

Glare rating at different ages: the limits of the UGR method applied to a real case study

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Abstract. The Unified Glare Rating approach (UGR) is widely used in standards to estimate glare caused by lighting. However, its formulation loses reliability when applied to specific LED sources, complex geometries and irregular lighting configurations. Moreover, the standard approach considers a uniform group of people between 20 and 40 years old without accounting for older subjects. The present work enquires a real case study of a conference hall at the Polytechnic School of Genoa, which is attended by both young students (aged between 20 and 25) and the university of the third age (over 60). The results of the UGR approach are compared to the empirical information collected by questionnaires proposed to the subjects of different age: glare perception is more relevant at younger ages, while it fades at older ages. The numerical results estimated a “perceptible” glare, with a slight underestimation for younger groups and overestimation for older subjects. In addition, the results of the questionnaire show that a proper automation control system could overcome or at least reduce the impact of the reported issues. So, the energy saving obtained by an automatic management of the lighting system is proposed to demonstrate its convenience in terms of both comfort and energy saving.

1. Limits and applications of UGR and the role of BACS

The Unified Glare Rating (UGR) represents the standard formulation introduced by CIE [1] and it has been preferred to other, similar indexes proposed by different standards (e.g., British Glare Index – BGI [2], CIE Glare Index – CGI [3], Glare Control Mark – GCM [4] or Visual Comfort Probability – VCP [5], or other European formulations [6]). Indeed, such an approach relates to the effort made by different research groups to carry out a solid and reliable objective approach to the subjective perception of discomfort glare. Generally speaking, the most agreed definitions of discomfort glare identify the phenomenon as temporary, attributing to it different intensities. As concerns the International Lighting Vocabulary, this kind of glare is uncomfortable, independently of losing the sight of objects [7]. On the other hand, the Illuminating Engineering Society of North America proposes a very similar formulation in which glare is addressed as “annoyance or pain”, caused by high luminance in the field of view [8].

Basing on the structure of the UGR classical index [1], the parameter is a dimensionless quantity, defined as follows:

$$UGR = 8 \log_{10} \left(\frac{0.25}{L_B} \sum \frac{L^2 \omega}{p^2} \right) \quad (1)$$

where:

L_B is the background luminance, that can be estimated as a function of the indirect illuminance

E_{ind} over the observer's eye: $L_B = \pi^{-1} E_{ind}$ [cd/m²];

L is the luminance of each lamp along the observer's direction of view [cd/m²];

ω is the solid angle of each lamp along the observer's direction of view [sr];

p is Guth's position index, expressing the angle of deviation from the line of sight [-]

In addition, Table 1 provides an overview about the range of UGR values associated with the subjective average perception of glare and the typical applications that are related. Clearly, the table is meant to provide a preliminary information as each standard determines specific limits according to the chosen application.

Table 1. UGR limits and likely glare perception for indoor environments.

Glare perception	Imperceptible	Perceptible	Disturbing	Intolerable
UGR value	<13	13-22	22-28	>28
Example	Technical sign, precision work	Reading, writing, classrooms, computer work, control work	Rough work, storage rooms, machine halls, stairs	Not admitted

Equation (1) clarifies the accounted features in the approach and the associated limits. In detail, one has:

- Geometrical irregular arrangements: this topic is very wide, and it is not strictly referred to peculiar rooms with an irregular (i.e., or non-rectangular) planimetry. Namely, the approach does not account for actual luminaire groupings (e.g. narrow lamp groups) and even regular room with very high ratios between the plan sizes and the mounting height. Some studies are available [9-11], although a unique and consolidated approach is still missing. Some standards, such as [12], propose a smaller step in angular intervals to better approximate irregular lamp layouts, while others tend to approximate an irregular room as a summation of rectangular ones.
- Non uniform light sources: the topic has been widely enquired by different studies [13-18] and even the UGR method has been updated introducing UGR' parameter to deal with non-uniform spatial distribution [19].
- Non standard lines of sight: the UGR considers the standard direction of view for a human standing/sitting which belong to a plane inclined of about -2° respect to the horizontal plane. Anyway, for specific applications (e.g., industrial ones), the line of sight might dramatically differ from the standard view and to the best of the authors' knowledge there is still no unified index or approach to evaluate the level of glare in these cases. The standards usually do recommend special care to avoid glare using a specific luminaire arrangement with appropriate shielding angles.

