 |
| | 8H | 16.6 | 17.0 | 17.0 | 17.3 | 17.7 | 16.5 | 16.8 | 16.9 | 17.2 | 17.6 |
| | 12H | ~~16.6~~ | 16.9 | 17.0 | 17.3 | 17.7 | ~~16.5~~ | 16.8 | 16.9 | 17.2 | 17.6 |
| 8H | 4H | 16.6 | 16.9 | 17.0 | 17.3 | 17.7 | 16.4 | 16.8 | 16.8 | 17.2 | 17.6 |
| | 6H | ~~16.5~~ | 16.8 | 17.0 | 17.2 | 17.7 | ~~16.4~~ | 16.7 | 16.9 | 17.1 | 17.5 |
| | 8H | 16.5 | 16.7 | 17.0 | 17.2 | 17.7 | 16.4 | 16.6 | 16.9 | 17.1 | 17.5 |
| | 12H | 16.5 | 16.7 | 17.0 | 17.1 | 17.6 | 16.4 | 16.6 | 16.9 | 17.0 | 17.5 |
| 12H | 4H | 16.5 | 16.9 | 17.0 | 17.3 | 17.7 | 16.4 | 16.7 | 16.8 | 17.1 | 17.5 |
| | 6H | 16.5 | 16.7 | 17.0 | 17.2 | 17.6 | 16.4 | 16.6 | 16.8 | 17.0 | 17.5 |
| | 8H | 16.5 | 16.7 | 17.0 | 17.1 | 17.6 | 16.4 | 16.5 | 16.8 | 17.0 | 17.5 |
| Variation of the observer position for the luminaire distances S | | | | | | | | | | | |
| S = 1.0H | | +3.6 / -7.0 | | | | | +3.8 / -5.9 | | | | |
| S = 1.5H | | +6.3 / -8.2 | | | | | +6.5 / -6.6 | | | | |
| S = 2.0H | | +8.3 / -9.0 | | | | | +8.4 / -7.4 | | | | |
| Standard table | | BK00 | | | | | BK00 | | | | |
| Correction Summand | | -1.6 | | | | | -1.8 | | | | |
| Corrected Glare Indices referring to 3100lm Total Luminous Flux | | | | | | | | | | | |

