Impact of Shading Devices on Daylight Quality in Offices

Simulations with Radiance

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Keywords

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Abstract

The impact of six exterior shading devices on daylight quality and on the potential for daylight utilisation in a standard, south-oriented office room was investigated through computer simulations with *Radiance*. The daylight quality was evaluated by considering four performance indicators: the absolute work plane illuminance, the illuminance uniformity on the work plane, the absolute luminance in the visual field and the luminance ratios between the work plane, VDT screen and surrounding surfaces. The results indicate that the overhang, white awning and horizontal venetian blind generated work plane illuminance levels that are more suitable for offices where traditional tasks are carried out. However, these devices did not prevent high luminance values at the window. On the other hand, the grey specular screen produced unacceptably low work plane illuminance, poor illuminance uniformity and unacceptably low luminance levels which resulted in unsuitable luminance ratios between the VDT screen, work plane and surroundings. The 45° venetian blind, white screen and blue awning provided work plane illuminance levels suitable for offices where a combination of paper and computer work is carried out. They also provided acceptable illuminance uniformity on the work plane, suitable luminance ratios between the work plane, VDT screen and surroundings and they significantly reduced the luminance of the window. However, the blue awning had a poorer performance in December than in June and the white screen resulted in high luminance values at the window, which indicates that the best device among the ones studied was the 45° venetian blind.

Contents

List of Symbols

A	Area (m^2)
a	Constant (= 8)
b	Variable (= 0.25/q)
BGI	BRS (Building Research Station) glare index
C	Unit vector perpendicular to the direction of gaze
c	Variable (= 1-a-b)
CGI	CIE glare index
CSP	Comfort satisfaction performance (index)
D	Daylight factor (%)
d	Variable (= 1-a-b-R_0)
DGI	Daylight glare index
DGI$_N$	New daylight glare index
DGR	Discomfort glare rating (index)
D_M	Daylight factor obtained from measurements (%)
D_S	Daylight factor obtained from simulations (%)
E	Illuminance (lx)
e	Weighting exponent (constant)
E_{av}	Average work plane illuminance (lx)
E_d	Direct vertical illuminance at the eye (lx)
E_e	Illuminance in the empty room (lx)
E_f	Illuminance in the furnished room (lx)
E_i	Indirect vertical illuminance at the eye (lx)
E_{max}	Maximum work plane illuminance (lx)
E_{min}	Minimum work plane illuminance (lx)
E_v	Vertical illuminance at the eye (lx)
E_{work_plane}	Illuminance on the work plane (lx)
f	Weighting exponent (constant)
Fv	Average luminance for the entire field of view (cd·m^{-2})
G	Glare constant
g	Weighting exponent (constant)
GI	Cornell formula (glare index)
H	Unit vector perpendicular to the direction of gaze
i	Constant (= -0.0175)

$I(\lambda)$	Spectrum power distribution function of the illuminant
J	Index measuring the visual acuity
j	Constant (= -4.0835)
k	Constant (= 1.0361)
L	Luminance (cd·m^{-2})
L_{adapt}	Average unshielded luminance of the surroundings (cd·m^{-2})
L_b	Background luminance or adaptation luminance (cd·m^{-2})
L_c	Average luminance of the ceiling (cd·m^{-2})
L_{ext}	Average vertical unshielded luminance of the outdoors (cd·m^{-2})
L_f	Average luminance of the floor (cd·m^{-2})
L_{paper_task}	Luminance of the paper task (work plane) (cd·m^{-2})
L_{ref}	Luminance of the reference reflector (cd·m^{-2})
L_s	Luminance of the glare source (cd·m^{-2})
$L_{surroundings}$	Luminance of surrounding surfaces (cd·m^{-2})
L_{target}	Luminance of the target point (cd·m^{-2})
L_{VDT}	Luminance of the VDT screen (cd·m^{-2})
L_w	Average luminance of the walls (cd·m^{-2})
L_{wall}	Luminance of the walls (cd·m^{-2})
L_{window}	Average vertical shielded luminance of the window (cd·m^{-2})
L_{wp}	Luminance of the window pane (cd·m^{-2})
M	Index of sensation for the *i*th glare source
m	Constant (= 1.8223)
n	Number of glare sources
P	Guth's position index
p	Number of window panes
PGSV	Predicted glare sensation vote (index)
q	Coefficient for glazing or coating type
RD	Relative difference (%)
R_{diff}	Diffuse reflectance (%)
R_{spec}	Specular (direct) reflectance (%)
R_{tot}	Total (direct plus diffuse) reflectance (%)
R_0	Reflectance at normal incidence (%)
R_θ	Reflectance at incidence angle θ (%)
SVR	Stationary virtual reality (index)
T	Vector between the eye and a luminance (target) point on the walls, floor or ceiling
T_0	Transmittance at normal incidence (%)
T_θ	Transmittance at incidence angle θ (%)
T_{diff}	Diffuse transmittance (%)
T_{spec}	Specular (direct) transmittance (%)
T_{tot}	Total (direct plus diffuse) transmittance (%)
UGR	Unified glare rating (index)

