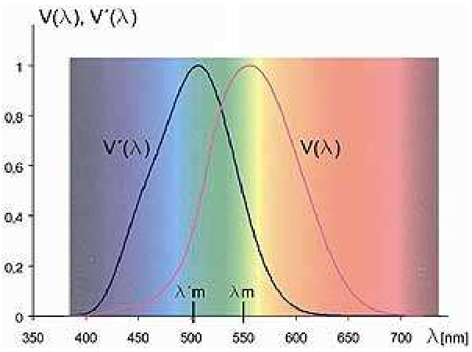
LIGHT, DAYLIGHT AND VISUAL COMFORT

Human eye and daylight 1/2

The sensitivity of the human eye is in the range 380 ÷ 800 nm. In daylight conditions, the average normal sighted human eye is most sensitive at a wavelength of 555 nm (green light at this wavelength produces the impression of highest "brightness" when compared to light at other wavelengths).
The spectral sensitivity function of the average human eye in daylight conditions (photopic vision) is defined by the CIE spectral luminous efficiency function V(λ).

The spectral sensitivity of the human eye under dark adapted conditions (scotopic vision) is defined by the spectral luminous efficiency function V'(λ).
By convention, these sensitivity functions are normalized to a value of 1 in their maximum



Human eye and daylight 2/2

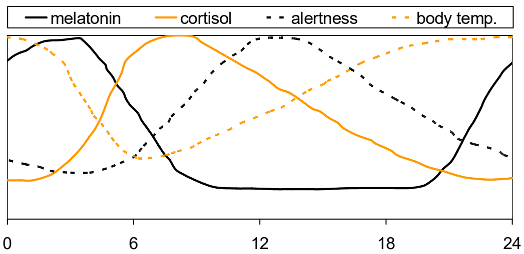
Daylight is the preferred lighting source (energy-efficient, flicker-free, dynamic and ensures excellent colour rendering). However, a good combination of daylight and artificial light is needed.

Direct effects: are caused by chemical change in tissues due to the energy of the absorbed light

indirect effects: are the regulation of the basic biological functions and the production of hormones, connected to light exposure.

The regulation of circadian rhythms, seasonal cycles and neuroendocrine responses is due to light stimuli

All the physiological processes should work optimally when exposed to daylight. According to this hypothesis, electric lighting should be as similar as possible to daylight



Visual comfort 1/2

Visual comfort is a subjective reaction to the quantity and quality of light within any given space at a given time. It depends on our ability to control the light levels around us.

Both too little and too much light can cause visual discomfort. Just as importantly, changes in light levels or sharp contrast can cause stress and fatigue, as the human eye is permanently adapting to light levels. It can vary depending on the following factors: time of exposition, type of light, the colour of the eye (light-coloured eyes tend to be more sensitive) as well as the age of the person.

Usually these aspects have to be fulfilled:

- Views of outside space & connected to nature
- Light quality
- Luminosity
- Absence of glare

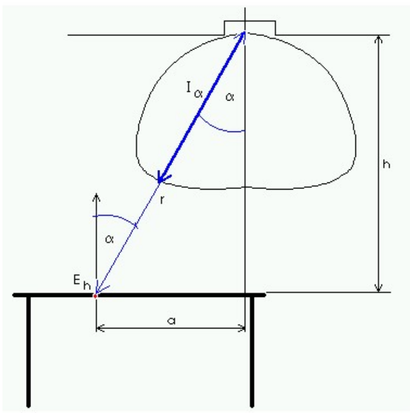
Visual comfort 2/2

Working in a window-less office, even under adequate light conditions, and working in an office with a view, are totally different experiences (positive impacts on mood and job satisfaction). Assessing a visual environment requires the analysis of three main factors – the sources of light (artificial/natural), the distribution of light within the space (colour, intensity) and its perception.

The availability of natural light varies constantly. Building design and choice of materials and equipment obviously play a decisive role. The control of light intensity means either reducing too much incoming light by shading, or compensating for low light levels with artificial light via BMS (Building Management Systems) leading to a successful balance in the combined use of artificial light and daylight.

