Conformity assessment of glare in buildings considering the uncertainty of the parameter \( UGR_L \)

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Abstract. The evaluation of discomfort related to glare is a common need in buildings, requiring conformity assessment defined in the standard EN 12464-1:2011, using the parameter \( UGR_L \) index and a related scale with threshold levels associated with perceptible behaviour transitions. The scale is defined for a dimensionless parameter related to the degree of psychological (discomfort) glare of an electric lighting installation in an indoor space. The aim of this paper is to provide a comprehensive understanding of the role of the \( UGR_L \) uncertainty in the conformity assessment procedure, being a critical quantity used in the definition of a decision rule under the new edition of the ISO / IEC 17025 standard. The impact of the uncertainty of the \( UGR_L \) quantity is shown using examples of decision rules in measurements near the transition limits of the scale.

1. Introduction
In buildings, an adequate lighting should allow individuals to perform different visual tasks efficiently and accurately. The degree of visibility and comfort required for a wide range of visual activities is determined by the type and duration of the activity [1]. A good lighting design should take into account not only the required illuminances but also other qualitative and quantitative requirements. To comply with these requirements, satisfaction of three basic human needs should be achieved: i) visual comfort, where individuals have a feeling of well-being; (ii) visual performance, where individuals are able to perform their visual tasks, even under difficult circumstances and during longer periods and (iii) safety.

The main parameters determining the luminous environment with respect to electric lighting and daylighting are: (i) luminance distribution; (ii) illuminance; (iii) directionality of light and lighting in the interior space; (iv) variability of light (levels and colour light); (v) colour rendering and colour appearance of the light; (vi) glare and (vii) flicker. With the present paper, the authors will address specifically the effect of glare, and in particular, the discomfort glare [1].

Glare is the result of the presence of undesirable light in the visual field of an observer and generally originates from one or more excessively bright light sources. The CIE International Lighting Vocabulary (ILV) defines glare as “the conditions of vision in which one experiences discomfort or a reduction in ability to see details or objects, due to an unsuitable distribution or range of luminance, or to extreme contrasts” [2]. Glare can be experienced either as discomfort glare (causes discomfort without necessarily impairing the vision of objects) or as disability glare (impairs the vision of objects without necessarily causing discomfort). In interior spaces disability glare is not a major problem if discomfort glare limits are met.
The rating of discomfort glare caused directly from the luminaires of an indoor lighting installation is calculated using the CIE Unified Glare Rating ($UGR_L$) tabular method, based on the following formula [1, 2]:

$$UGR_L = 8 \log_{10} \left(0.25 \sum \frac{L^2 \omega}{p^2}\right),$$

where $L_B$ is the background luminance, calculated as $E_{ind} \cdot \pi^\frac{1}{2}$, in which $E_{ind}$ is the vertical indirect illuminance at the observer’s eye, in lux; $L$ is the luminance of the luminous parts of each luminaire in the direction of the observer’s eye, in cd/m$^2$; $\omega$ is the solid angle, in steradian, of the luminous parts of each luminaire at the observer’s eye; $p$ is the Guth position index for each individual luminaire which relates to its displacement from the line of sight [3-5]. The use of this parameter in the design of electric lighting installations implies the definition of upper limits applied to different degrees of reflectance of materials, walls, ceilings, floors and other working planes, considering specific lighting design solutions, such as the positioning and characteristics of luminaires.

The $UGR_L$ estimated value of the lighting installation shall not exceed the values referred in [1]. The recommended limiting values of the $UGR_L$ form a series whose steps indicate noticeable changes in glare. The series of $UGR_L$ is: 10 (imperceptible), 13 (just perceptible), 16 (perceptible), 19 (just acceptable), 22 (unacceptable), 25 (just uncomfortable) and 28 (uncomfortable). This quantitative scale of visual discomfort is based on the classification proposed initially by Hopkinson [6], supported on the statistical analysis of human qualitative perception of representative samples.

The conformity assessment requires the comparison of the glare rating estimate (in this case, $UGR_L$) and its uncertainty with the transition values of the scale of visual discomfort showed above. The decision of compliance should be supported by a decision rule.

2. Glare index measurement uncertainty evaluation

The knowledge about the measurement uncertainty is essential for a rigorous conformity assessment. This section presents the measurement uncertainty evaluation related to the glare index, based on the example presented in [5], which describes a simplified calculation approach for this quantity.