V	Unit vector in the direction of gaze
V^{a}	Visual acuity
V^{a}_{max}	Maximum visual acuity
VCP	Visual comfort probability (index)
$V(\lambda)$	Photopic luminous efficiency function of the human eye
x	Minimum daylight illuminance level in the work area (lx)
y	Manual switch-on probability
z	Variable (= $\theta/90$)
α	Variable (= $5.2+0.7q$)
β	Constant (= 2)
ϕ	Luminous flux (lm)
γ	Variable (=$(5.26+0.06p)+(0.73+0.04p)q$)
λ	Wavelength (nm)
δ	Angle between the normal to a section of a light beam and the direction of that beam (°)
θ	Angle of incidence with respect to the glazing normal (°)
φ	Angle between V (direction of gaze) and T (target point)
φ_{hor}	Angle between V and the projection of T onto plan C-V
φ_{vert}	Angle between V and the projection of T onto plan V-H
ρ	Reflectance (%)
$\rho_{average}$	Average reflectance (%)
ρ_{wall}	Reflectance of the walls (%)
ρ_{ref}	Reflectance of the reference reflector (%)
$\tau_{average}$	Average transmittance (%)
$\tau(\lambda)$	Spectral transmittance (%)
ω	Solid angle subtended at the observer's eyes (sr)
ω_c	Solid angle subtended at the observer's eyes by the ceiling (sr)
ω_f	Solid angle subtended at the observer's eyes by the floor (sr)
ω_N	Solid angle subtended by the glare source to the point of observation (sr)
ω_s	Solid angle subtended by the glare source (sr)
ω_w	Solid angle subtended at the observer's eyes by the walls (sr)
ψ	Angular displacement of the glare source from the line of sight (°)
Ω	Solid angle (sr)
Ω_{pN}	Position factor depending on the geometry of the window and the distance from the observation place to the centre of the window area
Ω_s	Solid angle subtended by the glare source modified by the effect of the position of its elements in different parts of the visual field (sr)
Φ_w	Configuration factor for the window

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1 Introduction

Recent decades have witnessed an increasing popularity for office buildings with extremely large glazing areas. Whether this is the result of improvements in the window U-value and construction techniques or an international architectural trend remains to be determined. What is certain, however, is that the developments in window technology have opened new possibilities to the architect, which are not only significant for aspects such as the exterior image of the building: they have a tremendous impact on the building's indoor climate and on the visual environment in the office.

Until now, frequently discussed issues connected with large glazing areas have been the problems of overheating and large cooling loads, that contribute to the general increase in the consumption of electricity in many countries. In Sweden, for example, the consumption of electricity for the operation of non-residential buildings has increased dramatically from 8.2 to 26.1 TWh between 1970 and 1999 (Statens Energimyndighet, 2000).

The discussion about large glazing areas has recently shifted focus as complaints about glare and visual disturbances have come to light. These problems have been exacerbated by the increase in the number of people spending their entire work day in front of a computer. In a recent field study, Christoffersen et al. (1999) interviewed over 1800 office workers and found that 95 % of them had a computer in their office and that working on the computer accounted for 55 % of their working time on average. The use of computers has the effect that the occupational visual performance nowadays often requires intense visual efforts that result in overloading both the eyes and the nervous system (Nazzal, 2000). Moreover, people who must look at a computer screen to perform their work are more susceptible to suffer from glare problems since the direction of their gaze is horizontal, and thus, windows are likely to be directly or indirectly (through reflections in the computer screen) in their visual field. The luminance of the sky visible through the window may rise to 10 000 cd/m^2 even on overcast days and may be several times greater than this if bright sunlit clouds are seen.

The problem is emphasised by the fact that most office workers prefer to work in the zone closest to the window to maintain a view out. In their field study, Christoffersen et al. (1999) discovered that 70 % of the employees using a PC were sitting in the third part of the room closest to the window area (although they had the possibility to move the computer), and 33 % of them had the window directly in their line of sight. Note that Küller et al. (1999) indicated that people sitting less than two meters away from a window have higher levels of activity, well-being and sociability than people sitting further away in the room, which may also explain the preference for sitting closer to the window.

The use of solar shading devices is one among the many "cures" proposed to solve the overheating and glare problems in modern offices. This solution is often more attractive to the architect than reducing the glazing area or using reflective or tinted glazing, which may alter the architectural character intended for the building. Moreover, there are indications that reducing window sizes do not prevent glare: Chauvel et al. (1982) showed that the glare index values are approximately constant, independent of window size, for a given set of conditions of sky luminance, room dimensions and interior surface reflectance. They concluded that the variable of consequence in glare discomfort appears to be the luminance of the sky as seen through the windows. Thus, the principal means of meeting a specified limiting daylight glare index is by limiting the luminance, or visibility of the sky seen through the window, by permanent means or by temporary means such as adjustable blinds or curtains.

Using solar-protective (reflective or tinted) or even advanced (i.e. electrochromic, photochromic, thermochromic) glazing is not a promising solution either. A recent investigation (Moeck, Lee & Rubin, 1996) indicated that advanced electrochromic glazing technology do not reduce illuminance to appropriate levels for computer work and do not prevent glare. Furthermore, this study highlighted that it is nearly impossible to control glare with electrochromic glazings since the sensors are unable to react to sharp changes in the luminance of objects in the field of view of the occupant (like a bright light source from the window, as an example).

Shading devices also have a few advantages over the other options: they can improve the light distribution in the room, they can reduce the window heat losses at night through a reduction in the window U-value, they are flexible and can be removed when the outdoor light level is low. Thus, the potential for daylight and solar heat gain utilisation is larger with shading devices than with the other solutions proposed.

Until now, most research about solar shading devices has focused on the energy aspect. Studies that have considered the impact of shading devices on daylighting have been sparse (Dubois, 1997) and have often primarily focused on the energy saving issue as well. Only a few investigations (e.g. Brown, 1993; Collett, 1983; Rabbidge, 1967; Bull, 1953) have taken into consideration the visual (comfort) aspect.

This report presents the results of a study on the impact of shading devices on daylighting quality and on the manual switch-on probability in individual office rooms. Although some consideration is given to energy use, the focus of this study is clearly placed on daylighting quality since little work has been achieved in this area before. The study was carried out by using computer simulations with the *Radiance Lighting Simulation System* (Ward Larson & Shakespeare, 1998). These simulations have been supplemented by measurements in the full-scale Daylight Laboratory of the Danish Building and Urban Research Institute in Hørsholm, Denmark, during the summer 2001. The results of these measurements are presented in a separate report (Dubois, 2001).