**Figure 4 – UGR table of the linear office luminaire**

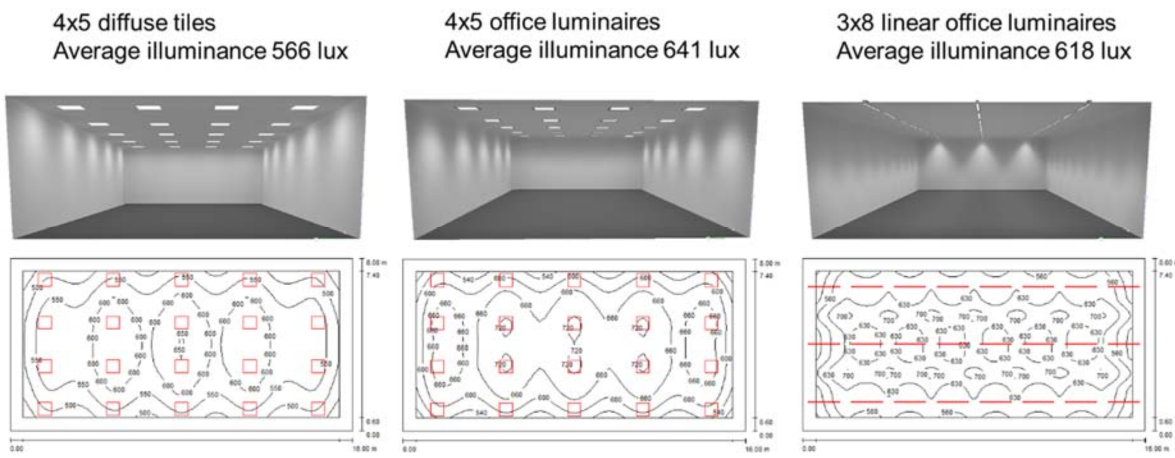


**Figure 5 – Room layout and illuminance distributions for the three different luminaires**

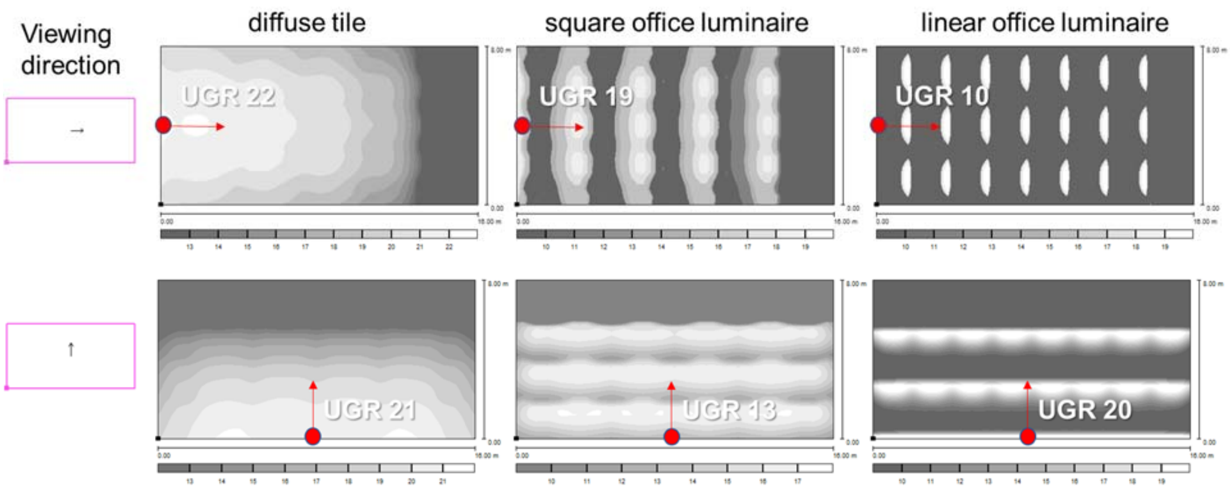


**Figure 6 – UGR point calculations at 1.2 m observer height**

The variation of the UGR point value as a function of observer position is also plotted in Figure 7, where the observer is on a line in the center of the room parallel to the long wall (indicated by the red dashed line in the top right of Figure 7), looking along the long side of the room. The value of the UGR point calculation varies with observer position, because luminaires may move out of the field of view of the observer. As a result the UGR value drops to 10 (no glare) when the observer is close to the wall that is in the viewing direction. For the diffuse tiles, the intensity distribution is Lambertian and the luminance is the same for every viewing direction. That is why the UGR does not change much when the observer changes position. Only when the luminaires move out of the field of view (are straight above or behind the observer) they no longer contribute to the UGR value. For luminaires with an intensity cut-off, there is also no contribution of luminaires that are relatively far away from the observer, even though they still may be in the field of view. For this reason, the luminaires with an intensity cut-off generally have a lower average UGR value, but the variation in UGR point values at different positions is larger.

It should be noted that the wild variations of the UGR value (between 1 and 10 UGR points for a small observer displacement of 200-300 mm) cannot be physically correct as the displacement is much smaller than the luminaire size. This error is caused by the fact that (in the used software) the contribution to UGR of a luminaire is evaluated only at the center point of the luminaire (see also Ashdown, 2005). This can be demonstrated by the following example. If the linear luminaires form a continuous line at the ceiling, the luminance distribution (and hence the UGR value) for an observer looking along that continuous line cannot vary much with observer position. Figures 8 and 9 show the variation in UGR when 11 luminaires of 1.5 m long are used to form three continuous lines at the ceiling. The observer is looking in the direction along the lines. The UGR value strongly varies between 10 and 20. When these luminaires are split up into 6 identical parts of 0.25 m long, the strong variation in UGR value disappears. This demonstrates that the variations seen in a UGR point calculation are partly caused by the calculation method itself and they are not related to any variation in glare experience in the real world. It should also be noted that a large part of the variations in UGR value of the linear luminaire *when viewed in the cross direction* are not an artefact of the calculation method, but related to the properties of the luminaire (i.e. caused by a combination of the intensity cut-off and a small luminaire size).