Illuminance

Illuminance is the amount of light striking a surface – also known as incident light, where the “incident” is the light actually landing on the surface. Illuminance is calculated as the density of lumens per unit area and is expressed using lux (lumens/m²). Illuminance is measure using a light meter

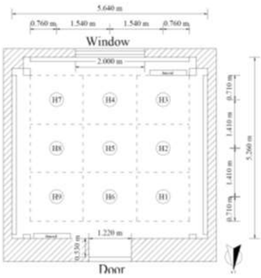


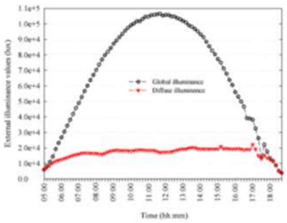
$$E_h = \frac{I_\alpha}{r^2} \cdot \cos\alpha = \frac{I_\alpha}{h^2} \cdot \cos^3\alpha$$

Example of illuminance values in a room

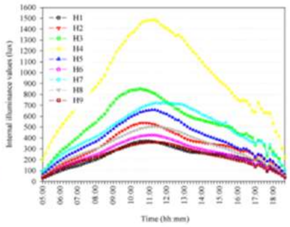
Wooden frame window with a total size of 2.0 m x 1.2 m with two conventional double low-emitting glazing filled with Argon (0.78 m x 0.90 m) and are quite clear glasses. Measurements in a clear sky day in June

Outdoor:
≅ 10,000 lux (clear day)
Indoor:
closest to windows
≅ 1,000 lux
in the middle area
25 ÷ 50 lux.
Additional lighting equipment is often necessary to compensate the low levels





a)



b)

Recommended values of illuminance

Activity Illumination	lux, lumen/m^2
Public areas with dark surroundings	20 ÷ 50
Simple orientation for short visits	50 ÷ 100
Working areas where visual tasks are only occasionally performed	100 - 150
Warehouses, Homes, Theaters, Archives	150
Easy Office Work, Classes	250
Normal Office Work, PC Work, Study Library, Groceries, Show Rooms, Laboratories	500
Supermarkets, Mechanical Workshops, Office Landscapes	750
Normal Drawing Work, Detailed Mechanical Workshops, Operation Theatres	1,000
Detailed Drawing Work, Very Detailed Mechanical Works	1500 ÷ 2000
Performance of visual tasks of low contrast and very small size for prolonged periods of time	2000 ÷ 5000
Performance of very prolonged and exacting visual tasks	5000 ÷ 10000
Performance of very special visual tasks of extremely low contrast and small size	10000 ÷ 20000

Daylight factor

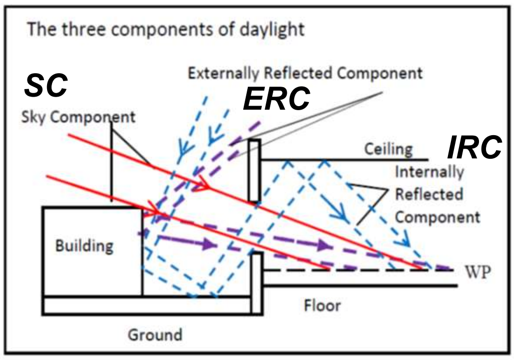
The daylight factor (DF) is the ratio of the light level inside a structure (E_i) to the light level outside (E_o) the structure:

$$DF = (E_i / E_o) \times 100 \quad [\%]$$

E_o is the simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky

Illuminance =
= SC + ERC + IRC

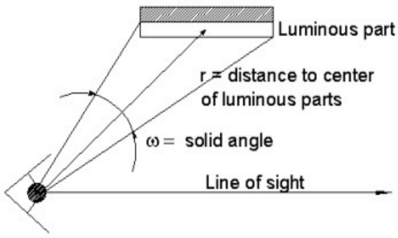
Natural lighting levels perceived on working planes (sufficient light for normal activities). Standard CIE overcast Sky for 21 September at 12:00 pm



Unified Glare Rating (UGR)

The Unified Glare Rating (UGR): how likely a luminaire and its operation in a room cause discomfort to those around it, taking into account the eye level and direction of view of the user. The lower the value, the less discomfort of the user.
A number of factors are considered when determining the UGR value: the measurement point, reflection factors and the location and operation of the lighting source. The lower the lighting discomfort or glare, the lower the value:

$$UGR = 8 \log \left[\frac{0.25}{L_b} * \sum \frac{L^2 \omega}{\rho^2} \right]$$



L_b is the background luminance (cd/m²),

L is the luminance of the luminous parts of each luminaire in the direction of the observer's eye (cd/m²)

UGR levels in EN 12464

The UGR classification includes five different quality classes, indicating the maximal UGR value which is permissible in particular spaces, named UGR-L (UGR Limit) values for a range of spaces are set out in the standard EN 12464-1:

- Technical drawing UGR <16
- Offices UGR <19
- Reception areas UGR <22
- Archives, stairs and lifts UGR <25
- Corridors and passageways UGR <28

A luminaire with a UGR lower than 10 will create negligible glare.

