A COMPARISON BETWEEN DGI OBTAINED THROUGH DIFFERENT METHODS AND PERCEIVED EVALUATION INDEX DDG

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ABSTRACT

Daylight is a relevant resource for comfortable building and for sustainable environment.

The main advantages of daylight for building occupants and environment are:

- physiological and psychological benefits for human being;
- energy saving derivable from an optimal integration of daylight and electrical light.

On the other hand, high levels of daylight could generate glare phenomena. As a consequence, the physiological and psychological advantages of daylighting could be strictly reduced.

In this paper, after a brief description concerning glare phenomena and indexes for discomfort glare, a comparison between the results of a work on perceived evaluation of DDG (Daylight Discomfort Glare) and the daylight glare evaluation index (DGI) is presented.

1. INTRODUCTION

Building occupants prefer to live and work in spaces with comfortable daylight levels and distribution. Especially in working areas, the daylight presence affects the worker's satisfaction, performance and productivity. Moreover, daylight if suitably integrated with electrical light, could be a relevant source for energy saving [1].

For these advantages, designers and engineers should use daylighting systems as much as possible.

On the other hand, too high levels of daylight in an indoor environment could be a disadvantage for optimal visual and climatic conditions and for physiological reactions to possible glare phenomena.

Glare [2] is defined as the particular condition that could cause discomfort or could reduce the visual performance, the visibility and the capability to define details and objects. It could be caused by an unsuitable luminance distribution or by high luminance contrasts within the field of view. The perceived discomfort sensation which is not necessarily associated with the possible reduction of the visual performance is defined as "*discomfort glare*".

The evaluation of visual performance and comfort in presence of artificial lighting systems is still object of research and discussion. Daylighting, in particular, presents more difficulties concerning its variability during the time. So, the evaluation of the subjective reaction to the indoor environment becomes complex, because discomfort glare is experienced well before any measurable effect could be detected.

The object of this study is to compare the results of Kim et al. [3], on perceived evaluation of daylight discomfort glare with the evaluation of daylight glare index (DGI).

The images of the field of view, analyzed in this paper, were processed and evaluated through a specific software developed in MATLAB and based on the HDR technique. Output consists of photometric and geometric values useful for the visual comfort evaluation [4]. This paper shows the limits and reliability of DGI.

2. PRINCIPAL DAYLIGHT GLARE INDEXES

The results of the research concerning discomfort glare are mostly analytical relations that usually express the perceived discomfort degree through an index.

Most of these indexes are:

- VCP - Visual Comfort Probability [5,6];

- BGI - Building Research Station Glare Index [7];
- UGR - Unified Glare Rating [8];
- DGI - Daylight Glare Index;
- DGP - Daylight Glare Probability [9].

All discomfort glare indexes that can be found in the literature as well as all the Sensory Physics comfort indexes, either being purely analytical or statistical, derive from empirical evaluations or from perceptive analysis carried out on samples.

The DGI was developed with an empirical method on the basis of perceptive analysis of the discomfort glare caused by uniform artificial light sources that simulated the natural light source above the line of sight. After several modifications the DGI equation is:

$$\text{DGI} = 10 \log \sum_{i=1}^{n} G_i \quad (1)$$

$$G_i = 0.478 \cdot \left(\frac{L_{s,i}^{1.6} \cdot \Omega_i^{0.8}}{L_b + (0{,}07 \omega^{0.5} \cdot L_w)} \right) \quad (2)$$

where $L_{s,i}$ is the average luminance of each glare source in the field of view [cd/m^2]; L_b is the average luminance of the background excluding the glare source [cd/m^2]; L_w is the average luminance of the window [cd/m^2]; ω is the solid angle subtended by each glare source [sr]; Ω is the solid angle subtended by each glare source modified [sr]: $\Omega = \int \frac{d\omega}{p^2}$, where P is the Guth's position index, it changes with the proximity with the line of sight [10].

However, in order to take into consideration also the relativity of the perception of discomfort glare as a function of the subject, the VCP takes into account also the subjects that are different from the average and that can have extremely different tolerance thresholds to discomfort glare.

The DGP (Daylight Glare Probability) [9] allows to obtain a discomfort glare evaluation in accordance with the results obtained through perceptive tests, by taking into consideration the whole visual field as well as the visual task. Such evaluation has been carried out through measurement obtained by means of CCD – camera technique on real conditions.