- Effects of age-related visual changes: besides the specific illnesses associated to the human eye and the sight, the approach considers a sample of healthy people, between 20 and 40 years old [20]. Thus, no parameter accounts for the change in sensitivity at different ages as life expectancy in the population increase [21].

More in general, the issue of glare rating belongs to the topic of Indoor Environmental Quality (IEQ) and visual comfort as defined in [22]: “*a subjective condition of visual well being induced by the visual environment*”. Within this context, the Building Automation and Control System (BACS) plays a central role to allow a real time, self-managed plant, also applied to the lighting system. Actually, the BACS are not strictly concerned with only energy saving, but they grant the target plant performances, using the minimum amount of artificial light and maximising users’ comfort. Different studies [23-26] estimate a saving of about 10-25%, by using adaptive lighting and blind control algorithm while highlighting a significant improvement in the perceived room comfort. Indeed, the simplified approach of the UNI EN ISO 52120, [27] introduces 4 classes (A – better, D – worst) for each energy intensive service, basing on the features of the existing BAC systems. Then, for each service (e.g. heating, cooling, lighting, etc), each class is associated to a numerical BACS factor (tabulated and reported in UNI EN ISO 52120) obtained by performing transient pre-calculations for different building types. This coefficient is then used to assess the energy saving in a proportional way, as illustrated in equation (2):

$$W_{L,BAC} = W_L \left(\frac{f_{BAC,el}}{f_{BAC,el,ref}} \right) \quad (2)$$

where:

W_L is the annual lighting energy need [kWh], calculated without accounting for BACS

$W_{L,BAC}$ is the annual lighting energy need [kWh], taking into account the contribution of BACS

$f_{BAC,el}$ and $f_{BAC,el,ref}$ are the BACS efficiency factors respectively for the current state of BACS and for the design stage of a better BACS class [-]

Among the cited works, [28] emphasizes that, while the introduction of BACS in a plant manually managed is highly advisable, a total automatization should be avoided as users strongly appreciate the possibility to act on the plant, in case of need or urgency.

As concerns the present work, the effects of age-related on UGR shall be enquired referring to a real case study of a hall at the Polytechnic School of Genoa which is attended by both young students (20-30 years old) and third-age university attendants (over 60) following a double approach:

- Experimental survey: a questionnaire is distributed to groups of students (younger and older), searching for the effects of glare and discomfort basing on their experience during the past semester provided that they constantly attended to classes late in the afternoon and during winter, where any eventual glare due to the artificial lighting is more likely to appear.
- Numerical model comparison: the outputs of the questionnaire are compared with the UGR index obtained by a numerical model of the room, validated in a previous Authors’ study. The target is to enquire the representativeness of the index for different age segments [29].

Then, an analysis of the potential saving on the energy consumption for lighting thanks to BACS shall be provided according to the simplified approach reported in UNI EN ISO 52120-1 [27]. Indeed, the questionnaire is formulated with a double goal: enquire the subjective perception of glare and understand if the main causes of glare are associated to features improvable by means of a better self-managed lighting system.

2. Case study: San Salvatore Hall and the survey set up

2.1 San Salvatore Hall

The hall (Figure 1) is a multifunctional room of the Polytechnic School of Genoa which is used for standard classes during the academic year, eventually hosting conferences and other events. It was a former church, bombed during WWII and partially rebuilt after the war, preserving the survived frescoes inside.