UGR and discomfort criteria

More in detail, looking at correspondence between UGR and comfort perceptions, one UGR unit represents the least detectable step in discomfort glare evaluation, and 3 UGR units represent an acceptability step in glare criteria. The relationship between calculated UGR value and Hopkinson's discomfort glare criteria is:

UGR	Discomfort Glare Crtiterion
10	Imperceptible
13	Just perceptible
16	Perceptible
19	Just acceptable
22	Unacceptable
25	Just uncomfortable
28	Uncomfortable

UGR and VCP (Visual Comfort Probability)

Another parameter which can be defined is the Visual Comfort Probability (VCP), which is a measure of discomfort glare for interior lighting applications. The visual comfort probability (VCP) is the probability that a normal observer does not experience discomfort when viewing a lighting system under defined conditions.

UGR	Visual Comfort Probability (VCP)
11.6	90%
16	80%
19	70%
21.6	60%
24	50%

Comparison between different parameters for glare sensations

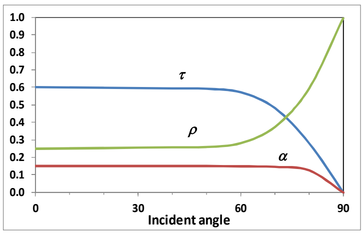
	imprecebtible	perceptible	disturbing	Intolerable
Unified Glare Rating (UGR)	<13	13 ÷ 22	22 ÷ 28	>28
CIE Glare Index (CGI)	<13	13 ÷ 22	22 ÷ 28	>28
Visual Comfort Probability (VCP)	80 ÷ 100	60 ÷ 80	40 ÷ 60	<40
Daylight Glare Index (DGI)	<18	18 ÷ 24	24 ÷ 31	>31
Daylight Glare Probability (DGP)	<0.30	0.30 ÷ 0.35	0.35 ÷ 0.40	>0.45

Another parameter which is used in lighting simulations is the **Useful Daylight Illuminance (UDI)**. This metric bins hourly time values based upon three illumination ranges, 0÷100 lux, 100÷2000 lux, and over 2000 lux. It is widely recognized that 2,500 lux is an excessive value, leading to glare.

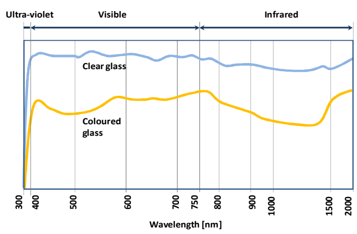
SOLAR RADIATION ON GLAZED COMPONENTS:

VISIBLE TRANSMISSION AND SOLAR HEAT GAIN

Properties of glazed elements



- Characteristic coefficients:
  - Reflection coefficient ρ
  - Absorption coefficient α
  - Transmission coefficient τ
- For glazed elements, these coefficients vary significantly according to the spectrum and the angle θ of the incident radiation
- However, for simplicity:
  - the coefficients are generally carried out at a normal incidence
  - are considered the values integrated on specific intervals of interest



$$M = \frac{\int_{\lambda_1}^{\lambda_2} M(\lambda) \cdot P(\lambda) \cdot d\lambda}{\int_{\lambda_1}^{\lambda_2} P(\lambda) \cdot d\lambda}$$