The DDG - Degree of Discomfort Glare [3] is based on some perceived tests performed on subjects placed opposite wide uniform and non-uniform light sources (simulated windows).

In this paper, revising the data obtained by Kim et al. [3], the DDG results were compared to the respective ones obtained by the DGI through the simulations of the same conditions.

The results here obtained show a lot of discrepancies of the DGI with the real perception of the samples.

3. APPLICABILITY AND RELIABILITY OF THE DGI

Nowadays, although the DGI is one of the main indexes for the daylight discomfort glare evaluation, for sources with non-uniform levels of luminance, its application presents some limits:

- **Instrumental limits**: in the DGI expression (1), luminance values and solid angles are not so simple to measure with traditional instruments [11].

  The geometrical parameters ω and Ω can be evaluated through the use of diagrams which are only valid when the line of sight is perpendicular to the window and passing through one of the lower corner. But there are a lot of cases in which the window is not perfectly perpendicular to the line of sight [12].

- **Interpretative limits**: the subdivision of window plane in three zones (sky, obstructions and ground) could be an excessive simplification. In real cases, in fact, the non uniformity of each of these areas could give incorrect and conflicting results. The window plane could be subdivided in homogenous areas, but the criteria to do that is not so clear [13]. Studies leaded at the DETEC laboratory – University of Naples, Federico II, based on HDR Image Analysis (Figs. 1 and 2) [4], showed different results with different subdivision of the window plane (Tables 1 and 2). So, the number of subdivisions influences the final result.

  In the first case, the window plane is subdivided in sky, obstruction and ground. In the second case, the luminance range is subdivided in four intervals with homogeneous luminance. The DGI values obtained in the two cases are different.

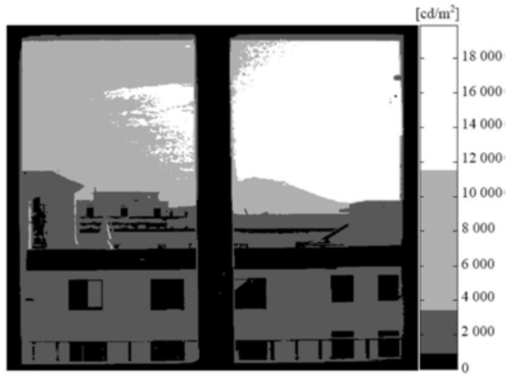


Fig. 1: Luminance mapping of a window

Fig. 2: Luminance mapping of the background

Also other researches, such as the ones carried out by Wienold and Christoffersen for the DGP definition showed that the use of technologies such as the CCD – camera allows a luminance mapping of the visual field, overcoming the difficulties of the traditional measuring devices [9].

- **Conceptual limits**: the background is not properly considered in the DGI formula. The solid angle of the background is not considered, apart from its luminance level.
- **Evaluation limits:** sensitivity about glare is changeable. Some researchers [14] showed that the perceived glare under real sky conditions was smaller than the DGI prediction . Also the ethnic differences of the subjects influence the evaluations under real sky conditions. Asiatic subjects seem to be more tolerant than Europeans to discomfort glare [15].

Table 1: DGI standard input data

	Range [cd/m²]	L_{si} [cd/m²]	ω_i	Ω_i	G_i
Sky	3421÷ 19923	11723	0,10	0,09	488
Obstruction	0÷3420	1167	0,16	0,13	16
Ground	-	-	-	-	-
ω	0,26				
L_w	5662				
L_b	260				
G	504				
DGI	**27**				

Table 2: DGI modified input data

	Range [cd/m²]	L_{si} [cd/m²]	ω_i	Ω_i	G_i
Sky1	3421 ÷11200	9226	0,05	0,04	174
Sky2	11201 ÷19923	13859	0,06	0,05	399
Obstruction1	0÷623	333	0,05	0,04	1
Obstruction2	624 ÷3420	1600	0,10	0,09	20
ω	0,26				
L_w	5662				
L_b	260				
G	594				
DGI	**28**				

4. DESCRIPTION OF THE EXECUTED COMPARISON TESTS

Many aspects about daylight discomfort indexes need further research. Sufficient experimental data on subjects are not present in literature, both in simulated and in real conditions.