The lighting system is formed by different lamps, all installed at about 10 m from the floor, all along the perimeter of the wall. The system is mixed, since part of the light is provided indirectly by means of reflections from the vault, while the other lamps provide direct lighting (Figure 2).



Figure 1. San Salvatore former church, now hall of the Polytechnic School of Genoa. On the left, in 1942 after the roof was destroyed by a bombing; on the right, nowadays [30].

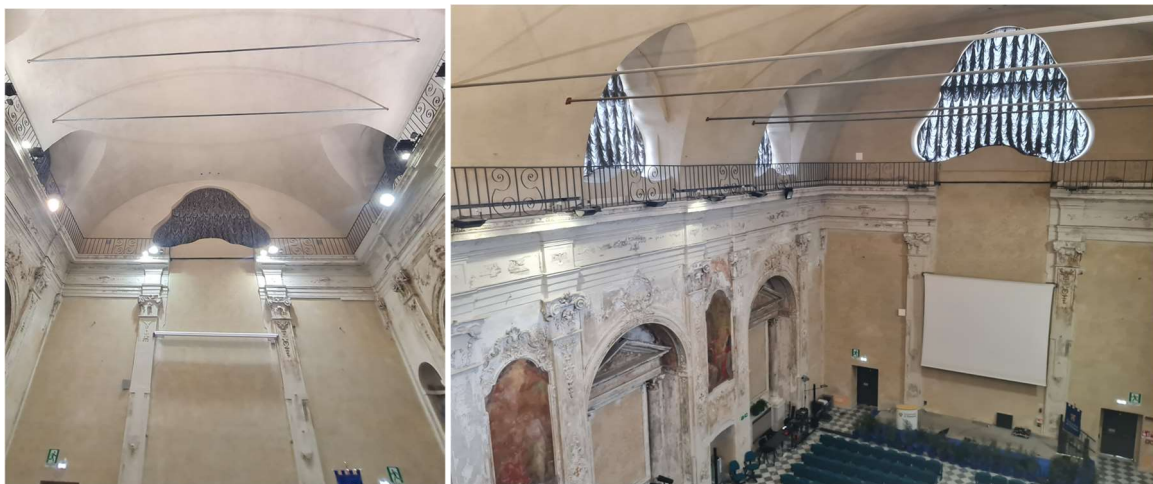


Figure 2. Inside of San Salvatore Hall and an overview of the existing lighting system.

As concerns the control system, only a manual control is present although the lamps are grouped so that different lighting configurations can be arranged (e.g. light only on stage, weak lighting all over the room, strong lighting, only indirect lamps, etc).

About 30 lamps are present: part of them still belongs to the original lighting system and they are discharge metal halide lamps (17500 lm – 360 W, mainly for indirect lighting) while the others

are LED which are gradually replacing the former lamps (4500 lm – 500 W, mainly for direct lighting). All the lamps present an almost uniform and large photometric solid, to grant a proper luminous intensity along all the considered directions.

The position of the lamps along the perimeter together with the high mounting height is very likely to cause discomfort glare as some lamps are likely to interfere with the line of sight of users sitting in the hall (e.g. Figure 2, on the left).

Finally, the hall can be divided into six main areas: the stage (at the bottom of the original church); four sectors in front of it and a group of stepped seats at the very bottom of the room.

2.2 Survey set up

The questionnaire is maintained unchanged with respect to the one formulated in [29], to allow a better comparison among the provided answers. Briefly recalling, the survey is structured to enquire the following key points, exploiting similar studies carried out and the available previous researches [31-33]: usual occupied seat and main visual tasks performed; comparison over a scale of any perceived discomfort, not only referred to light and sight, and eventual point out of any potential annoying lamp. Within these four thematic areas, the results can provide a direct comparison with other uncomfortable perceptions (e.g., hall too cold during winter) and they also provide more information about which location and performed task are more likely to get affected by glare.