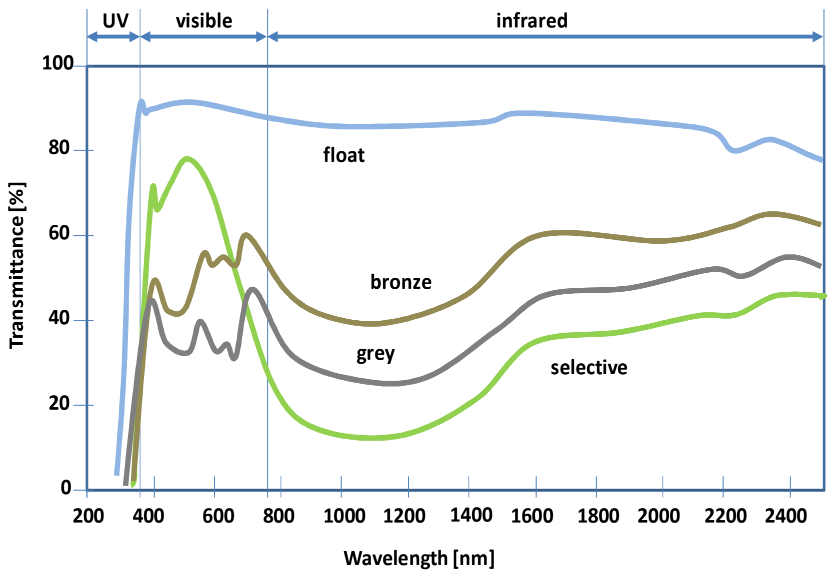
Visible: 380-780 nm
Solar: 300-2500 nm

Solar trasmission coefficient (τ_s)

- The value is obtained by an integration of solar radiation in the range (300 to 2500 nm) and weighted by the intensity curve for the solar energy AM equal to 2.

$$\tau_s = \frac{\int_{300\text{nm}}^{2500\text{nm}} E(\lambda) \cdot \tau(\lambda, \theta) \cdot d\lambda}{\int_{300\text{nm}}^{2500\text{nm}} E(\lambda) d\lambda}$$

Solar trasmission coefficient (τ_s)



Calculation methods

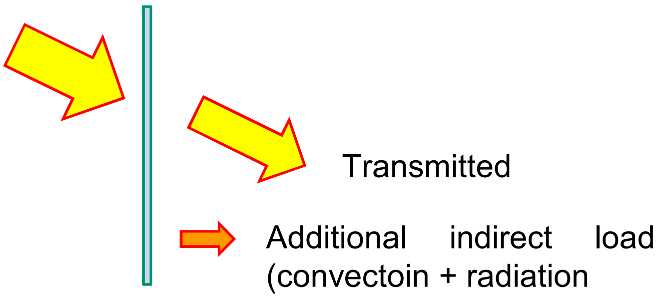
There are three ways to calculate the Solar Heat Gain (*SHG*):

1. Solar transmission through a reference clear glass panel
2. Solar transmission compared to the overall incident radiation
3. Detailed calculation within the elements which form the glazing system

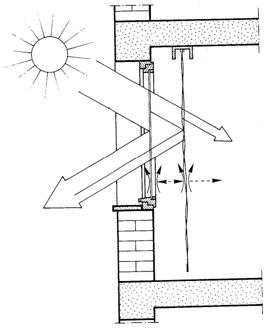
Coefficient of shading (Cs)

It is the ratio between the solar factor of the analyzed glass and solar factor of a reference one (clear glass, 3 mm):

$$C_s = \frac{I_{gl}}{I_{ref,gl}}$$



$$I_{ref,gl,k} = I_{b,k}\left(B_{b,k} + A_{b,k}\right) + \left(I_{d,k} + I_{g,k}\right)\left(B_{d,k} + A_{d,k}\right)$$



$$B_b = \sum_{j=1}^{6} b_j (\cos\theta)^{j-1}$$

$$A_b = 0.253 \cdot \sum_{j=1}^{6} a_j (\cos\theta)^{j-1}$$

$$B_d = 2 \cdot \sum_{j=1}^{6} \frac{b_j}{j+1}$$

$$A_d = 0.506 \cdot \sum_{j=1}^{6} \frac{a_j}{j+1}$$

j	b_j	a_j
1	-0.00885	0.01154
2	2.71235	0.77674
3	-0.62062	-3.94657
4	7.07329	8.57881
5	9.75995	-8.38135
6	-3.89922	3.01188

$$q_{s,k} = S_k C_{s,k} I_{ref,gl,k}$$

Example of solar radiation passing through a reference glass

Solar thermal flux $I_{ref,gl}$ transmitted by the reference glass on 21 July at 42° N latitude (W/m^2)

