A new daylight glare evaluation method

A comparison of the existing glare index and the proposed method and an exploration of daylighting control strategies

Ali A. Nazzal MSc PhD [†] and

Acharawan Chutarat Ph.D. Candidate [*]

[†] Dept. of Electrical and Communicat. Eng., Helsinki University of Technology, P.O.Box 3000, FIN-02015 HUT, Finland

[*] Dept. of Architecture, Massachusetts Institute of Technology, 77 Mass. Ave. # 5-418, Cambridge, MA 02139, USA

Abstract

A proper glare prediction method is needed to promote visual comfort at workplaces. Only a few formulae have been proposed for discomfort glare of daylight origin, and they are inadequate in real daylight situations. No standard monitoring procedure is available for daylight glare evaluation on a comparative basis. This paper introduces an improved glare evaluation method consisting of a standard monitoring protocol and advanced formulae. The method has been tested against the existing glare evaluation system of Chauvel on different types of window transmittances using Radiance, a lighting simulation program. Moreover glare from another daylighting control strategy - the light shelf - was investigated. The proposed method appears to yield sensible and consistent glare values. The method was developed with the hope that architects and lighting designers would adopt it as an easy and reliable method for evaluating discomfort glare from daylight. Given reliable results, the DGI_N procedure was coded into a small program and incorporated with Radiance to compute daylight glare indices. The future work, which is an ongoing research, is to create the use of scientific-knowledge computational tools in the later stages of design in an effort to provide optimum choices of daylighting design with respect to light level and glare using the new glare algorithm.

List of symbols

a	Width of the window [m]
a'	Width of the pyramid [m]
ab	Actual glass area above 0.9 m in the facade [m^2]
abτ	Effective window area [m^2]
b	Height of the window above 0.9 m when calculating EWH [m]
	Height of the whole window when calculating the configuration factor ϕ_i of the window [m]
b'	Height of the pyramid [m]
c	Width of the facade [m]
d	Distance from the observation place to the centre of the window area [m]
d'	Distance between the sensor and the pyramid opening [m]
DGI_N	Daylight Glare Index (N refers to "new")
$E_{v1\ unshielded}$	Average vertical unshielded illuminance from the outdoors [lux]
$E_{v2\ unshielded}$	Average vertical unshielded illuminance from the surroundings [lux]
$E_{v3\ shielded}$	Average vertical shielded illuminance from the window [lux]
EWH	Effective window height [m]
$L_{adaptation}$	Average vertical unshielded luminance of the surroundings [cdm^{-2}]
L_b	Background luminance [cdm^{-2}]
$L_{exterior}$	Average vertical unshielded luminance of the outdoors [cdm^{-2}]
L_s	Source luminance [cdm^{-2}]
L_w	Window luminance [cdm^{-2}]
L_{window}	Average vertical shielded luminance of the window [cdm^{-2}]
ω	Solid angular sub tense of the source at the eye [sr]
ω_N	Solid angle subtended by the glare source (window) to the point of observation [sr]
Ω	Solid angular sub tense of the source modified for the effect of the position of its elements in different parts of the field of view [sr]
τ	Transmission of the window plane

1 Introduction

Building occupants generally prefer to live and work in a well daylighted space. The physical working environment, particularly the visual environment such as admission of daylight for indoor illumination, affects occupant satisfaction and worker performance and thereby also productivity. Daylight was one of the main considerations in building design to the first half of the last century. Then daylight was moved to a lower level of priority in the design process so that windows at most fulfilled the user's need to have a view only. In recent years the use of daylight as a light source has won renewed interest, mainly as a result of the need for energy savings and also because of the psychophysical reasons (the psychological and physiological need for light). Nowadays daylight is again one of the most important quality characteristics of the interior lighting of buildings.

The relationship between an individual and the physical environment is complex. Usually the occupant becomes conscious of the physical environment when it is uncomfortable. However, even minor effects may accumulate and lead to functional and psychological disorders when the eye keeps on trying to maintain a visual effort exceeding its physiological possibilities. If daylight is usually the preferred source of light, very high daylight availability in the interior environment is often contrary to optimum visual conditions and sunlight appears to create a whole host of psychological reactions. Glare is one of the major factors affecting visual comfort. If that problem can be solved, not only the visual comfort will be improved but also the savings of electric energy for artificial lighting can be increased due to the improved efficiency of daylight for the indoor illumination.

2 The grounds for a new method

The latest glare evaluation methods have been useful in prediction of discomfort glare from artificial light sources but only a few formulae have been proposed for discomfort glare of daylight origin (5,6,8,9,10,11). None of them predicts discomfort glare from daylight or particularly from direct sunlight. A single, internationally acceptable phenomenological glare formula and evaluation method has not been attained and no standard monitoring procedures are available. Glare is problematic also for the daylight-dependent control systems. Most of them react only to the horizontal illuminance, which however, is not sufficient for user comfort.

The subjective response to a lighting environment is complex, and impressions of glare discomfort are influenced also by other visual sensations, many psychological variables, testing conditions and individual variation (4). The net effect of these factors on the judgement process can lead to a systematic error resulting in variability of the ratings, which may not correlate the variability in the stimuli being rated. This has been the case in a number of glare assessments in artificial lighting. The situation must be even worse in real daylight. Also, it is not possible to measure directly an objective response because discomfort is experienced long before any measurable change in task performance can be detected. This gives occasion to ask whether subjective assessments are useful at all because they are not reliable. Mathematical glare prediction is objective, free from the errors that psychological and personal factors will bring.

However, the monitoring procedures for mathematical glare prediction may have problems. *CCD cameras* have been recently applied in glare evaluation in combination with a software to convert the signal level of the CCD camera into the actual luminance, or even to measure direct discomfort glare indices (UGR or VCP) (2). It must be taken into consideration that UGR and VCP are not valid for daylight. The relation between the signal level and the resulting luminance value differs with shutter speed, and there is a difference between the spectral sensitivity curve of the CCD camera and the one of the human eye. Therefore both an extensive calibration and $V(\lambda)$ correction are necessary. In addition, the time-consuming mapping, the data output of relative luminance values instead of absolute values and possible insufficiency of the accuracy for the purpose all have been found disadvantages of the CCD camera. Mapping of the parameters required for the calculation of DGI with *standard spot luminance meters* is not sensible either because daylight circumstances may change rapidly.

Evaluation of daylight discomfort glare in *test chambers with simulated windows* (3,4,5,12,13,14) will bring difficult problems since such a window is a large uniform and stable source of artificial light, and the psychological difference in the visual content of the field of view is obvious. In real daylighted spaces many kinds of lighting stimuli occur simultaneously. Therefore it is difficult to apply the glare index formula obtained from a laboratory experiment directly to the discomfort glare from real daylight, or to compare test results from test chambers and daylighted spaces. However, the equations of *Hopkinson* and *Chauvel* and all existing glare indices are based on experiments with uniform light sources and should therefore not be applied when discomfort glare is caused by non-uniform light sources. Also *using artificial light in the room* during the daylight glare measurements [5,6,11] makes it difficult to evaluate glare caused by windows.

Successful lighting and ergonomic design of workplaces requires a proper method and process for predicting glare. Daylighting design is a hard problem since its properties - such as sky conditions, lighting intensity and distribution, colours and radiant energy - vary over time. The principal aim of this work was to develop a new, mathematical glare evaluation method that would be valid for direct sunlight, and to implement the new glare algorithm into a computer program using Radiance that provides luminance values. Consequently, it would be possible by this method to define with ease and reasonable accuracy the glare level caused by windows in a room space in the form of a daylight glare index and to assist the selection of daylighting systems.