The survey is proposed to two classes of Students of the third-age university who attended to evening classes respectively in the past two semesters (more than 180 people). Namely, both classes used the room mainly in late evening and during the shortest days of the year, so the results can be considered a representative base to provide an interesting overview of the glare perception in the older segments of the population. In addition, the same results are compared with the class of younger students (between 20 and 30 years old) who used San Salvatore hall during winter and answered to the same questionnaire.

3. Comparison of numerical and empirical results

In the present section, we present the results about glare obtained both basing on the validated, numerical model and on the results of the survey over differently aged groups of students.

3.1 Glare estimation from the numerical model

The model is built in Dialux Evo environment (Figure 3) and it performs the evaluation of UGR index according to CIE and UNI EN 12464-1 standard [6]. In a previous Authors' work [29], it has been validated basing on illuminance values measured onsite, so the results reported below are associated to a larger degree of precision and representativeness.

Basing on the validated, numerical results, the UGR ranges between 10 and 19 as worst result all over the nodes belonging to the calculation grid. Basing on Table 1, the glare is “perceptible” but still compliant with the maximum allowed by different standards for average tasks, such as reading, writing, computer work, control work.



Figure 3. Overview of the numerical model of San Salvatore Hall and extract of the UGR calculation referred to the speaker's stage.

3.2 Glare estimation from the questionnaire

All the enquired users had no specific sight problems or illnesses except the natural aging of the eye. The following tables resume the outcomes from the different questions in an aggregated form, keeping the distinction between the two groups. The outcomes are presented without further comments which are formulated in the next section.

- Usual seats: both young and older users are equally distributed over the different sectors, even though there is a slight preference for the seats at the very bottom of the hall.
- Most frequent visual tasks performed: also in this case, both groups are aligned: between 70% and 80% of the users (independently from the age) looks at the presentation shown on the stage and copies or writes down occasional notes. Almost nobody reads or extensively writes in the room.
- Possible causes of discomfort in the hall: the main results are resumed in Table 2. Among the available options, issues associated with lighting (e.g., shadowed areas, glaring lights, etc) are mixed with other features of indoor comfort (e.g., environment temperature, acoustic quality or seating comfort).

Table 2. Possible causes of discomfort: aggregated results.

Number of comfort issues concerned with lighting at the very first three places	3 comfort issues with lighting	2 comfort issues with lighting	1 comfort issue with lighting	No comfort issues concerned with lighting
Young group	20%	20%	33%	27%
Older group	3%	7%	20%	70%

- Perceived glare for different tasks: the users were asked to associate a mark from 1 to 4 to the level of perceived glare when performing different visual tasks (1 = negligible; 4 = intolerable). The main results are resumed in Table 3 aggregated for the two groups.

Table 3. Level of perceived glare for different visual tasks: aggregated results.

		Reading	Writing	Looking at the stage	Copying from the stage
Imperceptible	Young group	46.5%	40%	53%	20%
	Older group	82%	79%	71%	75%
Perceptible	Young group	46.5%	26.7%	13%	0%
	Older group	13%	18%	24%	20%
Disturbing	Young group	7%	26.7%	27%	67%
	Older group	4%	3%	5%	4%
Intolerable	Young group	0%	6.6%	7%	13%
	Older group	1%	0%	0%	1%

- Perceived effects due to potential discomfort glare: the users were asked for any potential discomfort that can be related to glare issues (e.g., headache). As for the previous topics, the aggregated results are available in Table 4.

Table 4. Perceived effects caused by discomfort glare: aggregated results.

	None	Moderate	Strong	Debilitating
Visual fatigue – young group	33%	53%	13%	0%
Visual fatigue – older group	62.8%	33.0%	4.2%	0%

- Identification of lights which might cause glare: besides of the previous questions, the enquired users were finally allowed to point out any light that resulted annoying according to their opinion. More in detail:
 - Younger group: all the investigated sample agreed that the lamps over the speaker's stage resulted glaring (Figure 4), independently from the seat position or performed visual task.
 - Older group: only 34 out of 188 total participants answered the question. They identified the same lamps pointed out by the younger group as glaring. Surprisingly, 7 people perceived as annoying also the emergency lamps over the doors near the speaker's stage.