In this paper, a study carried out by Kim et al. [3] has been considered as reference for some comparison tests, in order to verify the applicability and the reliability of the DGI and to confirm the needs to take into consideration the variability of the perception of discomfort glare from a subject to another.

The study of Kim et al. is based on "perceived tests" where glare is expressed as the Degree of Discomfort Glare (*DDG*). The window pane was divided into two parts, the upper one representing the sky (L_{up}) and the lower one representing the obstructions (L_{down}), as shown in Fig. 3. The window was located in a sky dome and the background luminance corresponded to the average luminance of the sky dome.

The tests condition of Kim et al. [3] were used to compare the results of the DDG with the DGI calculated in the same conditions through a purpose-built software created for daylight glare simulation and for the calculation of the DGI.

Moreover, the comparison was executed with different evaluation of the parameters that make up the DGI equation:

a. *standard method* - The L_w value was calculated (Fig. 3) as the average luminance of the whole window, weighed up with respect to the relative areas of sky, obstruction and ground, through the following equation:

$$L_w = \sum_{i=1}^{N} \frac{\frac{\omega_i}{\omega_{tot}} L_i}{N} \tag{3}$$

where N is the number of sources.

The results are reported in Fig. 4.

b. *first method* - L_s is equal to L_w, the later calculated according to equation (3). Then, only one G_i was taken into account, on the hypothesis that it was possible to consider the window with a uniform luminance assuming an average luminance value weighed with the solid angle.

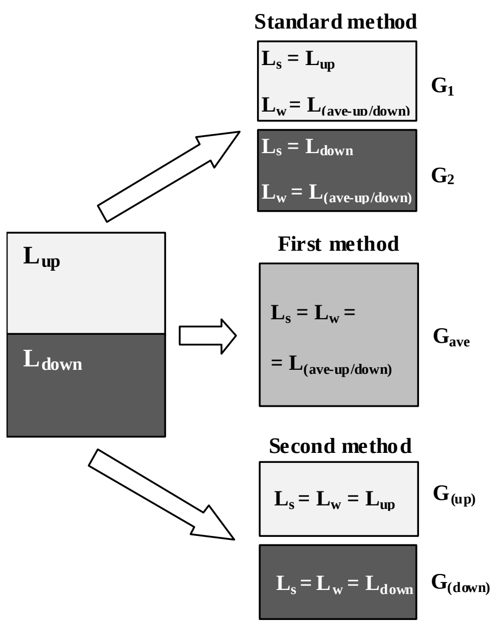
Through this method, the DGI values were calculated and reported in Fig. 5.

c. *second method* - The two parts of the window were considered as two separated sources, each one with a uniform luminance distribution. Thus, the following parameters were fixed:

- $L_{s1} = L_{w1} = L_{up}$
- $L_{s2} = L_{w2} = L_{down}$

The results are shown in Fig. 6.

All the results make it clear that there is a considerable discrepancy between DGI and DDG applied to the same cases. But, while in the first and in the second method, a rating scale problem is evident, for the standard method results are completely different, absolutely not comparable.



$$G_1 = \frac{0{,}48\, L_{up}^{1,6}\, \Omega_{up}^{0,8}}{L_b + 0{,}07\, \omega_{(up+down)}^{0,5}\, L_{(ave-up/down)}}$$

$$G_2 = \frac{0{,}48\, L_{down}^{1,6}\, \Omega_{down}^{0,8}}{L_b + 0{,}07\, \omega_{(up+down)}^{0,5}\, L_{(ave-up/down)}}$$

$$G_{ave} = \frac{0{,}48\, L_{(ave-up/down)}^{1,6}\, \Omega_{(up+down)}^{0,8}}{L_b + 0{,}07\, \omega_{(up+down)}^{0,5}\, L_{(ave-up/down)}}$$