3 Concept of the new method

3.1 Parameters

The method is based on the *Chauvel*'s modification of the Cornell large-source glare formula (Eqn.2) to calculate daylight glare indices [5,6] in ordinary work and habitable rooms. The Cornell formula of *Hopkinson* (Eqn.1) takes into consideration the source luminance and the background luminance [8,9,10]. The parameters in the modified version by *Chauvel* are the source luminance, the window luminance and the background luminance:

$$G = 0.478 \sum \frac{L_s^{1.6} \times \Omega^{0.8}}{L_b + 0.07 \times \omega^{0.5} \times L_s} \quad [1]$$

where
L_s is the source luminance [cdm^{-2}]
L_b is the background luminance [cdm^{-2}]
ω is the solid angular sub tense of the source at the eye [sr]
Ω is the solid angular sub tense of the source modified for the effect of the position of its elements in different parts of the field of view [sr]

$$G = 0.478 \sum \frac{L_s^{1.6} \times \Omega^{0.8}}{L_b + 0.07 \times \omega^{0.5} \times L_w} \quad [2]$$

where
L_s is the source luminance: luminance of the patch of visible sky, of the obstructions and of the ground seen through the window [cdm^{-2}]
L_b is the background luminance: luminance of the interior surfaces [cdm^{-2}]

L_W	is the window luminance [cdm^{-2}]
ω	is the solid angular sub tense of the source at the eye [sr]
Ω	is the solid angular sub tense of the source modified for the effect of the position of its elements in different parts of the field of view [sr]

However, the monitoring protocol to measure the needed parameters has not been presented either in the publications of *Chauvel* or *Hopkinson.* Moreover, the summation sign in the two formulae makes both methods mathematically anomalous; since summation has to be over solid angles in the field of view, Ω must be to the power 1 (the summation must be proportional with the solid angle).

When compared with each other, both *Chauvel*'s method and the new DGI_N method use the basic glare parameters: size of light source; luminance; and position of the light source in the field of view. The equations utilised in the two glare evaluation procedures contain necessarily similar components but differ fundamentally in the determination of the sources of luminance and solid angles. In the new DGI_N method, the apparent solid angle $\boldsymbol{\omega_N}$ subtended by the window (Eqn.11), and the solid angle $\boldsymbol{\Omega_{pN}}$ subtended of the source (Eqn.12) are modified to include the effect of the *observation position (the position of the measuring equipment)* and configuration factor. The weight of the background luminance is large in *Chauvel*'s method that affects the average luminance of the visual field or adaptation luminance. A large glaring source such as a window also covers a too large area on the retina to be clearly distinguished from the background. Therefore the background luminance cannot be accurately defined and was rejected in this new method. Instead of that, the term of adaptation luminance was introduced because of the greater impact the immediate surround luminance has on discomfort glare sensation in comparison to the background luminance. The adaptation luminance includes the contribution of the source.

The parameters here are:

- the *window luminance* (Eqn.5): the source luminance
- the *adaptation luminance* (Eqn.6): the luminance of the surroundings including reflections from the internal surfaces
- the *exterior luminance* (Eqn.7): the luminance of the outdoors, caused by direct sunlight, diffuse light from the sky and reflected light from the ground and other external surfaces

3.2 Calculation procedure

The room can be occupied or unoccupied, with or without shading devices in the window, but the monitoring protocol assumes the room to have only vertical window(s). There are no limitations for the window size, shape, position or orientation. Because the measurement position is in the same horizontal plane as the centre of the window, the method is not, however, recommended for windows right under the ceiling such as clerestory windows in an industrial hall. This is because the difference between the measurement position and the position of the observer's eyes would be too big. In that case, the measurement could predict less glare than the observer would perceive when looking up towards the window and a brighter part of the sky. On the other hand, windows like that would be at the periphery of the visual field and would be notably less glaring. In regard to lighting, no artificial lighting is permitted but both daylight and sunlight can be measured. This is an advantage over the other daylighting calculations which all have assumptions not to include direct sunlight portion into a room [15,16]. The degree of discomfort glare is reflected in Daylight Glare Index, DGI_N (where N refers to “new”). As stated earlier, Ω must be to the power 1. This can be easily done since:

$$10\log_{10}\left(L_{exterior}^{1.6} \times \Omega_{pN}^{0.8}\right) = 8\log_{10}\left(L_{exterior}^{2} \times \Omega_{pN}^{1}\right)$$

[3]

The DGI_N can be calculated as:

$$DGI_N = 8\log_{10}\left(0.25\frac{\sum\left(L_{exterior}^{2} \times \Omega_{pN}\right)}{L_{adaptation} + 0.07\left(\sum\left(L_{window}^{2} \times \omega_N\right)\right)^{0.5}}\right)$$

[4]

The three parameters included in Eqn.4 are calculated as follows:

$$L_{window} = \frac{E_{v3\ shielded}}{2\phi_i \times \pi}$$ **[5]**

where L_{window} is the average vertical luminance of the window, calculated from the reading of the sensor with the shielding pyramid [cdm^{-2}]

$E_{v3\ shielded}$ is the average vertical illuminance from the window at the sensor with the shielding pyramid [lux]

$$L_{adaptation} = \frac{E_{v2\ unshielded}}{\pi}$$ **[6]**

where $L_{adaptation}$ is the average vertical luminance of the surroundings, calculated from the reading of the sensor without shielding [cdm^{-2}]

$E_{v2\ unshielded}$ is the average vertical illuminance from the surroundings at the sensor without shielding [lux]

$$L_{exterior} = \frac{E_{v1\ unshielded}}{2\ (\pi - 1)}$$ **[7]**

where $L_{exterior}$ is the average vertical unshielded luminance of the outdoors, calculated from the reading of the sensor without shielding [cdm^{-2}]

$E_{v1\ unshielded}$ is the average vertical illuminance from the outdoors at the sensor without shielding [lux]

The configuration factor ϕ_i of the window from the observation place (the position of the measuring equipment) is calculated as follows [19]:

$$A = \frac{X}{\sqrt{1+X^2}} \qquad B = \frac{Y}{\sqrt{1+X^2}}$$

$$C = \frac{Y}{\sqrt{1+Y^2}} \qquad D = \frac{X}{\sqrt{1+Y^2}} \qquad \textbf{[8]}$$

$$\phi_i = \frac{A \arctan B + C \arctan D}{\pi} \qquad \textbf{[9]}$$

$$X = a / 2d$$
$$Y = b / 2d \qquad \textbf{10]}$$

where	a	is the width of the window [m]
	b	is the height of the window [m]
	d	is the distance from the observation place to the centre of the window area [m]

The calculation of the solid angle and form factors can easily lead to mistakes. The apparent solid angle $\boldsymbol{\omega_N}$ subtended by the window, and the solid angle $\boldsymbol{\Omega_{pN}}$ subtended of the source are here defined accurately using particular formulae (Eqn.10,11) developed for this purpose [15,16]. However, in the modification by *Chauvel* these parameters are not calculated but estimated: $\boldsymbol{\Omega}$ is derived from the Peterbridge solid angle diagram, $\boldsymbol{\omega}$ is taken from the semi-sinusoidal Waldram solid angle diagram, and $\mathbf{L_b}$ is derived from the BGI nomograph.

No advice was found in the literature as to how many segments the window should be divided when calculating ω and Ω [1]. In this research, the consistency of ω_N was tested by calculating the value for an undivided window (1.55 x 1.35 m) and for the same window divided into four segments. The $\boldsymbol{\omega_N}$ values were nearly identical: 0.3841 for the undivided window, and 0.3835 as a sum of the four-quarter parts (0.096 for each). The number of segments does not have any essential influence on ω_N. This suggests that this is a stable part of the calculation. ω_N for a whole window is used in these calculations [16].

$$\omega_N = \frac{\quad}{d^2}$$

accurate to 1% for X, Y < 0.5

accurate to 5% for X, Y < 1 **[11]**

where	ω_N	is the solid angle subtended by the glare source (window) to the point of observation [sr]

Then must be

$$\Omega_{pN\ window} = 2\,\pi\,\phi_i$$

accurate to 1% for X, Y < 0.1 **[12]**

Eqn.10 provides accurate results also in comparison with computer calculations using the "Simpson rule" integration, i.e. step by step for single elements. The arguments of both angle functions (Eqn.10, 11) are only dependent on the horizontal respectively vertical dimension of the window. So, if both values for width and height of the window will be exchanged, nevertheless the same solid angle should result [15,16].

3.3 Measuring tools

Daylight discomfort glare is defined by a special arrangement of three illuminance sensors inside the room. A difficult series of frequent spot luminance measurements is not required but the novel monitoring methodology calls for continuous, automatic measurement of shielded and unshielded vertical illuminances from which the window (source) luminance, adaptation luminance and exterior luminance can be derived and the DGI_N to be calculated. The sensors should be spot sensors (concentrated into a spot, see Figure 3b). The sensors are mounted vertically on a tripod according to the midpoint of the window looking at its centre (Figure 1). This is because the luminance distribution within the window plane is non-uniform and can therefore cause more glare than uniform light sources when positioned perpendicular to the line of sight [21]. The glare sensation is largest at 0° from the viewpoint (Figure 2).