1.1 Objectives

The main objective of this study is to assess and compare the impact of different shading devices on daylighting quality in individual office rooms. A second objective is to investigate the impact of these shading devices on the manual switch-on probability and on the daylight factor in order to draw some conclusions about the daylight utilisation potential of each shading alternative studied.

A few other specific objectives are stated below:

- Through a literature review, identify a set of simple performance indicators allowing to evaluate the daylight quality;
- Develop a method to apply these performance indicators to assess the daylight quality in an office room;
- Identify the physical characteristics of the shading device which contribute to good or poor daylight quality in order to propose general design guidelines for shading systems.

1.2 Scope and limitations

In this study, the daylight quality is assessed by considering a few performance indicators, which are defined through a review of the literature in the field. These performance indicators consist of directly "measurable" physical quantities e.g. illuminance and luminance values or the relationship between these quantities e.g. luminance ratios. The study does not involve any real office worker and should thus be appreciated as a function of this major limitation.

Moreover, most of the performance indicators used to assess the daylight quality were originally developed for artificial lighting systems. Many researchers (e.g. Slater & Boyce, 1990; Boubekri & Boyer, 1992; Chauvel et al., 1982) have pointed out that people seem to have a higher tolerance for glare from daylight origin than from artificial lighting and it is possible that some requirements used in this study were thus too severe. More research is needed in this field to determine the requirements which should be applied to situations with daylighting.

Also, the office room studied was a standard, south-oriented, rectangular space with one window. Only one orientation and one room configuration were studied. Moreover, the room was empty since a preliminary study with furniture indicated that furniture did have a significant impact on the illuminance distribution in the room but that the illuminance distribution was specific for each furniture arrangement. Since a large variety of furniture arrangements are found in reality, it was difficult to define one single arrangement valid for all the other arrangements. The decision was thus made to perform the study with an empty room. This situation is further away from reality but it is more likely to represent an "average" light distribution in the room.

The study was entirely carried out through computer simulations and thus bears the limitations of the simulation tool used. Moreover, since shading devices tend to be used on sunny days, most simulations were performed for sunny sky conditions. However, shading devices are also used under intermediate sky conditions–for example, to avoid the sight of a bright cloud passing by. The intermediate sky conditions, which are common in Scandinavia, were not considered at all in this study.

Finally, the analysis of the impact of the shading devices on energy use is limited to a study of the manual switch-on probability based on the work by Hunt (1980, 1979). This analysis does not allow to determine the absolute (i.e. in kWh) energy savings during the year but it allows to appreciate the relative potential for daylight utilisation of each shading alternative studied.

1.3 Terms and definitions

Some general and technical terms used throughout this report are defined in this section. This section is thus primarily intended for non-initiated readers. Other readers are urged to start reading this report from Section 2 Daylight quality.

Illuminance

The illuminance E at a point of an area is the quotient of the luminous flux $d\phi$ received by an area element dA containing that point and the area of that element (CIE, 1987):

$$E = \frac{d\phi}{dA} \tag{1.1}$$

The SI unit of illuminance is the lux (lx).

Lux

One lux is the illuminance produced on a surface of area one square metre by a luminous flux of one lumen (lm) uniformly distributed over that surface:

$$\mathrm{lx} = \mathrm{lm} \cdot \mathrm{m}^{-2} \tag{1.2}$$

Lumen

The lumen is the SI unit of luminous flux. One lumen is the luminous flux emitted in unit solid angle (steradian) by a uniform point source having a luminous intensity of one candela (9th General Conference of Weights and Measures, 1948, in CIE, 1987):

$$\mathrm{cd} = \mathrm{lm} \cdot \mathrm{sr}^{-1} \tag{1.3}$$

Candela

The candela (cd) is the SI unit of luminous intensity. The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian (16th General Conference of Weights and Measures, 1979, in CIE, 1987).

Luminance

The luminance (in a given direction, at a given point of a real or imaginary surface) is the quantity defined by the formula:

$$L = \frac{d\phi}{dA \cdot \cos\delta \cdot d\Omega} \tag{1.4}$$

where $d\phi$ is the luminous flux transmitted by an elementary beam passing through the given point and propagating in the solid angle $d\Omega$ containing the given direction; dA is the area of a section of that beam containing the given point; δ is the angle between the normal to that section and the direction of the beam (CIE, 1987). The SI unit of luminance is the candela per square meter ($\mathrm{cd} \cdot \mathrm{m}^{-2}$):

$$\mathrm{cd} \cdot \mathrm{m}^{-2} = \mathrm{lm} \cdot \mathrm{m}^{-2} \cdot \mathrm{sr}^{-1} \tag{1.5}$$

Daylight factor

In temperate cloudy regions, such as Great Britain and north-west Europe, it has become customary to specify interior daylighting in terms of the daylight factor. The daylight factor (D) is the ratio of the illuminance at a point on a given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky. The contribution of direct sunlight to both illuminances is excluded. Glazing, dirt effects, etc., are included. Also, when calculating the lighting of interiors, the contribution of direct sunlight must be considered separately. (CIE, 1987).

Glare

Glare is the condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or to extreme contrasts (CIE, 1987). Glare has also been defined as a subjective phenomenon caused by the magnitude of visible noise interfering with the perception of visual information due to an uncomfortably bright source of light in the field of vision (Hopkinson, Petherbridge & Longmore, 1966).