	Horizontal	**South**	**West**	**North**	**East**
6	**84**	**38**	**38**	**109**	**369**
7	**257**	**76**	**76**	**104**	**593**
8	**440**	**106**	**106**	**106**	**650**
9	**595**	**172**	**129**	**129**	**604**
10	**717**	**262**	**147**	**147**	**481**
11	**795**	**331**	**158**	**158**	**295**
12	**824**	**359**	**162**	**162**	**164**
13	**805**	**341**	**257**	**159**	**159**
14	**737**	**279**	**446**	**150**	**150**
15	**623**	**191**	**584**	**133**	**133**
16	**474**	**115**	**648**	**111**	**111**
17	**296**	**83**	**616**	**110**	**83**
18	**116**	**47**	**435**	**115**	**47**
19	**3**	**2**	**29**	**12**	**2**

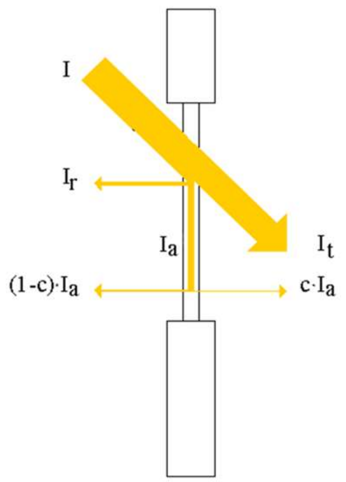
Example of values for Cs and U-value

	C_s [-]	U [W/(m² K)]
Single clear glass (3 mm)	**1**	**6.33**
Single clear glass + clear venecian blind (45°)	**0.36**	**3.76**
Single clear glass + dark venecian blind (45°)	**0.50**	**3.76**
Single clear glass + medium courtain	**0.68**	**3.76**
Double clear glazing	**0.77**	**2.95**
Double clear glazing + clear venecian blind (45°)	**0.39**	**2.17**
Double clear glazing + dark venecian blind (45°)	**0.47**	**2.17**
Double clear glazing + medium courtain	**0.56**	**2.17**
Double clear low emission glazing	**0.55**	**1.85**
Triple clear glazing	**0.65**	**2.09**

Solar factor (Fs, g, SHGC o TSET)

- Ratio between the total energy transmitted through the surface and the incident energy on the glazing
- Global transmitted energy = direct transmitted energy + energy absorbed and exchanged (radiation and convection) with the indoor environment

$$F_s = \frac{I_t + c \cdot I_a}{I} = \tau_e + c \cdot \alpha$$



- Other names:
  - SHGC, Solar Heat Gain Coefficient
  - TSET, Total Solar Energy Transmittance

Correlation between Cs and g

Since the reference glazing has g = 0.89, it is easy to demonstrate that the solar factor and the shading coefficient are linked via the following equation:

$$C_s = \frac{I_{gl}}{I_{gl,ref}} = \frac{g}{0.89}$$

In this case the solar energy entering the room is easy to determine for a generic angle of incidence by means of the following equation:

$$q_{s,k} = \frac{S_k \cdot g_k \cdot I_{gl,ref,k}}{0.89}$$

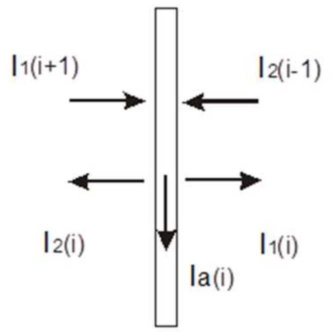
Detailed calculation: step 1

Named i the generic glazing element, $I_1(i)$ is the radiation leaving the glass on the external surface and $I_2(i)$ is the radiation leaving the glass on the internal surface, which depend on the boundary conditions and on the characteristics of the considered glazed element. The equations defining the absorbed and the leaving energy of the solar radiation on a glazing element can be defined through the following equations :

$$I_1(i) = I_1(i+1) \cdot \tau(i) + I_2(i-1) \cdot \rho_1(i)$$

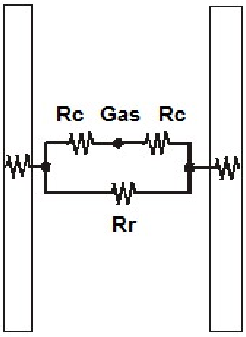
$$I_2(i) = I_2(i-1) \cdot \tau(i) + I_1(i+1) \cdot \rho_2(i)$$