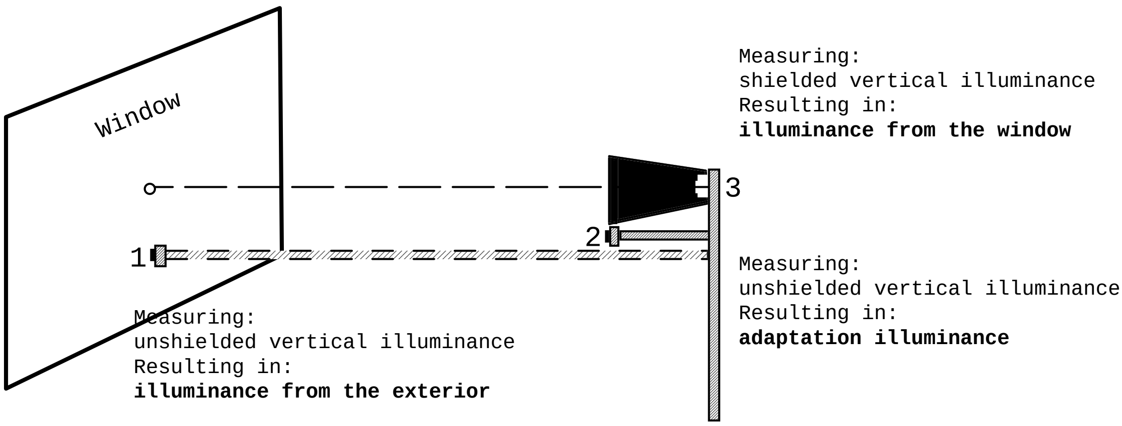


Figure 1 A set of three vertical sensors to evaluate discomfort glare

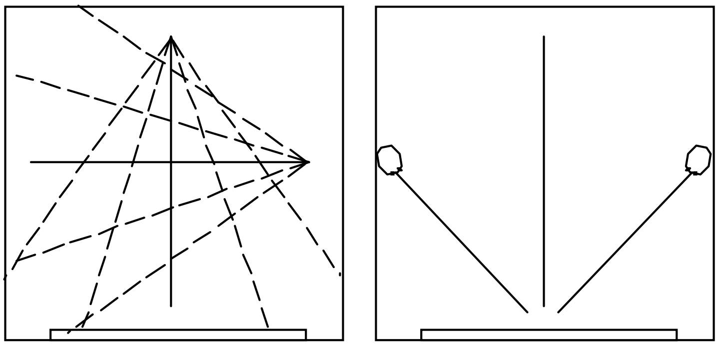
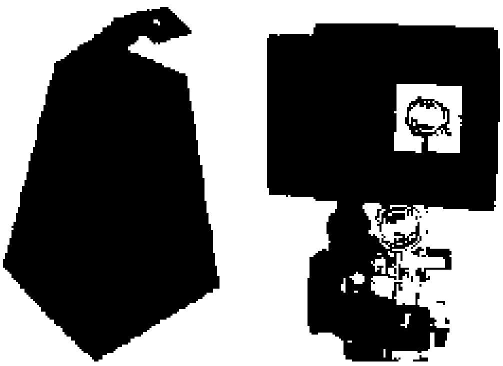


Figure 2 Glare sensation is worst when the observer is facing the window; especially at 0 degree from the viewpoint, DGI_N level appears to be the largest

Here a view straight onto the window is considered. Of course the experience at the instrument position may be much worse than the seated viewing position (due to what can be seen through the window from each position) but here the objective is to define only the worst-case condition. The calculation of DGI_N is based on the average luminance of the window wherefore small areas of high brightness within the overall window area are not considered. Photographs are used to record additional glare phenomena. Worth noticing is also that a real test subject could not be placed facing the window without influencing the results through the visual and psychological factors and disability glare that would be obvious in the presence of direct sunlight. Nevertheless, placing a test subject facing the window has been the practice in numerous glare researches [5,6,8,9,10,11,12,13,20].

Location of the sensors

- the unshielded sensor N° 1 (not necessarily mounted on a tripod but can be placed separately) is placed close to the middle point of the window at a distance of 0.20 m from the glazing (Figure 1) to measure *the exterior illuminance.*
- the unshielded sensor N° 2 is placed on the level of the opening of the shield for the sensor N° 3 (Figure 3 b,c) to cover a semicircular 180° area to measure *the adaptation illuminance.*
- the shielded sensor N° 3 (Figure 3 a,b,c) is placed at the level of the midpoint of the window (Figure 1) and is adjusted with a shield, black pyramid (with mat finish free of any reflections), to cover the rectangular window entirely without gathering light from the surroundings to measure *the window (source) illuminance.*



a. b.

c.

Figure 3 a The black pyramid to shield the sensor N° 3
b The unshielded sensor N° 2 and the shielded sensor N° 3
c The unshielded sensor N° 2 placed on the level of the pyramid opening

The distance between the window and the shielded sensor

To establish an appropriate procedure for the measuring of the parameters on a comparative basis under real sky conditions, subdivision of a room into three specific lighting areas (*the high daylight area, medium daylight area and low daylight area*) based on the effective window height, EWH, is recommended (7). The subdivision of a room is made according to the dimensions of the window and facade as it is shown in Figure 4. Room dimensions, however, are disregarded because the target is to define glare situation only in vicinity to the window.

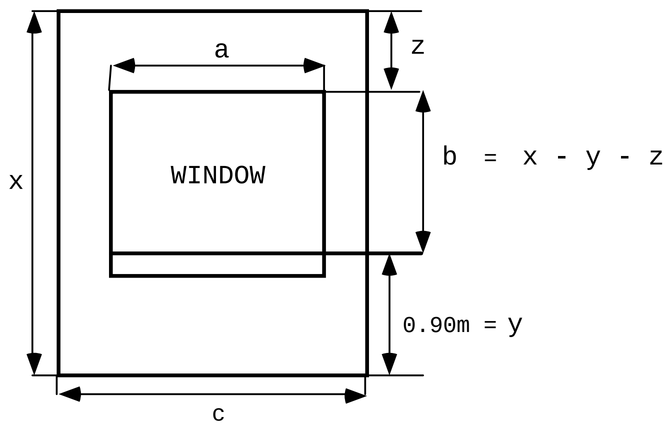


Figure 4 Determination of effective window height, EWH

The dimensions of the window and facade are then used in Eqn.12:

$$EWH = (ab\tau) / c \qquad \textbf{[13]}$$

where	EWH	is effective window height [m]
	$ab\tau$	is effective window area [m^2]
	ab	is the actual glass area above 0.9 m in the facade [m^2]
	a	is the width of the window [m]
	b	is the height of the window above 0.9 m [m]
	τ	is the transmission of the window plane
	c	is the width of the facade [m]

According to the value of EWH:

- *high daylight area* (where artificial light is not usually needed) starts at the facade and has a depth of appr. 2 x EWH
- *intermediate daylight area* starts at the border of the high daylight area and has a depth of appr. 1.5 x EWH
- *low daylight area* (where artificial light is usually needed) is the remaining part of the room

The perceived degree of discomfort glare is generally lower at the back of the room than near the facade [13,18]. This is because the degree of discomfort glare is dependent on the sky luminance, and the sky can usually be seen only from the high and intermediate daylight area. As the glaring sky occupies the largest part of the visual field in the high daylight area, wherefore it is disliked as a working place, the back edge of the intermediate daylight area was considered suitable as the position of the shielded sensor N° 3.

The measurement position based on EWH is completely different from the “mid-point of the walls” standard that has been used in electric lighting. The evaluation positions in the centre of each wall viewing normal to the wall is inadequate for daylight conditions where the light distribution as function of the distance from the window is to be determined for the needs of daylight control.

Geometric description of the shield

When the window dimensions are known and the distance between the window and the shielded sensor has thereby been determined, it is possible to shape the pyramid according to that information (Figure 5). The shape of the shield, however, can be also different from pyramid (e.g. a cube), provided that the sensor is totally covered by the shield and can “see” only the window and the inner surface of the shield that is black and free of any reflections. The shape of the opening of the shield, and the distance between the opening and the shielded sensor, are essential and are derived from Eqn.13, 14. Thus the distance can be calculated according to Eqn.15 and the dimensions of the shield opening according to Eqn.16.