Glare depends on many factors: the luminance level to which the eye is adapted (background luminance), the luminance of the glare sources, their relationship and position relative to the line of sight of the observer, the solid angle subtended at the eye by the glare source and the number of glare sources (Hopkinson, Petherbridge & Longmore, 1966). Glare is also dependent on many visual and aesthetic factors such as the interior qualities of the room (material, reflectance and colour of interior surfaces) and the spectral composition of light (Berman et al., 1996). Regarding glare of daylight origin, Chauvel et al. (1982) claimed that glare from windows is compounded by some visual and aesthetic factors such as the quality of the view out, the appearance of the window as well as the visual and aesthetic interior qualities of the room.

Two types of glare are normally distinguished: *disability* and *discomfort* glare. They are distinct both in a physical as a well as a psychological sense (Hopkinson, Petherbridge & Longmore, 1966). Glare is also normally categorised on the basis of the path of light. Direct glare is caused by sources directly visible within the field of view while reflected (or indirect) glare originates from a glossy surface that reflects an image of the light source. Discomfort and disability glare can be caused by either direct or reflected light (Moore, 1985).

Disability glare

Disability glare is the type of glare that impairs vision or causes a direct reduction in the ability to see objects without necessarily causing discomfort (CIE, 1987). Disability glare is due to a scattering of light in the ocular media of the eye, which is not perfectly transparent. This scattered light is superimposed upon the retinal image, which reduces the contrast of the image and may thus reduce visibility and performance (IES, 1993). Phillips (in Ward Larson and Shakespeare, 1998) described disability glare as a kind of "veiling luminance" occurring in the ocular media. This veil of luminance due to scattering of light within the imperfect optical media of the eye causes a portion of the light energy to be diverted from the image of the light source to other regions of the retina.

Discomfort glare

Contrary to disability glare, discomfort glare causes discomfort without necessarily impairing the vision of objects (CIE, 1987). Discomfort glare is a sensation of annoyance or pain caused by high or non-uniform distributions of brightnesses in the field of view (IES, 1993). While the cause of disability glare is well known (intra-ocular light scattering), that of discomfort glare is less well understood (IES, 1993; Sivak & Flannagan, 1991). According to Hopkinson, Petherbridge & Longmore (1966), the origin of this sensation of discomfort appears to be compounded of two effects: contrast and saturation. Contrast results when a light source, possibly of only moderate brightness is seen in an environment of much lower brightness. Saturation results when any part of the retina, even the whole retina, is stimulated by light at such a level that the maximum possible rate of neural response from the retinal elements is generated. For example, a snow-covered landscape illuminated by full sunlight is completely devoid of contrast, but most people experience acute discomfort due to the saturation of the whole visual response mechanism (Hopkinson, Petherbridge & Longmore, 1966). Some laboratory studies (Fugate & Fry, 1956; Fry & King, 1975) have related discomfort glare to pupillary activity, but such data are yet insufficient to be applied in engineering practice (IES, 1993).

Direct and indirect glare

A distinction is also made between direct and indirect glare. Direct glare is caused by the vision of bright objects, large contrasts or self luminous objects situated in the visual field, especially near the line of sight. Indirect glare or glare by reflection is produced by reflections, particularly when the reflected images appear in the same or nearly the same direction as the object viewed (CIE, 1987).

Indirect glare involves two forms: reflected glare and veiling reflections. Reflected glare is usually caused by a mirror image of the light source in the offending zone reflected from e.g. highly polished wood or glass-covered desktops (IES, 1993) while veiling reflections occur when the visual task produces a mirror angle between the eye and the luminaries or another bright object, and contrast of the task itself is reduced. This effect is called veiling reflections because the luminances of the task details and their background become more alike (IES, 1993). Pencil handwriting is highly susceptible to veiling reflection, as pencil graphite can act as tiny mirrors (Baker, Fanchiotti & Steemers, 1993).

Brightness

Brightness is the attribute of a visual sensation according to which an area appears to emit more or less light (CIE, 1987).

Transient adaptation

Transient adaptation is the term used to describe the neural changes that occur quickly (less than 200 ms) in the adaptation process where the visual system adjusts its operating characteristics as a result of changes in the brightnesses within the field of view (IES, 1993).

Visual field

The extent of the visual field seen by a person when looking straight ahead must be divided into monocular and binocular portions. The monocular field is generally considered to extend approximately 90° temporally, 60° nasally (depending on the prominence of the nose), 70° inferiorly (restricted by the cheek), and 50° superiorly (restricted by the brow). The monocular visual fields overlap to form a combined binocular field, the central 120° of which is seen by both eyes. (IES, 1993).

According to Loe, Mansfield & Rowlands (1994), even if the visual field is almost 180° horizontally and 120° vertically, the part which has a significance for visual comfort evaluations is a band of 40° centred at normal eye height. Carter et al. (1994) demonstrated the importance of the surfaces in front of the subject, compared with surfaces to either side when assessing the room brightness. The most important factors appeared to be the luminance of the walls, particularly those forming the background to the tasks as perceived by the subjects, which determined the relative brightness of the tasks. In general, ratings of brightness increased as the average luminance within a 40°-wide horizontal band centred about the eye increased but there is some evidence that surfaces in front of the subject had a greater influence than surfaces to the side, and also that dark room surfaces, notably ceilings, outside the 40° band adversely influenced the assessment of brightness. In a publication about shading screens, Fontoynont (2000) considers that a central cone of vision of 30° is significant for visual comfort. Other authors (Paule, 2000; Meyer, Francioli & Kerkhoven, 1996) consider that the visual field consists of two main parts: the ergorama and the panorama. The ergorama is a cone of 60°, centred about the line of sight while the panorama is a cone of 120-140° centred about the line of sight. According to Meyer, Francioli & Kerkhoven (1996), maximum luminance ratios of 1:3 in the ergorama and 1:10 in the panorama should be respected.