The studied example considers a square room with length $X$ and width $Y$ equal to 6 m and a ceiling height of 3 m. The height of eye level for a seated person is 1.2 m above the floor, therefore, the distance $H$ between the height of eye level for a seated person and the ceiling is estimated to be 1.8 m. The reflectance is assumed to be 0.7 for the ceiling, 0.3 for the walls and 0.2 for the floor. A height of 3 m. The height of eye level for a seated person is 1.2 m above the floor, therefore, the

The first calculation step consists in an initial glare index estimate obtained by linear interpolation from reference tabular glare data (Table 7.10 [5]). Based on the relation between $X$, $Y$ and $H$ ($X = Y = 3.3H$), an initial glare index estimate of 11.06 is obtained from the interpolation of four tabular estimates.

The second calculation step involves the application of corrections related to: (i) a mounting height above 1.2 m eye level different than 2 m; (ii) a total downward luminous flux different than 1000 lm; (iii) extra correction terms for different luminaire sizes or lamp types than the ones related to the reference tabular glare data. In the studied example, these corrections are once again obtained by linear interpolation from reference tabular data (Tables 7.10 and 7.11 [5]).

The quantification of the corresponding uncertainty components is given by the differences between the interpolation estimates and the closest tabular estimates, described by triangular probability distribution functions based on the assumption that the estimates are the most probable values of the distribution. The reduced size of the experimental data used for the interpolation, does not allow to assume a Gaussian or a t-Student probability distribution function. No information regarding the measurement uncertainty of the tabular estimates is found in [5] and, therefore, it is not considered in the evaluation.

In this example, a linear mathematical model (addition of initial glare index and corresponding corrections) of the simplified approach was considered suitable, allowing to use the GUM
conventional method [7] for the determination of the glare index measurement uncertainty. The measurement uncertainty budget (Table 1) includes the main contributions for the calculation. Regarding the degrees of freedom, the assigned values were estimated using the GUM approach for type B sources of uncertainty (equation G.3 of Annex G of the GUM, being the value of uncertainty reliable to 10%).

**Table 1.** Glare index measurement uncertainty budget.

| Input quantity                     | Estimate | Probability function | Standard uncertainty | Degrees of freedom |
|------------------------------------|----------|----------------------|----------------------|--------------------|
| Initial glare index                | 11.06    | Triangular           | 0.29/√6=0.12         | 50                 |
| Correction due to lamp luminous flux | 4.88     | Triangular           | 0.22/√6=0.090        | 50                 |
| Correction due to height above eye level | -0.20    | Triangular           | 0.20/√6=0.082        | 50                 |
| Correction due to luminaire length | 0.32     | Triangular           | 0.31/√6=0.13         | 50                 |

The final glare index estimate was equal to 16.06 with a combined standard uncertainty of 0.21 and 178 effective degrees of freedom (obtained using the Welch-Satterthwaite formula), for which a coverage factor of 1.97 is obtained for 95 % of confidence interval. Thus, the 95 % expanded uncertainty is 0.42.

### 3. Decision rule for conformity assessment using glare index measurement uncertainty

The growing need to assure that performance of buildings meets all the applicable requirements, namely, to conditions related to comfort, brings the interest to understand how conformity assessment should be developed and how decision rules are applied for measurement quantities such as glare index and, also, how its measurement uncertainty is accounted for.

Currently, the definition of decision rules to support conformity assessment, taking into account the uncertainty associated with the estimate of parameters is subject of reference documents based on statistical approaches of the problem [8]. This is the subject of particular importance nowadays, as it is one of the major changes introduced in the recently revised ISO/IEC 17025:2017 [9] supporting the reference scheme for the accreditation of testing and calibration laboratories.

The approach to establish the decision rule (criterion) can have two options (with single upper limit): to consider an approach making a direct comparison between the estimate and its expanded measurement uncertainty with the upper tolerance limit (the adopted approach); or the definition of a guard band based on the expanded measurement uncertainty interval.

In the case studied, experimental values were obtained for the estimate of the UGR_L parameter, its standard uncertainty, u(UGR_L) and the significance level expected (usually, of 95 % confidence), being the decision rule (for upper tolerance limit proximity T_U – a similar approach should be considered for the lower tolerance limit T_L) with a significance level of α the following.