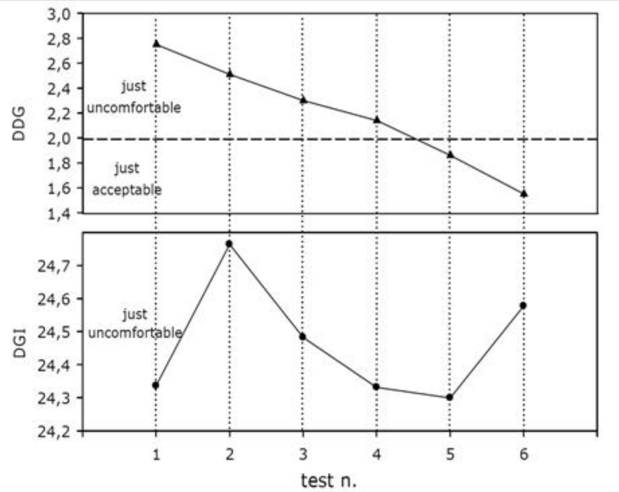
$$G_{up} = \frac{0{,}48\, L_{up}^{1,6}\, \Omega_{up}^{0,8}}{L_b + 0{,}07\, \omega_{up}^{0,5}\, L_{up}}$$

$$G_{down} = \frac{0{,}48\, L_{down}^{1,6}\, \Omega_{down}^{0,8}}{L_b + 0{,}07\, \omega_{down}^{0,5}\, L_{down}}$$

Fig. 3: Subdivision of the window plane and schemes of the three different evaluation methods of the DGI, with the relative equations utilized in the tests

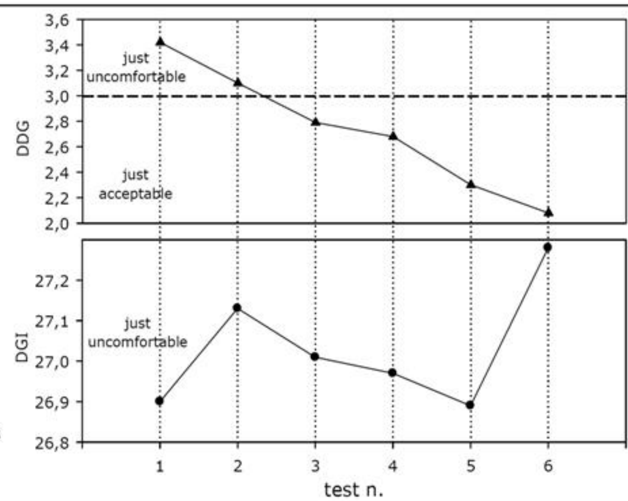
L_b variable L_{up} = 4080 cd/m²						
Test	Lup	Ldown	Lb	Lw	DDG	DGI
1	4080	4080	149	4080	2,75	24,34
2		3300	130	3690	2,51	24,76
3		2370	117	3225	2,30	24,48
4		1720	109	2900	2,14	24,33
5		840	98	2460	1,86	24,30
6		110	88	2095	1,55	24,58

DGI and DDG values in function of luminances
($88 < L_b < 149$ and $L_{up} = 4080$ [cd/m²])



L_b variable L_{up} = 8290 cd/m²						
Test	Lup	Ldown	Lb	Lw	DDG	DGI
1	8290	8290	191	8290	3,42	26,90
2		6100	172	7195	3,10	27,13
3		4560	148	6425	2,79	27,01
4		3140	129	5715	2,68	26,97
5		1520	127	4905	2,30	26,89
6		130	109	4210	2,08	27,28

DGI and DDG values in function of luminances
($109 < L_b < 191$ and $L_{up} = 8290$ [cd/m²])



L_b variable L_{up} = 17200 cd/m²						
Test	Lup	Ldown	Lb	Lw	DDG	DGI
1	17200	17200	420	17200	4,00	28,72
2		12230	417	14715	3,88	28,76
3		8240	362	12720	3,63	28,57
4		6130	344	11665	3,46	28,49
5		4570	330	10885	3,10	28,47
6		250	280	8725	2,89	28,85

DGI and DDG values in function of luminances
($280 < L_b < 420$ and $L_{up} = 17200$ [cd/m²])