Figure 4. Lamps perceived as glaring or annoying by both groups (red circles). The lights are over the speaker's stage.

3.3 Comparison of the results

The results, illustrated in the former paragraphs, allow two levels of analysis.

- Comparison between the two differently aged groups: both the younger and older groups used the hall in the same period, almost in the same seats and performing the same visual tasks. However, the results coherently highlight a general and dramatic loss in the perception of glare in the older group from the discomfort (e.g. not enough light to write notes) up to the lighter effects (e.g. visual fatigue). This result appears to be in contrast with the aforementioned studies in the former part of the present study. Actually, almost all studies agree that glare sensitivity increases with age as the eye becomes more sensible to the external stimulation. On the contrary, the current results are in open contrast with this statement; in addition, the number of enquired people (over 180) and the uniformity of the answers allow to exclude any eventual lower sensitivity in specific individuals. Anyway, the result must be properly put into context: according to the UGR method, the expected glare should only be “perceptible” in the worst cases (as in Table 1, UGR < 19). In addition, the enquiry required a comparison with other possible causes of discomfort intentionally not linked to visual tasks and lighting which might result more disturbing for the specific case

study. In the end, the main tasks performed would actually either have a short duration (e.g. writing brief notes) or involve visual tasks which might be not too demanding.

- Besides of this aspect, all groups commonly find the lamps over the speaker's stage annoying. Indeed, the considered lamps present a steeply inclined aiming point with a very high likeliness of glaring the users sitting below, as clearly visible in Figure 2.
- Furthermore, the glaring contribution of emergency lights represents another interesting topic. In fact, their contribution in the UGR method is not accounted for, accordingly to the UNI EN 1838 [34] which avoids glare calculations for lamps specifically adopted for emergency lighting. Anyway, the survey results clearly indicate that during standard usage, the contribution of the emergency lamps to the perception of glare is not negligible, especially for the older group. Within this context, either their contribution should be accounted for, or specific lamps working only in case of urgency should be adopted. This specific feature represents both an interesting future development for the present study and it is perfectly aligned with the consolidated state of art about the increased glare sensitivity in older subjects.
- Comparison between subjective questionnaire and numerical estimation of the UGR index. Basing on the previous comments about the results of the questionnaire from the two groups, the UGR method suggests a level of glare between 10 and 19, representing a “perceptible glare”. While this evaluation can be considered aligned with the opinion of the younger group, it is slightly overestimated in the case of the older one. In every case the method itself does not identify any critical issue for the lamps above the speaker’s stage, while this problem is commonly recognised by both groups.

4. Preliminary estimation of the energy saving due to BACS

The answers to the survey allow further considerations in the field of BACS. Indeed, the main issues associated to discomfort illustrated in the previous sections can be mitigated or even almost solved by means of an optimized self-managed lighting system.

While the benefits in terms of comfort are evident, this section is meant to provide a preliminary estimation of the advantages carried by a BAC system with respect to energy saving, following the simplified approach by UNI EN ISO 52120-1 [27]. The current lighting system falls in BACS class D, due to the presence of only manual switches, on and off. Basing on table A.3 of UNI EN ISO 52120-1, $f_{BAC,el,ref} = 1.06$. Then, an improvement in the automation of the lighting system can lead either to B class ($f_{BAC,el,B} = 0.94$) or to A class ($f_{BAC,el,A} = 0.89$).

Basing on Equation (2), the percentage preliminary saving can be expressed as a ratio between $f_{BAC,el}$ and $f_{BAC,el,ref}$. Table 5 resumes the savings for the two cases, as well as the minimum requirement for the BACS to fall into A or B class.