2 Daylight quality

A comprehensive research was initiated a few years ago at the National Research Council (NRC) of Canada with the aim to define lighting quality. This research, which focused on artificial lighting systems, can be used as a background for a discussion about daylight quality as well. Many articles have been produced from this research (Veitch & Newsham, 1995, 1996; Veitch, 2000; Tiller & Veitch, 1995, etc.). In one of these articles (Veitch & Newsham, 1995), the authors assert that lighting quality is the success or failure of a lighting design to meet the needs of end users. According to them, lighting quality exists when a lighting system:

- Creates good condition for seeing
- Supports task performance or setting appropriate behaviours
- Fosters desirable interaction and communication
- Contributes to situationally-appropriate mood
- Provides good conditions for health and avoids ill-effects
- Contributes to the aesthetic appreciation of the space

Veitch & Newsham (1995) claim that lighting quality is not directly measurable but is an emergent state created by the interplay of the lit environment and the person in that environment. In the language of the environmental psychologist, lighting quality is a construct i.e. an intangible condition that has no physical counterpart. In other words, one cannot measure quality in the same sense as one measures length, mass, or lumen output (Veitch & Newsham, 1996). Therefore, lighting quality can only be assessed indirectly using behavioural measures (Veitch & Newsham, 1995).

While this is fundamentally true, these statements provide little guidance on how lighting quality can be assessed in a real design situation, where the building is not yet erected or where a large number of design parameters must be evaluated. Behavioural studies have the drawback of being rather time-consuming since a large number of subjects is needed to evaluate a single situation. In the case of shading devices, it would be unrealistically demanding to use behavioural studies to evaluate all the existing types of shading devices under a few different sky conditions. It is evident that a simpler method must be developed.

Veitch (2000) recently proposed a start for research-based lighting guidelines frames in terms of internal psychobiological (visiblity, photobiology, stress and arousal) and psychological (attention and environmental appraisal, perceived control, effect and expectations) processes for achieving lighting quality. These lighting guidelines are still not fully developed and according to Veitch (2000), much research remains in "human factors research" (encompassing biological and psychological processes and effects) to fully understand the lighting effects on individual well-being and yield useful applications and specific guidelines for real situations. Thus, while the work of Veitch and Newsham on lighting quality is important and fundamental for this field, it has not yet resulted in concrete guidelines to evaluate lighting quality in office environments.

Some more concrete tips were provided by the "Quality of the Visual Environment Committee" of the IESNA (Illuminating Engineering Society of North America) (Miller, 1994). This committee identified ten factors that contribute to lighting quality, (which may be used to evaluate daylighting quality as well):

- Brightness (comparative luminance) of room surfaces
- Task contrast
- Task illuminance
- Source luminance (glare)
- Color spectrum and color rendering
- Daylight (view)
- Spatial and visual clarity
- Visual interest
- Psychological orientation
- Occupant control and system flexibility

While aspects such as visual interest, psychological orientation, occupant control and system flexibility can hardly be assessed without using behavioural studies, factors such as comparative luminance, task contrast, task illuminance and source luminance can easily be studied by using computer simulations, scale models or even full-scale measurements. This provides a much simpler approach for evaluating lighting quality in a case where many alternatives must be studied. This approach was thus taken in this study since it allows to evaluate a large number of shading systems under many different daylighting conditions with moderate efforts.

2.1 Performance indicators to assess daylight quality

In this study, the quality of daylighting in the space is evaluated by considering a few factors, which we call “performance indicators”. The performance indicators considered are:

- The absolute work plane illuminance
- The illuminance uniformity on the work plane
- The absolute luminance of surfaces in the room
- The luminance ratios between the work plane (paper task), VDT (video display terminal) screen and surroundings.

These performance indicators are also in the list of the “Quality of the Visual Environment Committee” of the IESNA (previous section) although they were given different names. The last five items in the IESNA’s list were not taken into consideration since it was not possible to do so with the method used (i.e. computer simulations). We also discarded colour rendering to simplify the study and only included monochrome (black, grey or white) shading devices instead.

Finally, we should mention that we considered using the (daylight) glare index or another formula of this type as a lighting quality indicator. However, this was discarded after we reviewed the literature about glare indices and found that there is a lack of supporting evidence that any of these glare indices can be used in the present context (i.e. with shading devices).

The performance indicators considered in this study are introduced in the following sections and the values which are normally accepted by different lighting standards, norms or guidelines are briefly discussed. The review of the glare indices is reported as well although this indicator is not used in the analysis.

2.1.1 Absolute work plane illuminance

Although recent research (e.g. Loe, Mansfield & Rowlands, 1994; Loe, 1997) points out that the luminance in the visual field is the most important determinant of lighting quality in a space, sufficient levels of illuminance on the work plane are required to ensure visibility and visual performance, especially in offices. A pilot study by Berrutto, Fontoynont & Avouac-Bastie (1997) indicated that the horizontal illuminance appeared to be a major lighting quality parameter. When the lighting power was limited in their experiment, people tended to reduce wall luminances more drastically than horizontal illuminances, suggesting that horizontal illuminance was a more crucial parameter.

For offices containing computer screens, the IESNA (IES, 1993) recommends to maintain illuminance levels at or below 500 lx on the horizontal work plane. Similarly, the CIBSE (1994) recommends to maintain the illuminance on the horizontal work plane of the VDT installations in the range 300-500 lx as far as practicable. Illuminances toward the lower end of this range are appropriate where the task is wholly, or substantially screen-based; where the task involves working on paper and on screen in roughly equal proportions, illuminances toward the higher end of the range are suitable. This is supported by the pilot study of Berrutto, Fontoynont & Avouac-Bastie (1997), which indicated an average preferred horizontal illuminance of around 325 lx for work on computer, while 425-500 lx was preferred for other tasks (reading/writing, receiving visitors). In that study, none of the 73 subjects chose a horizontal illuminance higher than 550 lx for work with a VDT screen.