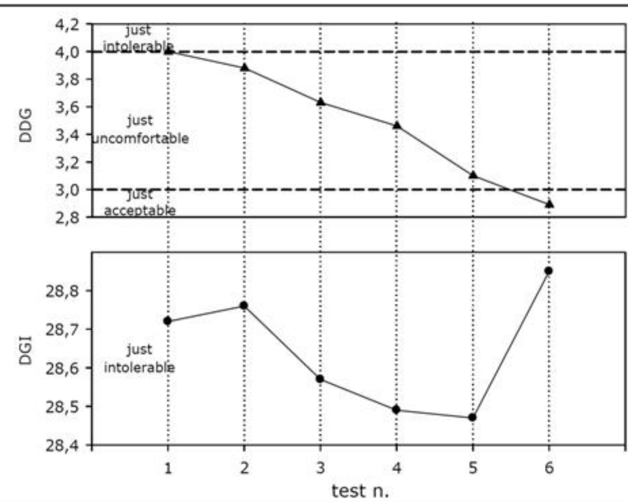
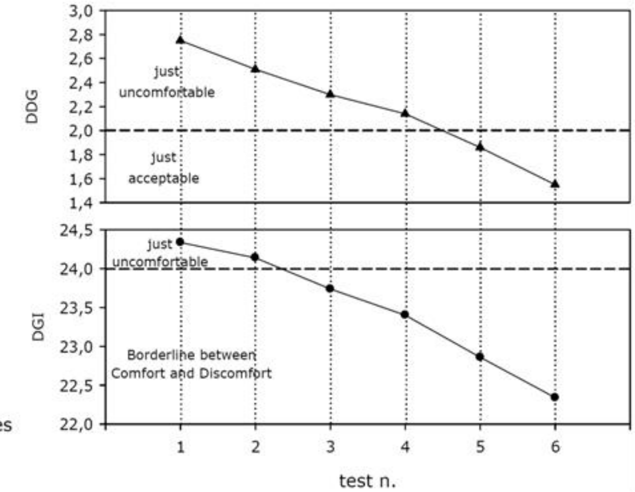


Fig. 4: "*standard method*" – L_b variable [cd/m²]
Results obtained comparing DDG values [3] with DGI values calculated by simulations with three fixed values of L_{up} and varying L_b. L_w is the average of L_{up} and L_{down}

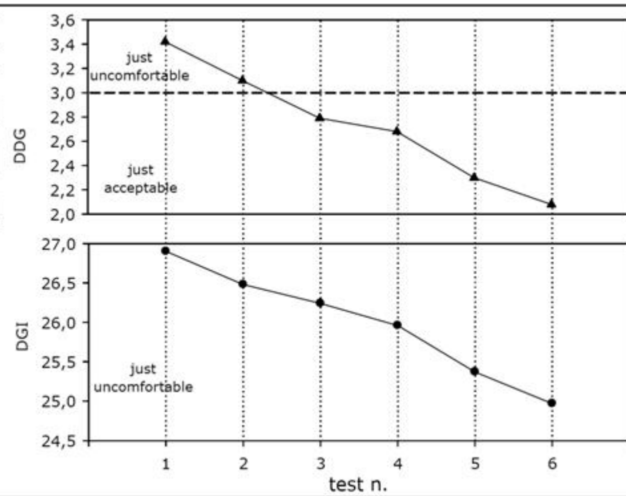
L_b variable L_{up} = 4080 cd/m²						
Test	Lup	Ldown	Lb	Lw	DDG	DGI
1	4080	4080	149	4080	2,75	24,34
2		3300	130	3690	2,51	24,14
3		2370	117	3225	2,30	23,74
4		1720	109	2900	2,14	23,40
5		840	98	2460	1,86	22,86
6		110	88	2095	1,55	22,34

DGI and DDG values in function of luminances ($88 < L_b < 149$ and $L_{up} = 4080$ [cd/m²])



L_b variable L_{up} = 8290 cd/m²						
Test	Lup	Ldown	Lb	Lw	DDG	DGI
1	8290	8290	191	8290	3,42	26,90
2		6100	172	7195	3,10	26,48
3		4560	148	6425	2,79	26,24
4		3140	129	5715	2,68	25,96
5		1520	127	4905	2,30	25,37
6		130	109	4210	2,08	24,97

DGI and DDG values in function of luminances ($109 < L_b < 191$ and $L_{up} = 8290$ [cd/m²])



L_b variable L_{up} = 17200 cd/m²						
Test	Lup	Ldown	Lb	Lw	DDG	DGI
1	17200	17200	420	17200	4,00	28,72
2		12230	417	14715	3,88	28,10
3		8240	362	12720	3,63	27,72
4		6130	344	11665	3,46	27,43
5		4570	330	10885	3,10	27,21
6		250	280	8725	2,89	26,54