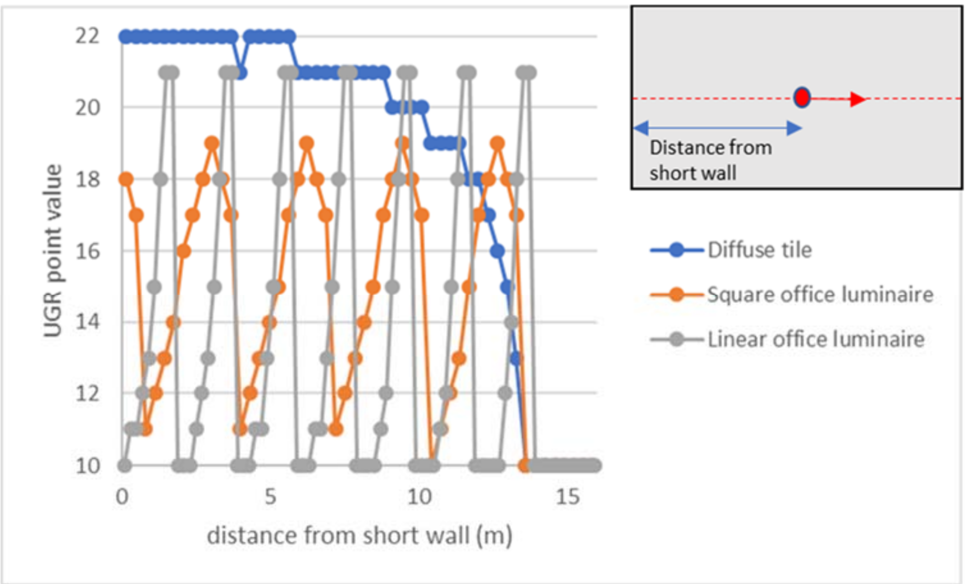


**Figure 7 – UGR point calculations at 1.2 m observer height in the middle of the room, along a line parallel to the long wall (dashed red line in top right figure)**

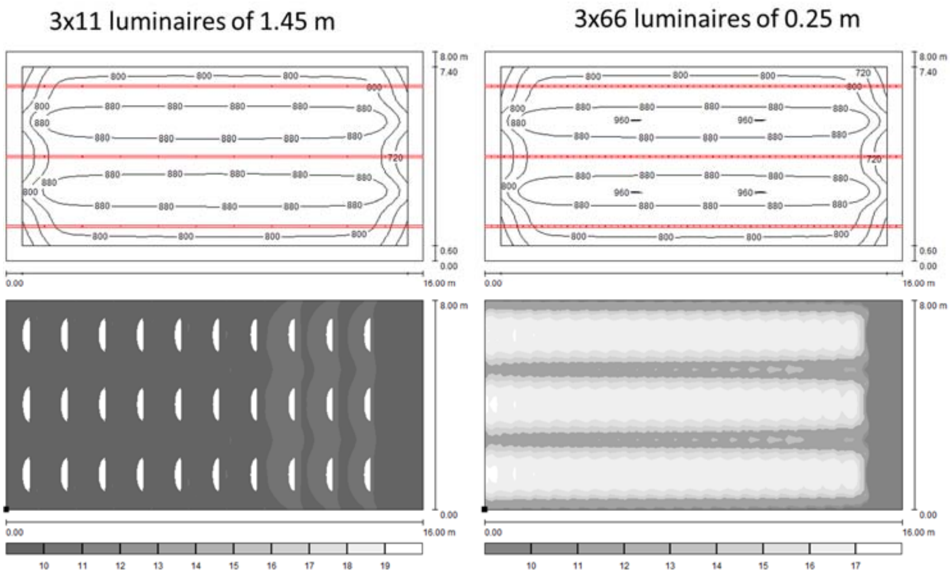


**Figure 8 – Workplane illuminance distribution (top figures) and UGR point calculations (bottom figures). The values are for a room with three continuous lines of linear office luminaires, either lines of 11 luminaires of 1.45 m long (left figures), or 66 luminaires of approximately 0.25 m long (right figures). The lighting in the room is identical, therefore all differences are the result of differences in calculation method (differences in discretization of the luminaire).**