For all tasks other than computer work, NUTEK (1994) requires that the average illuminance directly on the (reading) task be at least 500 lx and the average work plane illuminance be at least 300 lx. Moreover, the overall lighting shall not be less than 100 lx at any point located 0.5 m from the room's inner walls on a plan located 0.85 m above the floor. They also recommend limiting the illuminance on the computer screen to 200 lx. The Danish standard DS 700 "artificial lighting in work rooms" (Arbejdstilsynet, 2000) is similar: a horizontal illuminance of 500 lx is required on the task area and the illuminance should not be below 100 lx at any point in the room. According to this standard, it is not generally desirable that the lighting be 200 lx in the whole room. It is only necessary that the task lighting provide the recommended lighting levels at the task area. In their field study, Christoffersen et al. (1999) measured the illuminance in 20 Danish office buildings to be 150-200 lx and found that 75 % of the workers in those offices rated the artificial lighting as acceptable.

However, it should be pointed out that some studies indicate that the minimum illuminance levels required in most standards may not be accepted by some users. A review conducted by the IESNA (IES, 1993 in Velds, 2000) indicated that judgements of optimum illuminances increased with age and task contrast. Most subjects preferred 1000 lx with high contrast and 1800 lx with low contrast. On average, the younger subjects (< 50 years) preferred 2000 lx, and the older subjects, 5000 lx, for both contrast levels. Studies by Begemann, Tenner & Aarts (1994) and by Begemann, van den Beld & Tenner (1995) showed that the average preferred (total) desk illuminance varied between 1100 to 3000 lx as a function of outdoor daylight conditions and sky type. Begemann, van den Beld & Tenner (1995) concluded that meeting biological lighting needs is very different from meeting visual needs, which forms the basis of today's indoor lighting standards. They concluded that indoor artificial lighting levels, which have been lowered following several energy crisis, should probably be classified as "biological darkness", as suggested by medical research. Research about the so-called non-visual effects of light has indicated the clear link between light and health. Light influences biochemical processes at single cell level, the activation of the central and autonomic nervous systems, the entrainment of diurnal rythms and the secretion of hormones, particularly the secretion of sleep (melatonin) and stress (cortisol) hormones (Küller & Wetterberg, 1995, 1993). Light also has an effect on behaviour and emotions as indicated by the work of Küller et al. (1999) and Küller & Lindsten (1992). Boyce & Kennaway (1987) showed that illuminance levels as high as 2500 lx did not suppress melatonin (the "sleep" hormone) to daytime levels, which contradicted Lewy et al. (1980 in Boyce & Kennaway, 1987) who found that bright artificial light of 2500 lx was able to suppress melatonin to daytime levels and that 500 lx was insufficient to do so while 1500 lx provided an intermediate amount of inhibition.

Moreover, Boyce (1973) carried out a study into the effect of age on visual performance and showed that significant improvements in performance, in terms of time taken to achieve a visual task, can be obtained when illuminance is raised from 500 to 750 lx for subjects in the 46 to 60 year age group. Also, Saunders (1969) carried out a series of experiments in which workers were asked to judge lighting levels for performing simple office tasks. From his results, it was clear that significant improvements ceased once 800 lx was reached. Bean & Bell (1992) set the optimum illuminance level for office lighting without VDTs at 800 lx and at 500 lx for offices with VDTs, since it is known that higher levels create too great a contrast between written material and the VDT screen. Finally, Inui & Miyata (1973 in Collins, 1994) found that the perception of spaciousness increases as the horizontal illuminance increases – as well as percentage of window area, room volume, and sky luminance – and that the more spacious an area is considered to be, the more "friendly" subjects find it.

In summary, most lighting standards require an illuminance of at least 500 lx on the task in offices where traditional (paper) work is carried out. In offices where the work in mainly computer-based, the work plane illuminance should be lower i.e. preferably between 300-500 lx. In any case, the work plane illuminance should never be below 100 lx. Much research in the field suggests that these lighting levels are low and that some users may prefer more light. Also, research about the non-visual effects of light (on health, behaviour) indicates that the lighting levels recommended in most standards are not sufficient to maintain health of humans. These illuminance requirements should thus be regarded as minimum lighting requirements.

2.1.2 Illuminance uniformity on the work plane

Illuminance uniformity has been said to be highly desirable, both across the working surface and across rooms (Veitch & Newsham, 1995). Excessive variation in horizontal illuminance may contribute to transient adaptation problems and should be avoided (CIBSE, 1994). Therefore, lighting standards often contain recommendations regarding the uniformity of illuminance on the work plane. These recommendations are expressed as the quotient of the minimum to the average or to the maximum illuminance on the work plane. Note, however, that Bean & Bell (1992) found that illuminance uniformity was far less important than illuminance level when they tried to correlate judgements of lighting quality by office workers and lighting performance index.