DGI and DDG values in function of luminances ($280 < L_b < 420$ and $L_{up} = 17200$ [cd/m²])

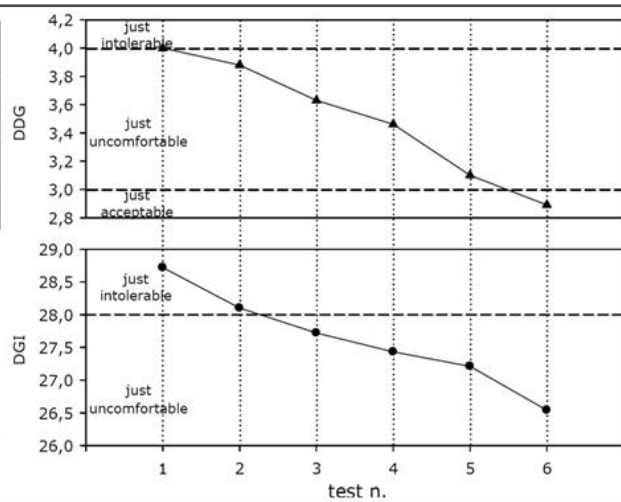
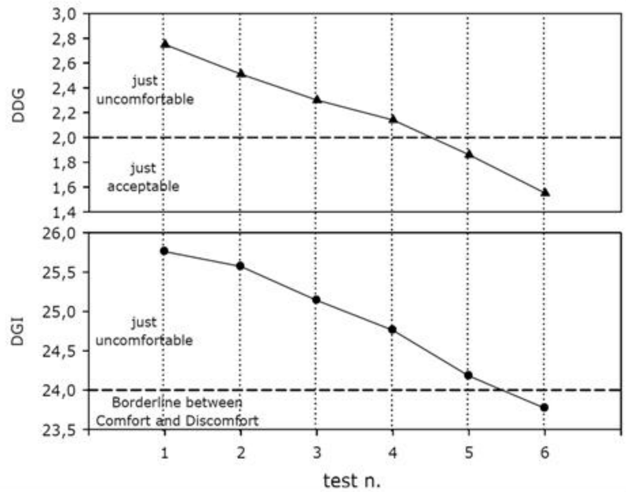


Fig. 5: "*first method*" – L_b variable [cd/m²]
Results obtained comparing DDG values [3] with DGI values calculated by simulations with three fixed values of L_{up} and varying L_b

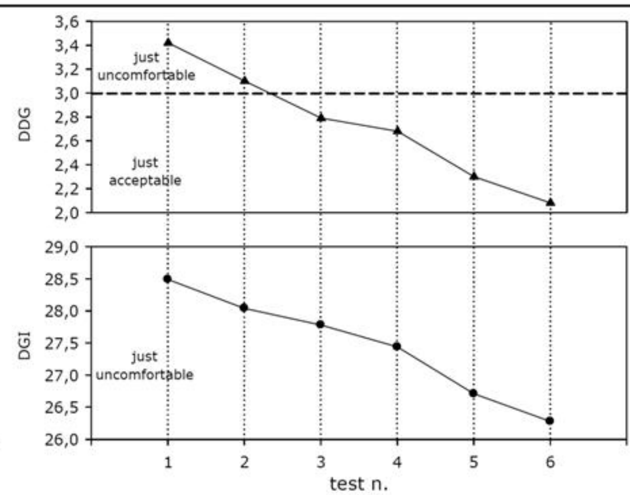
L_b variable L_{up} = 4080 cd/m^2						
Test	Lup	Ldown	Lb	Lw	DDG	DGI
1	4080	4080	149	0	2,75	25,76
2		3300	130	0	2,51	25,57
3		2370	117	0	2,30	25,14
4		1720	109	0	2,14	24,76
5		840	98	0	1,86	24,18
6		110	88	0	1,55	23,77

DGI and DDG values in function of luminances
(88 < L_b < 149 and L_{up} = 4080 [cd/m^2])



L_b variable L_{up} = 8290 cd/m^2						
Test	Lup	Ldown	Lb	Lw	DDG	DGI
1	8290	8290	191	0	3,42	28,49
2		6100	172	0	3,10	28,04
3		4560	148	0	2,79	27,78
4		3140	129	0	2,68	27,44
5		1520	127	0	2,30	26,71
6		130	109	0	2,08	26,28