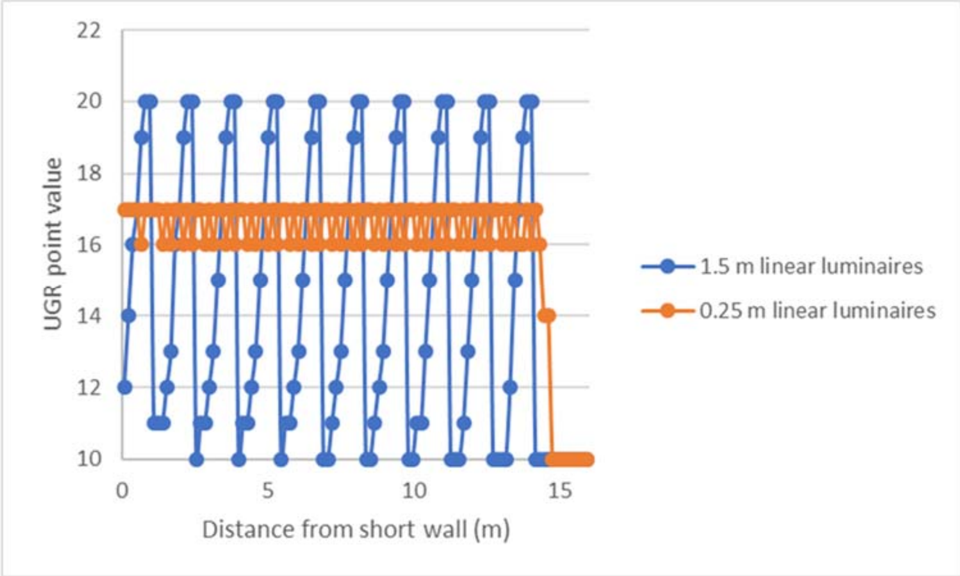


**Figure 9 – UGR point calculations at 1.2 m observer height in the middle of the room, along a line parallel to the long wall. The values are for a room with three continuous lines of linear office luminaires, either lines of 11 luminaires of approximately 1.5 m long, or 66 luminaires of approximately 0.25 m long.**

## 2.3 Naïve averaging method

The high density of luminaires used in the tabular method (S=0.25H) solves the unphysical variations in UGR values to a large extend. To apply the UGR method to a lighting installation that does not match the tabular method constraints, a similar averaging is clearly needed. To remove the strong periodic variations related to specific luminaire positions, the average UGR value is calculated for all grid points in an area defined by the luminaire spacing in both directions. In our calculations, we have used a dense grid of 10x10 grid points per luminaire. Figure 10 shows these luminaire areas (blue boxes) closest to the standard observer position, and the corresponding average UGR values.