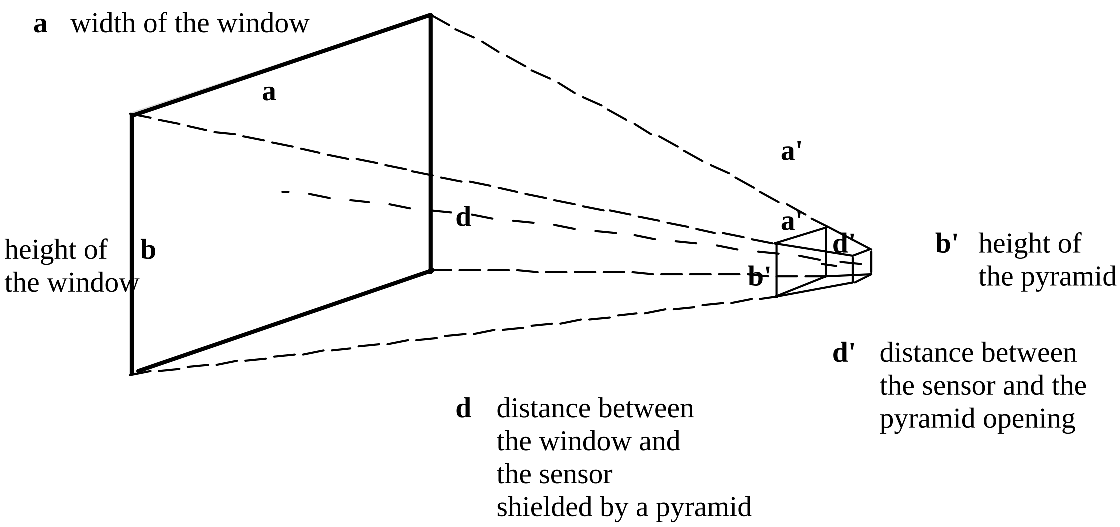


Figure 5 Similarity of triangles is the base for shaping the opening of the pyramid

Supposed that the sensor shielded by the pyramid is concentrated into a spot:

$$\frac{a}{2d} = \tan\alpha = \frac{a'}{2d'} \qquad \frac{b}{2d} = \tan\beta = \frac{b'}{2d'} \qquad \textbf{[14]}$$

$$\frac{a'}{a} = \frac{d'}{d} = \frac{b'}{b}$$ **[15]**

Thus the distance between the opening and the shielded sensor can be calculated:

$$d' = \frac{db'}{b}$$ **[16]**

and the dimensions of the shield opening can be calculated as:

$$a' = \frac{ad'}{d} \qquad b' = \frac{bd'}{d}$$ **[17]**

where	a	is width of the window [m]
	a’	is width of the pyramid [m]
	b	is height of the window [m]
	b’	is height of the pyramid [m]
	d	is distance between the window and the shielded sensor [m]
	d’	is distance between the sensor and the pyramid opening [m]

Recording of the parameters

To select the worst situation, the measurements are carried out in clear sky conditions when the sun is in the direction of the window(s) resulting in direct sunlight in the room. Exterior, adaptation and window illuminance is measured simultaneously every second by automatic data acquisition system (15,16). Note that in case of direct sunlight hitting the measuring equipment, all the three sensors should be exposed to sunlight.

4 Testing the applicability of the method

4.1 Measurements in a test room

The experimental arrangement took place in an ordinary office room. The test room had white wall and ceiling finishes and a grey floor, and one south-facing side window with double-glazing of normal clear glass in the middle of the wall. Performance of two different types of metallic polyester filters, silver and bronze, was tested on their ability to obstruct direct solar radiation in order to reduce discomfort glare and discrepancies in light distribution within the room. Clear glass without any filters was used as a reference. The filters were installed at the inner window surface (15). No psychophysical experiments were used to avoid problems that psychological and individual variation of test subjects, without dispute, would bring. The measurements were carried out in the following circumstances:

Geographical location Helsinki, Finland (latitude 60° N, longitude 25° E, meridian 30°)

Time	Every hour from 11 a.m. to 1 p.m. in April-June	
Sky	Clear	
Room	3.7m x 2.7m x 2.68m, located on the third floor (6m from ground)	
	Ground is covered by green grass with the reflectance of 0.12	
	Ceiling	- reflectance 0.70
	Walls	- reflectance 0.65
	Floor	- reflectance 0.30
Window	South facing with no obstructions, 1.55m x 1.35m	
	75 % transmittance (for visible light) for double clear glazing	
	30 % transmittance (for visible light) for double clear glazing with bronze filter	
	15 % transmittance (for visible light) for double clear glazing with silver filter	
	1. Vertical illuminance at 0.20 m off the window (interior)	
	2. Vertical illuminance at 1.93m off the centre of the window 1.50m above the floor	
	3. Vertical illuminance at 2.10m off the centre of the window 1.58m above the floor with a shield (pyramid)	

Exact dimensions of the test room and thus the basis of determination of the distance (d) between the shielded sensor N^o 3 and the window, as well as the shape of the shield, are shown in Figure 6. According to the above information:

$$EWH = (1.55m \times 1.35m \times 0.75) : 2.66m = 0.59m \approx 0.60m$$

and therefore

- the high daylight area has a depth of 1.20m
- the intermediate daylight area has a depth of 0.90m

Thus the correct distance (d) between the shielded sensor and the window is on the back edge of the intermediate daylight area:

$$1.20m + 0.90m = 2.10m \text{ (Figure 6)}$$

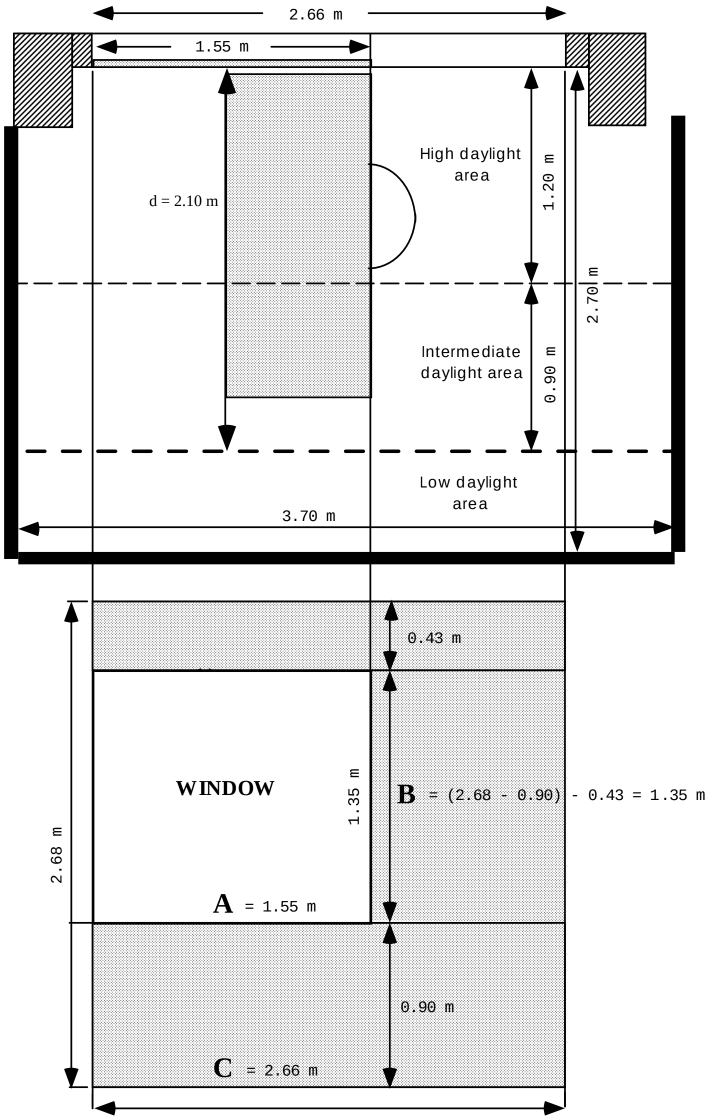


Figure 6 Exact dimensions of the test room

The midpoint of the window, and thus the level of the sensor N^o 3, is at a height of 1.58m (Figure 6). The distance between the shield opening and the sensor inside was chosen to be 0.17m. Thus the dimensions of the opening are according to Eqn.16 (Figure 7):

$$a' = \frac{ad'}{d} = \frac{1.55\text{m} \times 0.17\text{m}}{2.10\text{m}} = 0.12\text{m} \qquad b' = \frac{bd'}{d} = \frac{1.35\text{m} \times 0.17\text{m}}{2.10\text{m}} = 0.11\text{m}$$