Slater & Boyce (1990) provide a list of some uniformity ratios recommended in some standards (Table 2.1). As shown in Table 2.1 The CIE (1986) and the CIBSE (1994) recommend that the uniformity of illuminance (minimum/average) over any task area and immediate surroundings should not be less than 0.8. When the precise size of the task area is not known, calculations can be based on an area measuring 0.5 m by 0.5 m located immediately in front of the observer at the edge of the desk or working surface. Similarly, Berrutto, Fontoynont & Avouac-Bastie (1997) found that illuminance uniformity on the desk of 0.8 (minimum/average) was preferred for reading/writing and that the preferred ratio was somewhat higher for receiving visitors in the room. Slater, Perry & Carter (1993) observed that the ratings of the difference in illuminance rise sharply when the illuminance ratio between desks in an office room is less than around 0.6. They concluded that an illuminance ratio of at least 0.7 (minimum/maximum) between work areas was unlikely to pose problems, confirming previous results of Saunders (1969). Slater & Boyce (1990) and Boyce & Cuttle (1994 in Velds, 2000) focused on the uniformity of the desk and suggested a minimum to maximum illuminance ratio of 0.7 or 0.5 if the work is primarily done in the central area of the desk. In most offices, the actively worked area on most desks is the central part, which is about 1 m in width (Slater & Boyce, 1990). In a further study, Carter & Slater (1992 in Carter et al., 1994) investigated the acceptable illuminance differences between working areas and adjacent ancillary areas in a simulated office and demonstrated that an illuminance ratio between the two of at least 0.5 is likely to be satisfactory.

Table 2.1 Illuminance uniformity recommended in some standards (in Slater & Boyce, 1990).

Source	Illuminance uniformity over task
CIBSE Code for Interior Lighting (1984)	$E_{min}/E_{av} > 0.8$
CIE Guide on Interior Lighting (1986)	$E_{min}/E_{av} > 0.8$
British Standards Institution BS 8206:Pt (1985) Code of Practice for Artificial Lighting	$E_{min}/E_{max} > 0.7$ $(E_{min}/E_{av} > 0.8)$
Deutches Institut für Normung. DIN 5035 Innenraumbeleuchtung mit kunstlichem licht (1979)	$E_{min}/E_{av} > 0.67$
Standards Association of Australia AS 1680 Code of Practice for Interior Lighting (1976)	$E_{min}/E_{av} > 0.67$
Nederlandser Stichting von Verlichtingskunde Aanbevelingen vor Binnenverlichting (1981)	$E_{min}/E_{max} > 0.7$

These uniformity ratios have been recommended mainly for artificial lighting. Slater & Boyce (1990) mentioned that the proposed criteria may not be appropriate for interiors lit by side windows. Slater, Perry & Carter (1993) maintain that daylit spaces often exhibit a much greater illuminance variation without causing significant complaints. Slater & Boyce (1990) also argue that although the illuminance across a desk placed perpendicular to the window will vary smoothly, it may well be that people's expectations about illuminance uniformity are different in the case of daylighting from side windows than for electric lighting from regular arrays of luminaries. The proposed criteria may only apply to illuminance distributions that vary smoothly over space. Sudden changes of illuminance in the space, such as are produced by some types of local lighting unit, may arouse greater sensitivity to illuminance non-uniformity.

In summary, many lighting standards require a uniformity ratio of 0.8 (minimum/average) or 0.7 (minimum/maximum), but some research indicate that a ratio of 0.5 (minimum/maximum) may even be acceptable. Some authors have argued that these criteria may not be appropriate for interiors lit by side windows, where the tolerance to illuminance non-uniformity may be greater than in the case of artificial lighting.

2.1.3 Absolute luminance of surfaces in the room

According to Rowlands et al. (1985), the criteria of task illuminance and its uniformity do not provide sufficient guidance on the adequacy and qualitative aspects of the visual environment. The luminance of different parts of the field of view must also be considered.

The importance of the luminance of elements located in the visual field is increasingly recognised as a major determinant of visual comfort. Many studies have indicated the importance of the distribution of luminance within a space and in particular the luminances of vertical surfaces: the walls are especially significant but the ceiling may also need to be included depending on the size and height of the room (Loe, 1997).

Already in the 1980s, a team of researchers surveyed photometric conditions and conducted a survey of occupants' opinion of the lighting in 912 workstations in 13 buildings across the United States. Five reports were generated from these data. Overall, it appeared that the pattern of luminance in the space (created by indirect ambient lighting systems with integrated furniture-mounted task lighting) resulted in low ratings of the lighting system. This called attention to luminance distribution as an important element in good lighting design (Veitch & Newsham, 1996).

Some years later, in a study involving 180 subjects, Van Ooyen, van de Weijgert & Begemann (1986) concluded that wall luminance contributes most to the way a room is experienced. Later, in a study about electrically lit spaces, Carter et al. (1994) demonstrated the importance of wall and vertical surfaces luminances. They found significant differences between the ratings of both adequacy and comfort of the lighting of an area in the office room with different lighting installations affecting the luminance of walls although the horizontal illuminance in the area was the same under all lighting installations. The same year, the National Institute of Science and Technology (NIST) conducted post-occupancy evaluations (POEs) in more than 20 buildings (Collins, 1994). They found that subjective brightness was clearly an important contributor to perceived lighting quality. Occupants rated spaces with lower average luminances as dim, while rating those with higher average luminances as bright. Furthermore, the data indicated that the relationship between subjective brightness and average room luminance was stronger than that between brightness and task illuminance. In other words, the occupants based their judgements of brightness on room luminance rather than task illuminance. A recent pilot study by Berruto, Fontoynont & Avouac-Bastie (1997) confirmed these findings. They found that whatever the task, wall luminance seemed to have a significant effect on users' satisfaction and appeared to deserve more attention. A pilot study carried out in Sweden (Bülow-Hübe in Wall & Bülow-Hübe, 2001) also suggests that luminance in the field of view is important for visual comfort. In this study, the author found no correlation between the measured illuminance in experimental rooms and the way the research subjects adjusted the shading device in the window. However, she observed some correlation between the use of the shading device and the presence of a bright sunlight patch in the room.

Maximum luminance values

Regarding luminance, the first rule is to avoid bright light patches in the visual field, which can cause disability and discomfort glare. According to Veitch (2000), direct glare and excessive luminance contrast can create arousal and stress.