$$I_a(i) = I_1(i+1) + I_2(i-1) - I_1(i) - I_2(i)$$



Detailed calculation: step 2

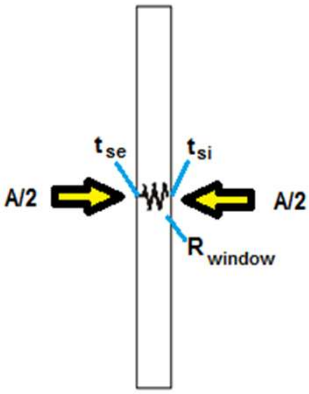
The general scheme for the thermal balance inside a window is defined by means of a resistance network, where conduction through glazing elements, convection and infrared radiation in cavities are considered. For the generic *i*-th element, defined 1 and 2 the inner and outer surface respectively, the following equation can be written:



$$S\frac{4\sigma_n T_m^3}{\left(\dfrac{1}{\varepsilon_{1(i+1)}+\varepsilon_{2(i)}-1}\right)}\left(t_{1(i+1)}-t_{2(i)}\right)+S\frac{\lambda_i}{s_i}\left(t_{1(i)}-t_{2(i)}\right)+$$
$$+Sh_c\left(t_{a(j)}-t_{2(i)}\right)=S\frac{I_a(i)}{2}$$

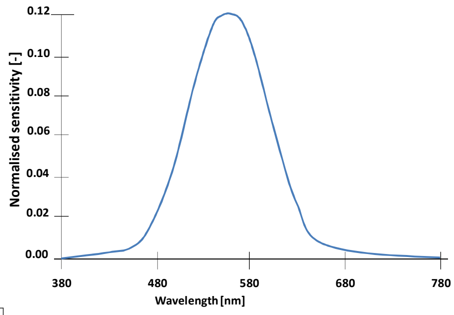
Detailed calculation: step 2 (simplified model for the heat transfer in the glazing)

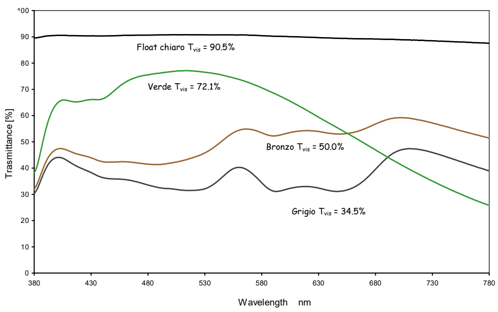
A simplest version of the model can be carried out by means of the overall resistance of the window R_{window} (without overall heat exchange coefficients with the indoor and outdoor environments), together with its overall absorption, transmission and reflection coefficients. In this way, the overall absorbed solar radiation can be split in two, hence it is included in the external and internal surface equations:



Transmission coefficient in the visible (τ_v)

The value is obtained by an integration operated in the visible range (380 ÷ 780 nm) and weighted by the perceptual curve of the human eye and the energy density of the solar spectrum.

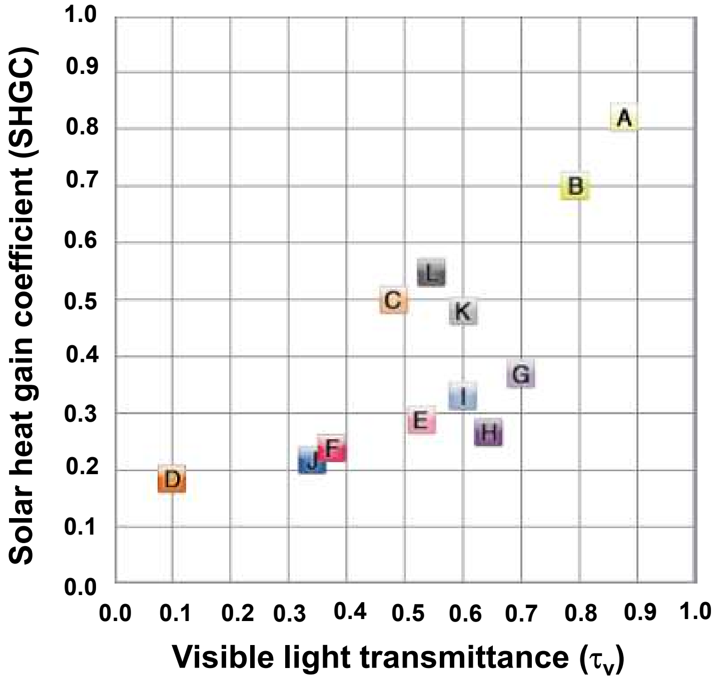




$$\tau_v = \frac{\int_{380\,nm}^{780\,nm} I(\lambda) \cdot V(\lambda) \cdot \tau(\lambda, \vartheta) d\lambda}{\int_{380\,nm}^{780\,nm} I(\lambda) \cdot V(\lambda)\, d\lambda}$$