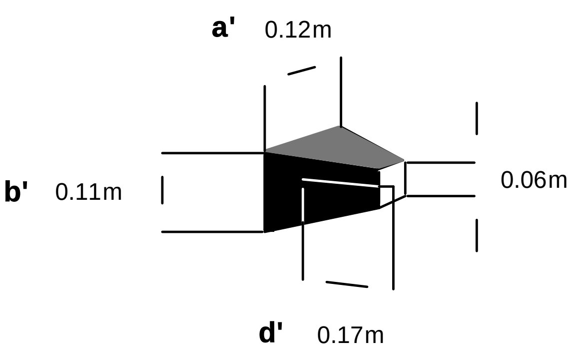


Figure 7 The dimensions of the shield

4.2 Simulations by computer

The real measurements laid a foundation for simulations. The simulations extended the investigation to cover other times of year and more daylighting control strategies, such as a light shelf. Moreover, the goal of this section was to determine how closely the new DGI_N and the existing DGI proposed by *Chauvel* are correlated.

Methodology

The experimental conditions were simulated by Radiance program. The room configurations and every items presented in the experiment were modelled and simulated (Figure 8). The window was south facing with no obstruction, located on the third floor of one building in Helsinki, Finland. The reflectance of the ceiling, walls, and floor were 0.70, 0.65 and 0.30. The ground was grass with the reflectance of 0.12. The window transmittances were 15%, 30% and 75%. The viewing point was located at sensor N^{o} 3 looking at the midpoint of the window. The field of view was an angle of 70 degrees measured in a horizontal plane perpendicular to the line of sight. As control, the simulations were run also for Fortworth, Texas, in the circumstances described above.

Radiance program simulating the experimental conditions was used to provide luminance values required for the new glare calculations. A Radiance script was written to calculate the luminance values for the whole year in clear sky conditions including direct sunlight onto the measurement point. In order to simplify the study, the simulations were calculated for every month at 10 days interval (day 1, 11, 21, 30 or 31) and every hour from 10.00 a.m. to 3.00 p.m. Once Radiance finished generating the required luminance values, the new DGI_N values were computed using the above equations. The existing glare index values were derived by glare utility program in Radiance.

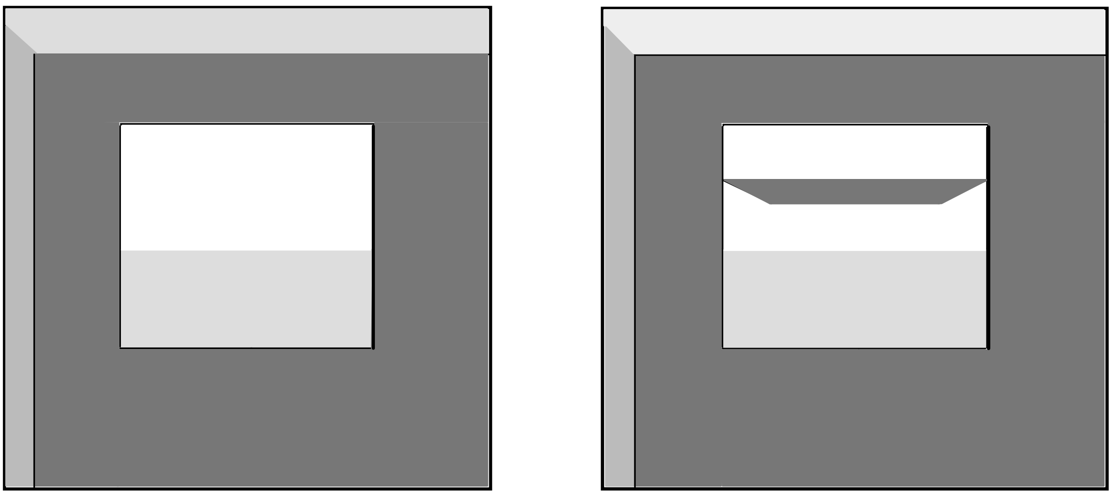


Figure 8 A view of the simulated test room without and with a light shelf

Finally simulations of the room with another daylighting control strategy, the light shelf, were explored in the circumstances of Helsinki using the new DGI_N evaluation method (Figure 8). Light shelves are horizontal solid fixtures positioned at right angles to either exterior or interior of both of windows. An external shelf with length of 1.55m and depth of 1.20m at 1.90m above the floor level was used here in the identical model room to the previous one (Figure 8). The upper and lower surfaces of the shelf were painted with white material of 70% reflectance. The window glazing was clear with 75% transmittance.

5 Results

5.1 Real measurements

Sky luminance usually has significant influence on discomfort glare. The performance of window filters is based on the reduction of window transmittance. The lowest measured (illuminance) and calculated (luminance) lighting parameters as well as the lowest DGI_N values were found with the silver filter and the highest with clear glass. The average value of the DGI_N was 30 for *clear glass* (exterior illuminance of 21000-46000 lux), 26 for a *bronze filter* (exterior illuminance of 7000-17000 lux) and 23 for a *silver filter* (exterior illuminance of 3000-8000 lux). The difference between a bronze filter and a silver filter, and between clear glass and the two window filters, was statistically significant according to the test of Friedman [15,16].

5.2 Simulations

Comparison between the two systems against different types of glazing

The graph provided in Figure 9 shows that the glare derived from the new DGI_N system is higher than that of *Chauvel*'s since the weight of the average luminance in *Chauvel*'s method is higher than what it is supposed to be. That makes the calculated glare in that method lower than normal. The two procedures differ significantly in how different light source and solid angles impact the total glare condition. It can be seen that the new DGI_N provides more reasonable results; the higher source luminance would provide more glare sensation. The variation with vertical illuminances was found even larger in the real experiments and in simulations run for the circumstances of Texas as presented in Figure 10. It seems according to the ongoing simulations that as the window becomes larger, the glare will increase (co-variance) but not to the extent predicted. This is because the glare source in occupying large part of the visual field increases the adaptation luminance, thus balancing out the effect of window size. The glare index of *Chauvel* behaves the opposite. Moreover, there is plenty of scatter in the DGI values; for example vertical illuminance of 39000 lux can result in the DGI value of 2 as well as 25.

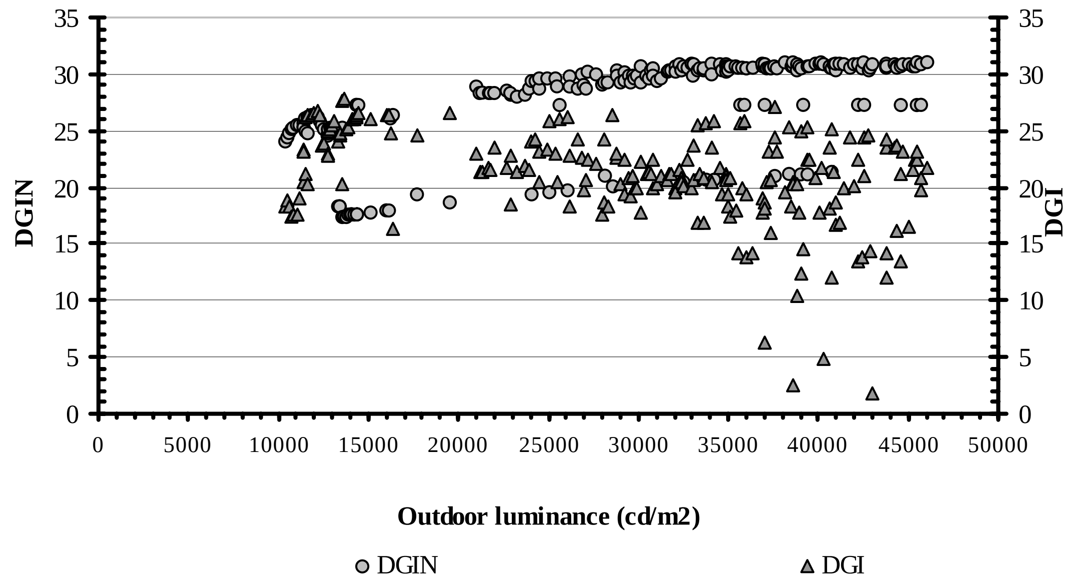


Figure 9 The new DGI_N and the DGI of Chauvel with clear glass as function of the vertical outdoor luminance in Helsinki, Finland