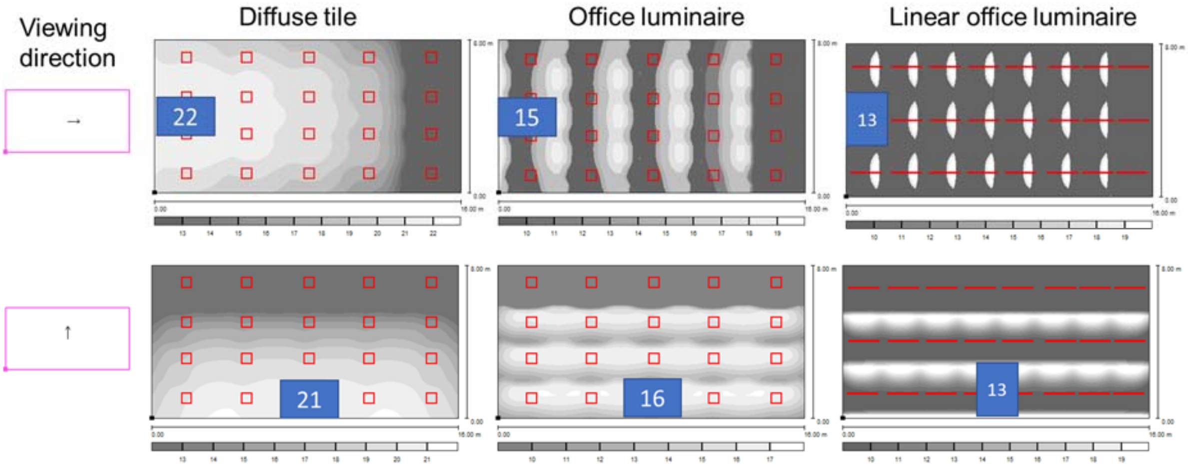


**Figure 10 – UGR point calculations at 1.2 m observer height. The blue boxes indicate the area defined by one luminaire spacing in both directions. The blue boxes give the average UGR point value in this area.**

For the diffuse tiles, the average UGR values correspond exactly to the tabular UGR values, they are slightly lower for the square office luminaire, but they deviate 3-4 UGR points for the linear office luminaire. These differences can be explained by the fact that the averaging is done differently in the tabular method.

## 2.4 New averaging method

To explain the averaging method, we introduce the quantity $S$, which is the summation inside the logarithm of the UGR formula:

$$S = 10^{R_{UG}/8} = \frac{0.25}{L_b} \sum_{i=1}^{N} \frac{L_i^2 \omega_i}{p_i^2} \quad (2)$$

In the tabular method, a high density of luminaires is used to average out spatial variations of the UGR value. If we copy the array of luminaires to create a second array of luminaires, displaced by a distance $\Delta x$ (smaller than the luminaire spacing), we get a new sum $S^*$ of the double array of luminaires:

$$S^* = \frac{0.25}{L_b^*} \sum_{i=1}^{N} \frac{L_i^2 \omega_i}{p_i^2} + \frac{0.25}{L_b^*} \sum_{j=1}^{N} \frac{L_j^2 \omega_j}{p_j^2} = \frac{S_1 + S_2}{2} \quad (3)$$

where we used the fact that the new background luminance $L_b^* = 2L_b$. The new value $S^*$ is therefore the average of the $S$ value of luminaire array 1 ($S_1$) and the $S$ value of the displaced luminaire array 2 ($S_2$), both as seen by the same observer. The averaging procedure of the tabular method is not averaging the UGR value, but the value of $S$.

The averaging done in equation (3) may also be interpreted in a different manner. The value $S_1$ is the contribution of the original luminaire array 1 to the original observer, but $S_2$ may also be interpreted as the contribution of luminaire array 1 to the observer that is displaced in a direction $-\Delta x$. Therefore the average value of $S$ is the average obtained by copying the luminaire array and displacing it with respect to the observer, but it is identical to the average obtained from a single luminaire array, evaluated on an array of observer positions that are displaced in opposite directions to the luminaire array displacements.

To obtain an average UGR value that may be compared to the average of the tabular method, we should average as follows:

$$\overline{R_{UG}} = 8 \log \bar{S} \quad (4)$$

Figure 11 shows the UGR values that are averaged over a luminaire area (blue area) according to equation (4). The values are in exact agreement with the tabular values, except for the linear office luminaire (15 and 16, while the tabular method gives 17 and 16).