Typical values of the overall thermal performance of a glass

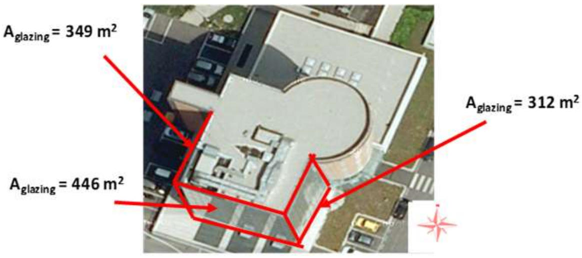
Description	U-value W/(m² K)	τ_v (%)	g-value (%)
Single clear glass (4mm)	6.0	91	89
4-12-4 mm (Air)	3.0	80	68
4-12-4 mm (Argon and low-emissivity)	1.5	77	58
4-12-4-12-4 (Air)	2.0	72	59
4-12-4-12-4 (Air and low-emissivity)	1.2	77	55
4-12-4-12-4 (Argon and low-emissivity)	0.5	70	45
4-12-4 mm (Air, medium reflective and low-emissivity)	1.6	29	30
4-12-4 mm (Argon, medium reflective and low-emissivity)	1.6	9	18



AN EXAMPLE OF OVERHEATING AND VISUAL DISCOMFORT IN AN OFFICE BUILDING

The analysed building

This building was chosen as it was recently constructed (2007), is relatively well documented and it is designed with South, West and East facing fully glazed façades.



Complaints related to thermal comfort; indoor temperatures were excessively hot during sunny days throughout most of the months of the year.

Moreover glare problems associated with the existing glazing

Pre- and post- analyses

- The monitoring of the selected building started during the second half of May 2009; film was not installed;
- Film installation started from the end of June 2009; most of film installation took place during July 2009; eventually, film application ended by August 2009;
- The monitoring of the demonstration building lasted until the end of September 2010.

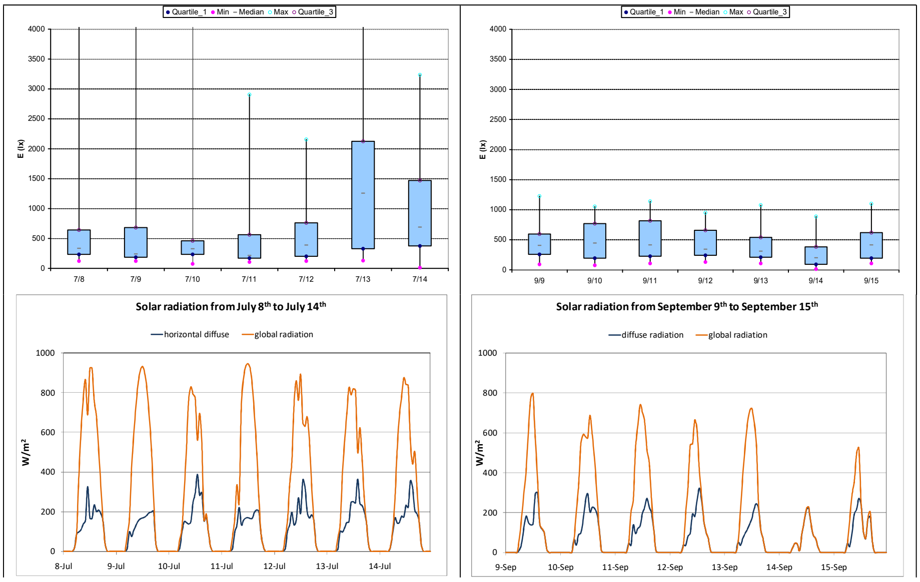
Condition	g-value	Total solar energy rejection	Visible light transmittance	Glare reduction	Thermal transmittance
Pre intervention glazing	0.43	57 %	τ_v = 59.3 %	33 %	U = 1.2 W m^{-2} K^{-1}
Post intervention glazing	0.15	85 %	τ_v = 13.6 %	85 %	U = 1.2 W m^{-2} K^{-1}