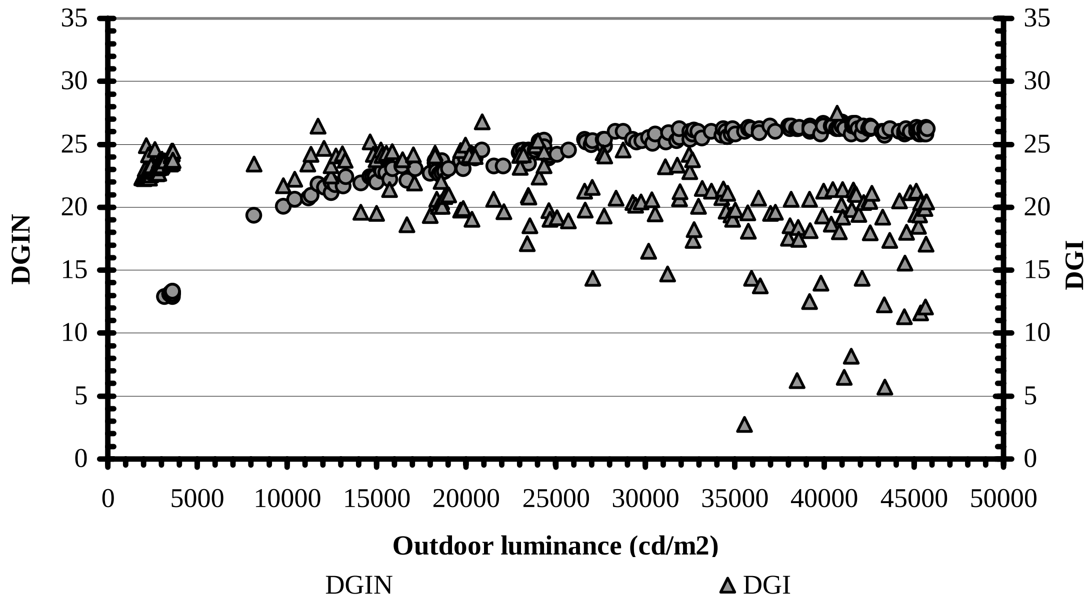


Figure 10 The new DGI_N and the DGI of Chauvel with clear glass as function of the vertical outdoor luminance in Fortworth, Texas

Typical for the variation of the exterior vertical illuminance in Helsinki (Figure 11) is that the greatest values occur in spring and autumn while the smallest values are found in winter. In Fortworth, Texas (Figure 12), the greatest values are found in winter whereas the smallest values occur in summer. The obvious explanation for the difference is the higher solar angle of Texas throughout the year.

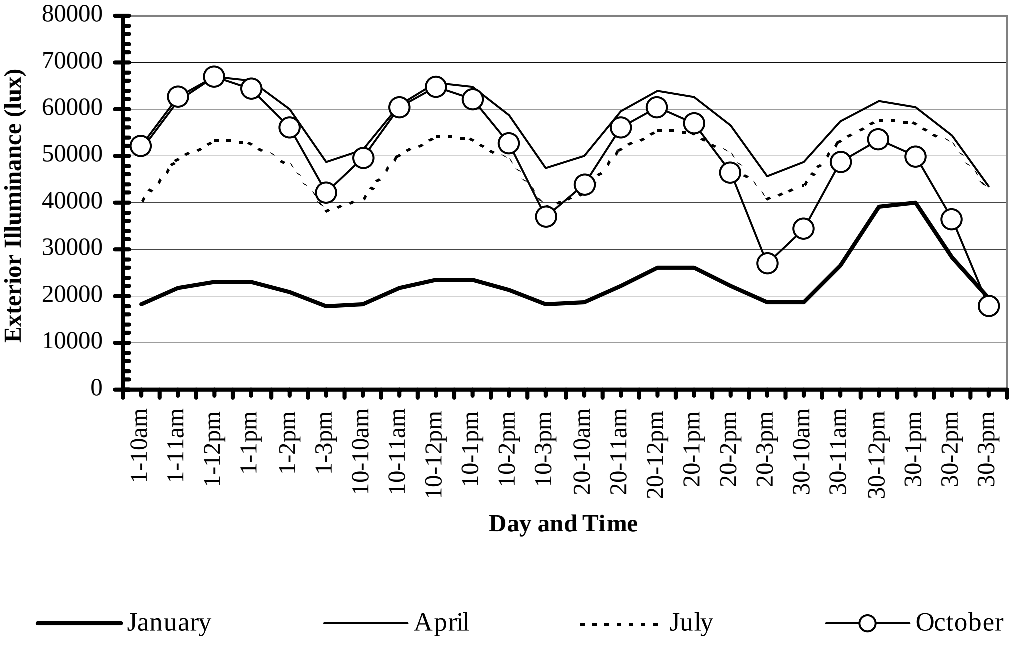


Figure 11 The variation of the exterior vertical illuminance in Helsinki, Finland, from 10 a.m. to 3 p.m. on the 1st, 10th, 20th and 30th of January, April, July and October.

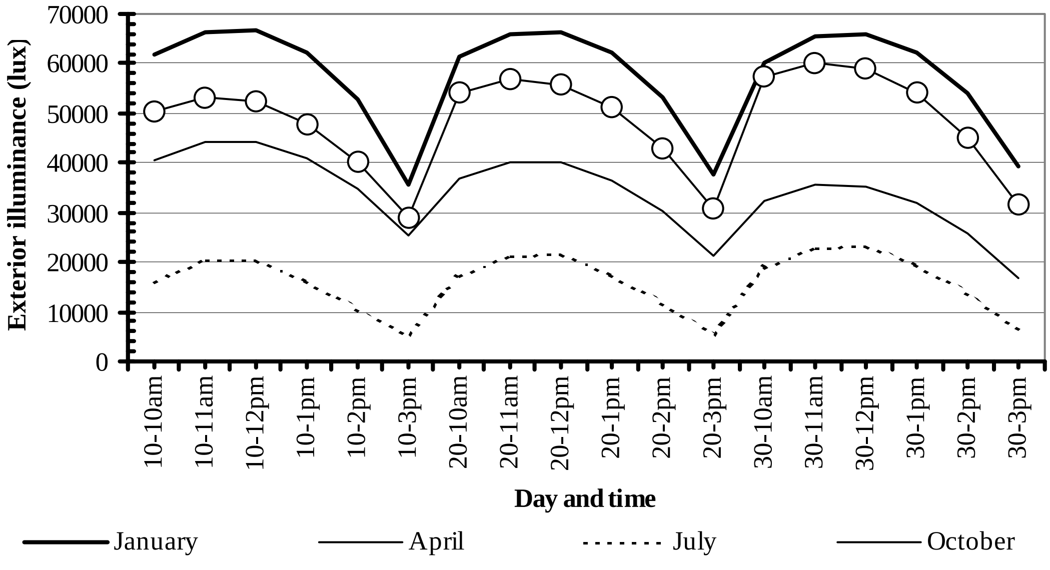


Figure 12 The variation of the exterior vertical illuminance in Fortworth, Texas, from 10 a.m. to 3 p.m. on the 1st, 10th, 20th and 30th of January, April, July and October.

The results of calculated glare for the whole year in Helsinki are shown in Figure 13 and 14. The smallest glare index values of the new method (Figure 13) occur in winter from the middle of October to the middle of February. This is because in Helsinki, both the lowest solar angle and the smallest vertical illuminance values on the window occur in winter respectively. The divergence between the different hours in winter can be explained by reflections; the DGI_N values are smaller at noon at 12 and 1 p.m. than at 10 or 11 a.m. and 2 or 3 p.m. The greatest glare index values occur between spring and autumn because of a greater solar angle and greater vertical illuminance at that time of year. The higher is the source luminance, the worse will be the glare sensation according to the new method. The glare index of *Chauvel* (Figure 14) behaves the opposite giving the smallest values in the end of April and in the end of August so that the greatest glare index values occur in December – January at the time of the smallest solar angle and the smallest vertical illuminance.