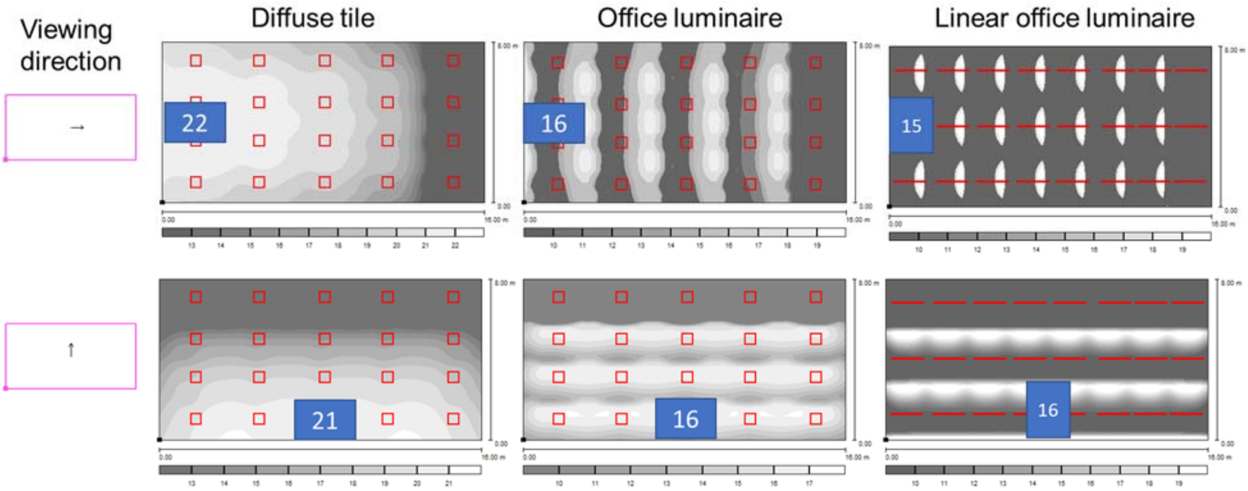


**Figure 11 – UGR point calculations at 1.2 m observer height. The blue boxes indicate the area defined by one luminaire spacing in both directions. The blue boxes give the average UGR point value in this area, calculated according to equation (4).**

The reasons for this remaining small deviation are: (1) the more extreme and largely unphysical UGR variations caused by a combination of a sharp intensity cut-off and the point approximation of a 1.5 m long luminaire; (2) the center of the averaging area does not coincide with the observer position at the wall (this issue is not present for observers that are more than half a luminaire spacing away from the wall); (3) averaging was based on integer UGR values, therefore accuracy cannot be better than about 1 UGR point; (4) the coarseness of the UGR calculation grid (UGR value was found to vary about 1 point when changing from a 5x5 grid per luminaire to 10x10); (5) the coarseness of the luminaire grid (S=0.25H) in the tabular method.

## 3 Conclusion

The tabular method provides robust and reliable UGR values that may be related to the limiting values that are prescribed by indoor lighting quality standards throughout the world. The drawback of this method is that it only applies to rectangular spaces with a rectangular luminaire grid that contains only one type of (quadrant symmetrical) luminaire. For non-standard conditions, the situation would need to be approximated such that it does fall within the tabular method boundary conditions.

When the UGR formula (1) is directly applied to any realistic lighting installation, the UGR value may be highly sensitive to the exact observer position: we have simulated huge variations with values between UGR 10 and UGR 20 using only a 200 mm displacement of the observer. We have demonstrated that a large portion of this sensitivity can be explained by the fact that the UGR contribution of each luminaire is evaluated only at the center point of the luminaire (in agreement with Ashdown, 2005). Such variations are not related to the variation in glare perception of real observers in the real world. Moreover, they cannot be related to the limiting values mentioned above.

Averaging the UGR value over an area around the observer reduces the deviations, but this ‘naïve’ averaged value still underestimates the tabular method value by several UGR points.

We have demonstrated that the tabular method does not average the UGR value itself. Instead the lighting conditions as seen by the observer are averaged. Mathematically, this means that not the logarithmic UGR value should be averaged, but the summation that is within the logarithm (Equation 4). By applying this new averaging method, a robust UGR value is obtained that agrees well with the value of the tabular method (up to about 1-2 UGR points deviation, as compared to the 10-point variation that is seen without averaging). To resolve the remaining deviations, the numerical UGR calculation method should be improved (finer grids of observer positions, better discretization of the luminaire).

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