With reference to the Authors’ previous study, an annual consumption of about 18’000 kWh is a reasonable estimate under standard usage for the current lighting system.

This range implies an annual saving between 1800 and 2700 kWh which can be roughly estimated equal to 500-800 €, assuming a unitary gross price for electricity of 0.30 €/kWh.

Table 5. Percentage energy saving for BACS falling into A and B classes, together with minimum requirements to reach the target classes.

	$f_{BAC,el}$ [-]	$f_{BAC,el,ref}$ [-]	Percentage energy saving [%] $(f_{BAC,el,ref} - f_{BAC,el})/f_{BAC,el,ref}$ [-]	Minimum requirements for the BACS
From D (current) to B	0.94	1.06	11.3%	Control occupancy: Automatic presence sensor. Auto ON (if people detected) + Auto OFF (within 10 min after no people is detected) Control according to daylight: twilight switch on/off
From D (current) to A	0.89	1.06	16%	Control occupancy: Automatic presence sensor. Auto ON (if people detected) + Dimmed OFF (30% within 10 min after no people is detected, 0% within 20 min) Control according to daylight: twilight switch with regulation of the illumination

5. Conclusions and future developments

In the present work, a hall at the Polytechnic School of Genoa (Italy) has been selected as the setting to explore the Unified Glare Rating approach (UGR) with a novel insight into how glare is perceived by older people. More in detail, a survey was carried out involving a younger group (30 individuals) and an older one (188 individuals). In addition, the outcomes have been compared with the numerical UGR estimation performed by using a model in Dialux Evo environment, validated with onsite measurements. In this way, the representativeness of the current UGR method has been tested also referring to a large sample of older individuals.

The following main conclusions have been carried out by comparing the results of the survey with the numerical estimation of UGR.

- The sensitivity to glare dramatically decreases in older people, as clearly stated by the outcomes. This result is in apparent contrast with most studies, which tend to highlight an opposite finding. However, it can be explained by considering the low expected intensity of glare (i.e., $UGR < 19$), the execution of visual tasks having a short duration or poorly demanding, the presence of other concurrent causes of discomfort. Indeed, a high sensitivity in the older group is also confirmed by the perception of glaring due to emergency lights.
- Both groups perceive the lamps of the speaker's stage as annoying. Indeed, these lamps have a strongly inclined aiming point which makes them very likely to cause discomfort glare.
- Some people belonging to the older group have complained about the emergency light above the safety exits, especially the ones nearby the speaker's stage. These lamps resulted too luminous, causing the perception of glare in the subjects under standard lighting conditions. Such issue covers an important topic: the standard approach neglects this kind of lamps since they are expected to work only for a very short time, in critical conditions. Anyway, as in this

case, part of the emergency light might be constantly on, even without urgency, and contributes to the perception of glare in some individuals.

- The numerical estimation of the UGR is almost aligned with the glare perception of the younger group, demonstrating the validity of the approach. However, the same estimation tends to be slightly overestimated in case of older subjects who experience an almost negligible glaring, if present.

In addition, the answers to the questionnaire were designed to investigate the extent to which BACS helps mitigate potential issues. These aspects were integrated with a preliminary estimate of energy savings, basing on the approach reported in UNI EN ISO 52120, showing a potential saving between 10% and 15%. With reference to the annual energy lighting consumption estimated by the Authors' in a previous work, this means an energy saving range between 1800 kWh and 2700 kWh according to the simplified approach reported in UNI EN ISO 52120. Assuming a unitary electricity price of 0.3 €/kWh, this in turn implies a cost saving under standard conditions between 500 and 800 €/year.

As concerns the future developments, the survey could be extended to a middle-aged group, to cover more uniformly all the range of potential users. In addition, the topic of glare associated to emergency lighting in standard conditions could be deepened both in terms of questionnaires to the users and of extension of the UGR calculation method.

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