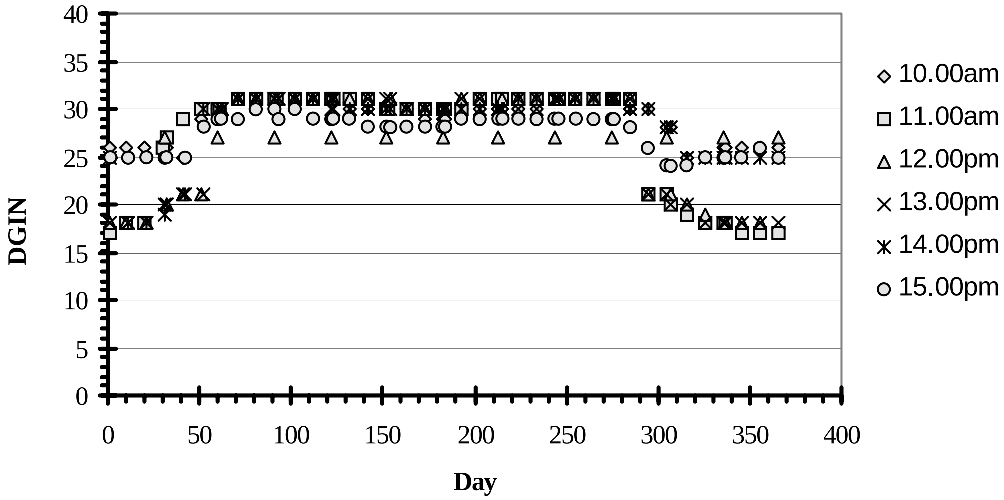


Figure 13 The DGI_N with clear glass calculated for the whole year in Helsinki

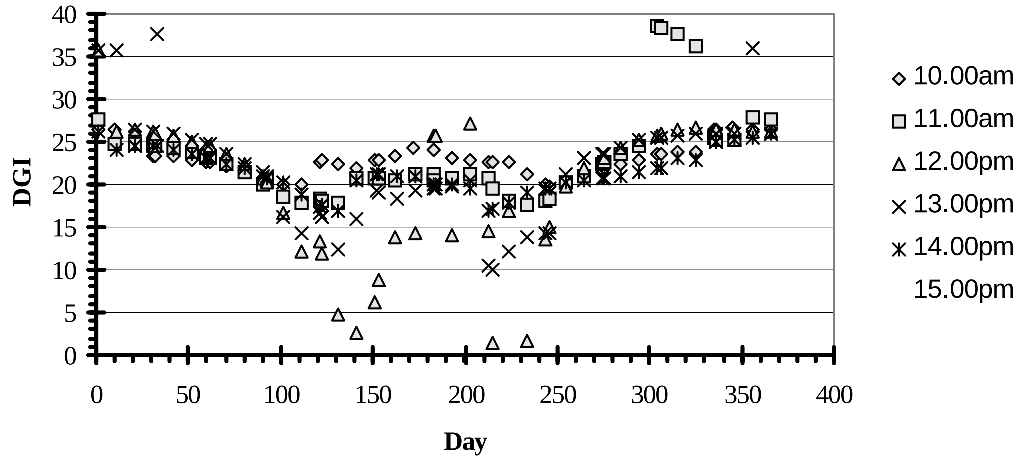


Figure 14 The DGI of Chauvel with clear glass calculated for the whole year in Helsinki

Light shelf calculations

Under clear skies, the light shelf reduces illuminance up to 90% within the place near to the window. The least reduction occurs in the back of the room. On sunny day in spring and summer, the illuminance in the back of the room reduces by 0-18%. Regarding the graph shown in Figure 15, glare levels reduced significantly in spring and summer since the light shelf provides shade that prevents direct sunlight penetrating into the room. The available daylight is more uniformly spread, improving visual conditions within the space, especially near the window. During the winter months (from the middle of November to the end of January), the glare levels for the room with a light shelf are still high and remain the same as that of the room without a light shelf. This is because the sun angle is low in the winter months at northern latitudes so that the light shelf is not very effective. However, the DGI_N appears small also in wintertime at certain times of day (11 a.m. and 2 p.m.); at noon (12 and 1 p.m.) sunrays come in without any impediment, and that is the case also early in the morning before 10 a.m. and late in the afternoon after 3 p.m., but at 11 a.m. and 2 p.m. the sunrays hit the underside of the light shelf at such angle that the rays are reflected into the room to balance out the glare effect. The reason for some negative values in the graph (Figure 15) is that some days sensor N° 1 was shaded by the light shelf while sensor N° 2 and 3 were exposed to direct sunlight.

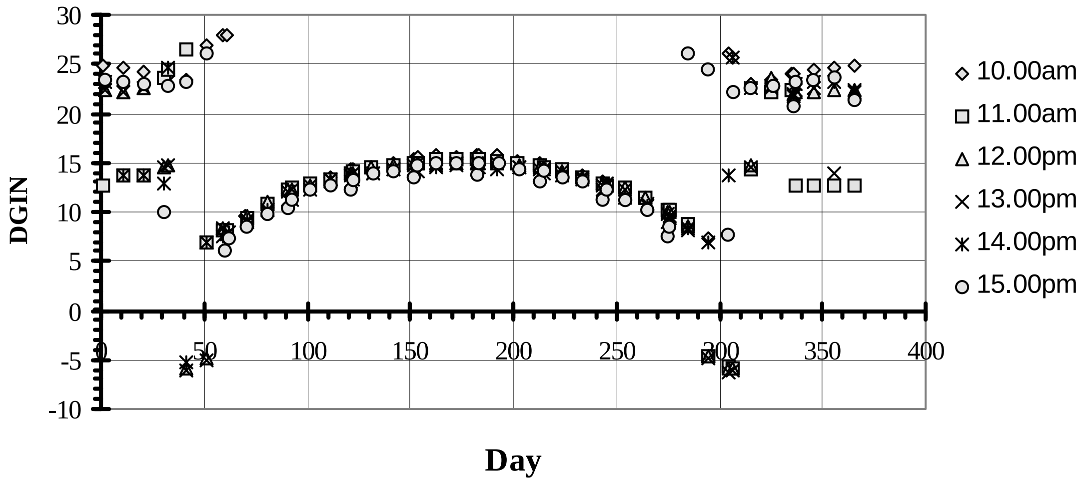


Figure 15 The DGI_N with a light shelf calculated for the whole year

The right DGI evaluation would represent eye perception in which the eye perceives light in logarithmic scale. The calculated exterior luminance, which has more effect on glare perception, is plotted into log scale for the whole year with and without a light shelf in Figure 16 a,b. The graph presents very close to the new DGI_N prediction. It can be concluded that new method is valid.