**Acceptance**, if is true the hypothesis H0, \( P(UGR_L \leq T_U) \geq (1 - \alpha) \), \( (2) \)

**Rejection** if the hypothesis H0 is false, \( P(UGR_L \leq T_U) < (1 - \alpha) \). \( (3) \)

The expression to test corresponds to

\[
P_C = P(\eta \leq T_U) = \Phi \left( \frac{T_U - UGR_L}{u(UGR_L)} \right).
\] (4)

This process is illustrated in figure 1 for the upper tolerance limit.
Figure 1. UGR\textsubscript{L} value and its uncertainty near the upper limit of a tolerance interval.

An alternative approach (Figure 2) is based on the definition of a guard band, \( G_u \), for a defined confidence interval of \((1 - \alpha)\), requiring that the measurement uncertainty applied to the estimates of the quantity is fixed. In this case, comparison can be made directly between the estimate and the guard band limit, which can be practical for engineering purposes. The guard band lower limit is obtained using:

\[
G_u = T_U - u(UGR_L) \cdot [\Phi^{-1}(1 - \alpha)].
\]

(5)

Figure 2. Guard band for upper tolerance and guarded acceptance defined with an expanded uncertainty of 95%.

4. Conclusions

The role of uncertainty in the conformity assessment procedure is relevant due to the fact that a larger value of uncertainty implies higher risk of rejection of the conditions evaluated with technical and economic impact.

To illustrate the need of using the criteria presented in order to make a decision, consider an estimate of 16.06 and uncertainty of 0.21, being the uncertainty probability distribution partially inside two scale categories [13, 16] and [16, 19]. In this case, the comparison with the transition value 16 gives the amount of probability above the transition value,

\[
P_C = P(\eta \geq T_L) = 1 - P(\eta \leq T_L) = 1 - \Phi\left(\frac{T_L - Y}{u(\eta)}\right) = 1 - \Phi\left(\frac{16 - 16.06}{0.21}\right) = 0.612.
\]

(6)

In this case, the probability of being lower than 16 is 38.8% and higher of 16 is 61.2%, thus the conformity assessment for 95% of confidence, related to the scale categories [13, 16] and [16, 19], is not conclusive.

Another illustrative example following the same approach, using an estimate of \( UGR_L \) of 15.6, an uncertainty of 0.3 and a confidence interval of 95% would have two distinct decisions, based on
equation (6): if the decision rule is based only on the estimate, it will be accepted for the scale category of [13, 16]; otherwise, accounting the uncertainty in the same test, it would be rejected.

\[ P_C = P(\eta \leq 16) = \Phi\left(\frac{16-15.6}{0.3}\right) = \Phi(1.33) = 0.909. \]  

This result shows that, despite the estimate is lower than 16, the probability of being higher than 16 is \((1 - 0.909)\), equal to 9.1\% (higher than 5\%) thus being rejected. As the uncertainty value increases, the probability of rejection of measurement conditions also increase. When the measurement uncertainty has the same value for the range of the scale, is possible to introduce an alternative approach based on the definition of guard bands near the tolerance limits, allowing to simplify the analysis by making the comparison of estimates directly with the reduced acceptance region \([7]\).

The second approach, based on the definition of a guard band, allows an analysis of the relation between the \(UGR_L\) uncertainty and the guard band near a transition limit of the scale. Using eq. (5) and the transition limit of 16 (meaning the scale classification of perceptible), Figure 3 shows the functional relation, including the areas of compliance and non-compliance (in this case, for the interval between 13 – just perceptible – and 16 – perceptible and uncertainties between 0 and 1). This type of analysis, can be useful in engineering processes, as it can give a quick indication of the guard band amplitude for an uncertainty within the interval selected, providing a simple way to apply a decision rule.

![Guard band variation obtained for a measurement standard uncertainty interval](image)

**Figure 3.** Guard band variation obtained for a measurement standard uncertainty interval.

The use of the parameter \(UGR_L\) in the decision making process relies on its comparison with the transition values of the quantitative scale of visual discomfort. This scale defines a classification based on a discrete set of transition values, for which conformity assessment is made, by the comparison of estimates and related uncertainties with scale transition values, being the uncertainty the key for the decision process. The proper use of statistics in the criteria adopted is, therefore, a relevant issue for the quality of the assessment and decision.

Future research work is intended to be made for the evaluation of the \(UGR_L\) measurement quality applying other calculation methods and models including a sensitivity analysis of input quantities. Other relevant daylighting and electric lighting quantities and parameters will also be addressed in the future.

**References**

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