DGI and DDG values in function of luminances
(109 < L_b < 191 and L_{up} = 8290 [cd/m^2])



L_b variable L_{up} = 17200 cd/m^2						
Test	Lup	Ldown	Lb	Lw	DDG	DGI
1	17200	17200	420	0	4,00	30,29
2		12230	417	0	3,88	29,60
3		8240	362	0	3,63	29,17
4		6130	344	0	3,46	28,84
5		4570	330	0	3,10	28,58
6		250	280	0	2,89	27,92

DGI and DDG values in function of luminances
(280 < L_b < 420 and L_{up} = 17200 [cd/m^2])

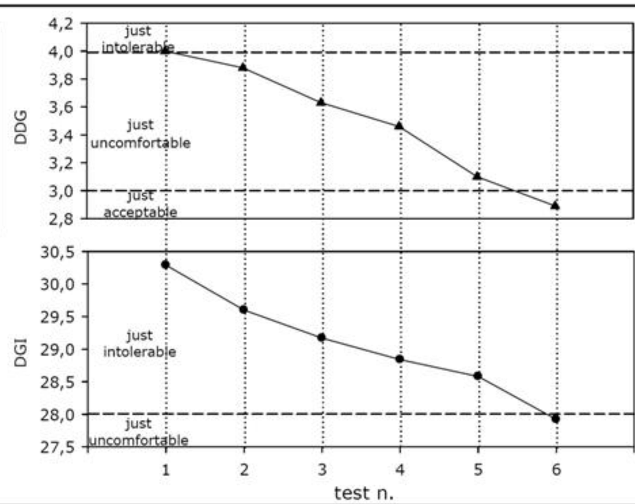


Fig. 6: "*second method*" – L_b variable [cd/m^2]
Results obtained comparing DDG values [3] with DGI values calculated by simulations with three fixed values of L_{up} and varying L_b

5. COMMENTS AND CONCLUSIONS

Glare certainly depends on four fundamental factors of the potentially glaring surface:

- Its solid angle;
- Its closeness to the line of sight;
- Its absolute luminance;
- Its relative luminance.

The DGI certainly takes into consideration such factors, through the solid angle ω, the solid angle Ω corrected by the position index, the luminance L_s of the potentially glaring surface, the average window luminance, L_w, and that of the background, L_b.

The comparison between the glare evaluation indexes, proposed in the present paper, shows that the DGI standard evaluation of the psychological glare, is not in accordance with the real discomfort felt by the subjects involved in the perceptive research on DDG. Fig. 4 shows that when the luminance of the lower part of the simulated window is reduced, the discomfort sensation of the subject gradually decreases:

In the first two cases, it passes from a just uncomfortable to a just acceptable situation (Figs. 4, 5 and 6); in the third case, it passes from a just intolerable to a just uncomfortable situation (Figs. 4, 5 and 6).

Otherwise, in the same conditions, the DGI presents a not well-defined trend. The comfort conditions change in a different way from that really perceived by the subjects. In particular when the terms at numerator and denominator of the DGI relation, respectively the partial luminances of the two distinct zones (L_s) and the average luminance of the window (L_w), DGI present different values.

This consideration is obtained modifying the application method of the DGI.

The *first method* takes into consideration a single window with the luminance value equal to the average luminance of the two separated surfaces. In the *second method*, the window is replaced with two windows with homogeneous luminance, and for which the partial luminance and the average one assume the same value (Fig. 3).

In both cases, DGI and DDG present a comparable trend, even if a difference between the two evaluation scale remains (Figs. 5 and 6).

In conclusion, the glare study object should be extended to the whole field of view, replacing the distinction between sky, obstructions, ground and background, with a subdivision in areas with homogeneous luminance the limits of threshold of which should be defined, from time to time, on the basis of the total dynamic range of the whole scene.

Moreover, like all the Sensory Physics comfort indexes, also the one relative to the daylight glare has to be based on statistical data, in order to take into account the variability of the perception of discomfort glare from a subject to another.

In the future it will be very important to improve the mentioned HDR Image Analysis System [4] in order to capture images and analyze results for further tests in real situation. The results obtained will be useful for defining a reliable glare index.

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