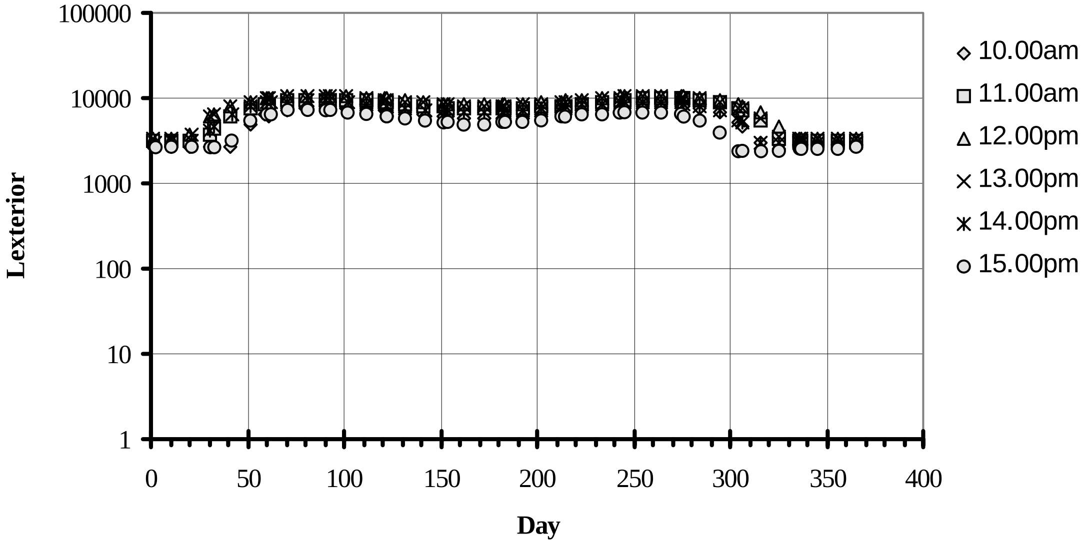


Figure 16 a L $_{exterior}$ without light shelf calculated for the whole year

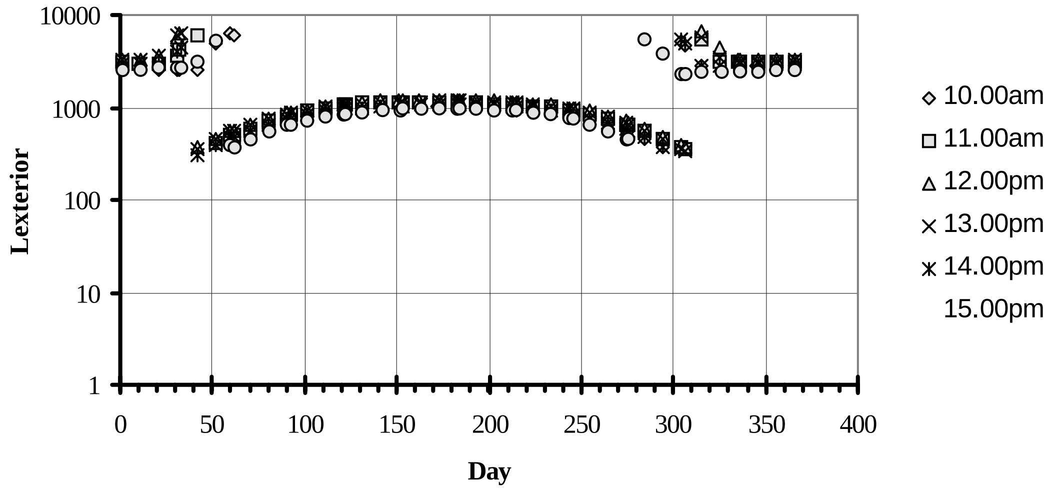


Figure 16 b L $_{exterior}$ with light shelf calculated for the whole year

6 Conclusions

The authors consider that discomfort glare can be predicted mathematically. Objective glare evaluation is an essential prerequisite for user comfort in modern buildings with innovative daylighting systems and daylight responsive lighting controls. The only reliable data for lighting control can be derived from the DGI, not from variable subjective assessments, but there is a need on more accurate DGI. The change from the obsolete Hopkinson's formula through *Chauvel*'s formula to the proposed formula is a great improvement.

The new DGI_N procedure appears to yield sensible and consistent glare values even in direct sunlight. These are invaluable in the assessment of daylight system performance. It is presumable that the DGI_N value of 31 (found with clear glass) is intolerable and the value of 24 (found with a silver filter) just acceptable if compared with the DGI scale of *Chauvel* [5]. The DGI_N will grow along with the increase in solar angle or vertical illuminance on the window, which is very reasonable, whereas the DGI of *Chauvel* behaves just the opposite; the higher is the solar angle or the vertical illuminance, the smaller will be the glare sensation. Obviously the method of *Chauvel* reacts first of all to the existence of the sun down close to the horizon and thereby to the sunrays entering the room, while the new method is sensitive to the growing vertical illuminance and thereby to the source luminance. This is in harmony with the observation of *Osterhaus* showing that the best correlation with perceived degree of discomfort glare was found for the vertical illuminance or the overall brightness in the visual field [17,18]. Moreover, scatter of the DGI values of *Chauvel* is very large. Because of these features, it is impossible to apply *Chauvel*'s formula to any daylight responsive lighting control system. The new DGI_N may have future applications in lighting control systems; the measurements will not cause problems since glare is determined based only on three illuminance values, and measuring the exterior illuminance is already included in the control systems. Daylight responsive lighting controls that react also on glare, by using a new glare algorithm based on the proposed new method, will improve visual comfort.

The new method was developed with the hope that architects and lighting designers would adopt it as the method for the assessment of daylight system performance. This could make the design and selection of daylighting systems and lighting controls easier. A tool for lighting designers, engineers and architects is now in process of preparation. The tool runs on C++ and has Java as a user interface. It will be running on the web so that a designer can get in from any platform. The tool is expected to be a welcome instrument for all of those who are struggling to create ergonomically optimal working environment where maximum visual comfort and maximum productivity can be achieved.

References

1 Aizlewood M E Measuring the performance of advanced daylighting systems *Proc. Daylighting ´98, International Conf. on Daylighting Technologies for Energy Efficiency in Buidings, Ottawa* pp 239-246 (1998)

2 Berrutto V and Fontoynont M Applications of CCD cameras to lighting research: review and extension to the measurement of glare indices *Proc. 23rd CIE Session, New Delhi* pp 192-195 (1995)

3 Boubekri M and Boyer L L Effect of window size and sunlight presence on glare *Lighting Res. Technol.* **24** 69-73 (1992)

4 Boyce P and Beckstead J Influences on discomfort glare ratings *Proc. 1st International Symposium on Glare, Lighting Research Institute, Orlando* pp 93-100 (1991)

5 Chauvel P, Collins J B, Dogniaux R and Longmore J Glare from windows: current views of the problem *Proc. Symposium on Daylight, Commission Internationale de l'Eclairage, Berlin (West)* pp 294-302 (1980)

6 Chauvel P and Perraudeau M *Daylight as a source of visual discomfort - Daylighting Atlas* (Lyon: Joule 2) p 17 (1995)

7 Christoffersen J and Velds M Monitoring procedures for the assessment of daylighting performance in buildings *IEA Task 21: Daylight in Buildings, Subtask A and B, Working document* p 23 (1998)

8 Hopkinson R G Evaluation of glare, *J. Illum. Eng.* June 1957

9 Hopkinson R G and Bradley R C A study of glare from very large sources, *J. Illum. Eng.* May 1960

10 Hopkinson R G Glare from daylighting in buildings, *Applied Ergonomics* **34** 206-215 (1972)

11 Iwata T, Shukuya M, Somekawa N and Tokura M Subjective response on discomfort glare caused by windows
Proc. CIE 22nd Session (1991)

12 Iwata T, Shukuya M, Somekawa N and Kimura K Experimental study on discomfort glare caused by windows
- subjective response to glare from a simulated window, *J. Architecture, Planning and Environment Eng.* **432** 21-33 (1992)

13 Iwata T, Shukuya M, Somekawa N and Kimura K Experimental study on discomfort glare caused by windows, Part 2 - subjective response to glare from actual windows, *J. Architecture, Planning and Environment Eng.* **439**
19-31 (1992)

14 Iwata T, and Tokura M Examination of the limitations of predicted glare sensation vote (PGSV) as a glare index for a large source: towards a comprehensive development of discomfort glare evaluation, *Lighting Res. and Technol.* **30** 81-88 (1998)

15 Nazzal A Evaluating and controlling discomfort glare of daylight origin in an office environment *Proc. EuroSun'98, 2nd ISES-Europe Solar Cong., Portoroz* pp II 3.15-1 – 3.15-7 (1998)

16 Nazzal A An evaluation method for indoor discomfort glare of daylight origin *Proc. EPIC'98, 2nd European Conf. on Energy Performance and Indoor Climate in Buildings, Lyon* pp 463-468 (1998)

17 Osterhaus W K E Discomfort glare from large area glare sources at computer workstations. Building with daylight: Energy efficient design. *Proc. International Daylight Workshop, University of Western Australia, Perth* (1996)

18 Osterhaus W K E Brightness as a simple indicator for discomfort glare from large area glare sources *Proc. 1st CIE Symposium on Lighting Quality, Ottawa* pp 113-119 (1998)

19 Siegel R and Howell J R *Thermal Radiation Heat Transfer* (New York: MacGraw Hill) (1972)

20 Velds M *Assessment of lighting quality in office rooms with daylighting systems* (Delft) p 209 (2000)

21 Waters C E, Mistrick R G and Bernecker C A Discomfort glare from sources of non-uniform luminance, *J. Illum. Eng. Soc.* **24** 73-85 (1995)