Thermal comfort measurements

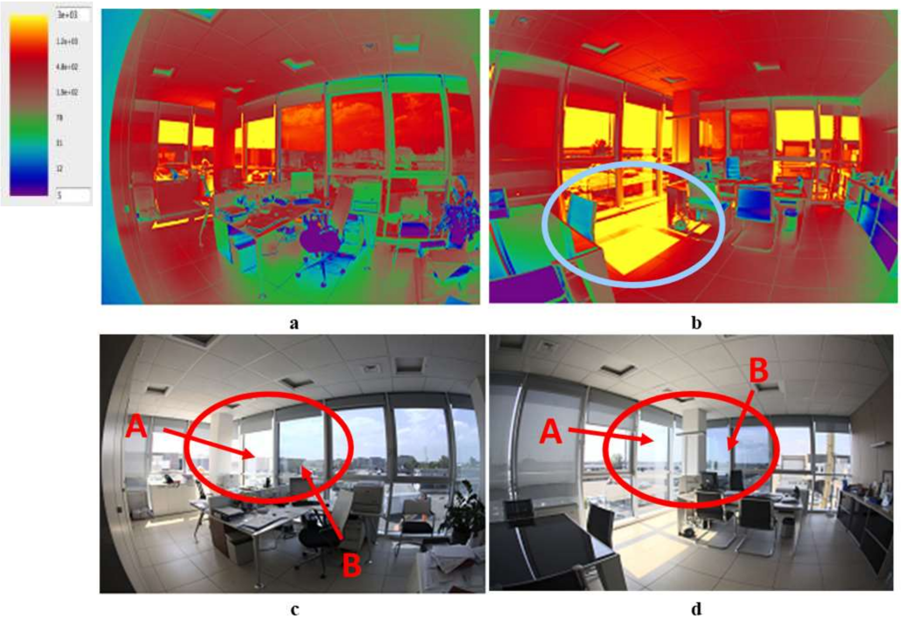
Although summer conditions in 2009 and 2010 were slightly different, it can be concluded that overheating periods were much higher in year 2009 before the film was installed.

Category [°C]	Percentage of total occurrences					
	July 2009 vs July 2010			August 2009 vs August 2010		
	Before	After	Change	Before	After	Change
< 24	0 %	0 %	+ 0%	0 %	2 %	+ 2%
≥ 24 and < 26	6 %	32 %	+26 %	10 %	46 %	+37 %
≥ 26 and < 28	44 %	53 %	+10 %	59 %	49 %	-10 %
≥ 28 and < 30	38 %	15 %	-23 %	24 %	3 %	-21 %
> 30	12 %	0 %	-12 %	7 %	0 %	-7 %

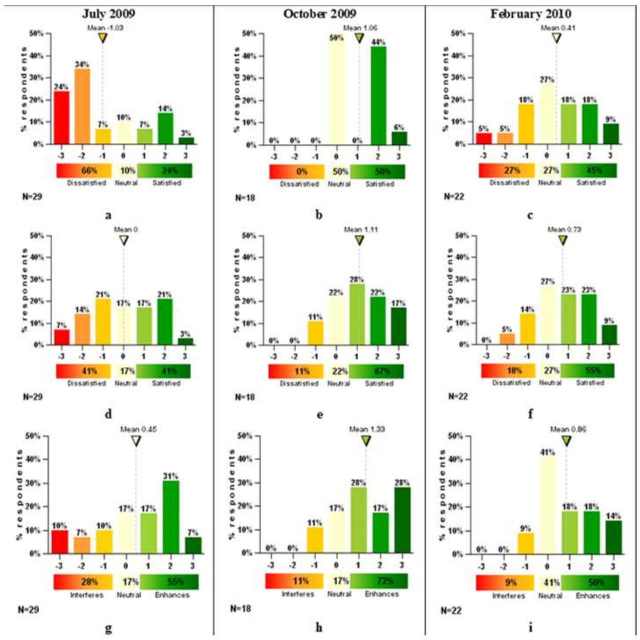
Visual comfort measurements



High Dynamic Range (HDR) imaging



Subjective evaluation by occupants



satisfaction about the experienced thermal environment

level of satisfaction about the visual comfort of the lighting

self reported influence of the indoor visual environment on the ability of performing a task

Simulations and lighting analysis