In Sweden, NUTEK (1994) requires that luminance values in an office space be kept below 1000 cd/m^2 (preferably below 500 cd/m^2) in the normal visual field[1] and below 2000 cd/m^2 (preferably below 1000 cd/m^2) outside the normal visual field. Similarly, the ISO Standard 9241-6 (ISO, 2000) recommends to limit the average luminance of lighting fixtures, windows or surfaces which can be reflected in the computer screen to 1000 cd/m^2 for screens of class I and II and to 200 cd/m^2 for screens of class III. In America, the ANSI/IESNA RP-1 VDT Lighting Standard (IES, 1993 in Moeck, Lee & Rubin, 1996) recommends that all room surfaces within the peripheral view, including the window, shall not exceed 850 cd/m^2 given an average VDT screen luminance of 85 cd/m^2 (respecting maximum luminance ratios of 1:10 between the VDT and the room surfaces within the peripheral view). For paper or reading tasks, this Lighting Standard recommends to maintain luminance levels below around 255 cd/m^2 for surfaces within close visual proximity (thus respecting maximum luminance ratios of 1:3 between the VDT and the directly adjacent surfaces). The CIBSE (1994) and Perry (1993) recom-

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[1] The normal visual field is defined as the area that extends 90° each side horizontally, 50° upward and 70° down from the horizon.

mend that surface luminances should not exceed 1500 cd/m^2 where work on computer is performed and that the luminance of the surfaces and objects facing the screen be kept low, preferably below 500 cd/m^2.

Thus, although the recommended values vary according to lighting standard, at least three sources recommend to avoid luminance values above around 1000 cd/m^2, and 500 cd/m^2 appears preferable, especially in offices with VDTs.

Minimum luminance values

Research also indicates that there are minimum and preferred luminance values for the walls. Van Ooyen, van de Weijgert & Begemann (1987, 1986) observed that wall luminance contributes most to the way a room is experienced. With increasing wall luminance, the room is felt to be more stimulating, and it is easier to concentrate on a task. According to Loe (1997), people prefer an interior to have a measure of "visual lightness" combined with a degree of "visual interest". The visual lightness refers to the brightness of the major surfaces within the main field of view, particularly the vertical surfaces. Rowlands et al. (1985) also showed that the adequacy of a space relates to the overall "brightness" of the space and that the pleasantness and attractiveness of the space relates to the luminance of the area of the binocular vision. Their experiment showed that as the luminance of this area increased, the assessment of quality also increased (except when the luminance of the luminaries was as high as 8000 cd/m^2). Note also that the ISO Standard 9241-6 (ISO, 2000) recognises this aspect since it states that, "apart from work plane illuminance, it is essential to consider vertical illuminance, especially when the impression of depth in the room plays an important role. In general, the impression of depth can be increased by increasing the illuminance of vertical surfaces".

In the experiment of Carter et al. (1994), lighting installations where the wall was darkest was considered both less adequate and less comfortable. Miller (1994) also reported that, in a pilot study with artificial lighting, 60 % of the 74 subjects preferred a scene where there was approximately equal lighting energy applied to the walls and the horizontal work plane. In that study, most people preferred the middle-to-high range of wall luminance (58-157 cd/m^2) but the author warns that there was some serious bias in the experiment making it somewhat unreliable. Van Ooyen, van de Weijgert & Begemann (1986, 1987) observed a marked relationship between the preferred work plane luminance and the wall luminance. The preferred wall luminance was dependent upon the task performed. Reading, writing and interviewing a person resulted in preferences that were all in the same range i.e. 30-60 cd/m^2. Work on a computer screen (with bright text against a dark background) called for somewhat lower luminances i.e. 20-45 cd/m^2. The preferred working task luminance was also dependent upon the task performed. The areas of preference for reading writing and interviewing were between 45-105 cd/m^2 while a somewhat lower desktop luminance (40-65 cd/m^2) was preferred when working on a computer screen. Note that these observations were made strictly under artificial lighting conditions. The authors admit that the experiments that included daylight had to be carried out under such a wide variety of weather conditions that no regions of preferred luminance could be established (van Ooyen, van de Weijgert & Begemann, 1987).

One study (Loe, Mansfield & Rowlands, 1994), where a commercial type interior was investigated, indicated that for the room to be assessed as "bright", the average luminance within a horizontal band of 40° centred about the eye needed to be at least 30 cd/m^2. In a review of research, Collins (1994) reports that scenes considered to be bright tend to have high surface luminances (above 100 cd/m^2) in the central field of view but that there is a point beyond which brightness becomes excessive: luminances above 800 cd/m^2 are considered glaring rather than bright. A pilot study by Berrutto, Fontoynont & Avouac-Bastie (1997) indicated preferred average wall luminances of around 120 cd/m^2 (60 cd/m^2 at eye level) for reading/writing tasks, 130 cd/m^2 (65 cd/m^2 at eye level) for receiving a visitor in the office room. They also found that for work on VDT screen, wall luminances inferior or at most equal to the VDT luminance were preferred and that a balanced (i.e. symmetrical) luminance was preferred for the walls surrounding the subjects on each side. Rothwell & Campbell (1987 in Tiller & Veitch, 1995) observed that subjects reported that the light was getting "dim" when the luminance on a simple visual acuity task ranged from 28 to 110 cd/m^2; luminances between 3.6 and 28 cd/m^2 were judged as "gloomy". Shepherd, Julian & Purcell (1989 in Tiller & Veitch, 1995) studied subjective judgements of three different ambient lighting levels in a complex realistic visual field. They found that ambient lighting was described as "gloomy" only when the adaptation luminance in the field of view ranged from 5 to 9 cd/m^2. The two other adaptation luminance conditions used in the experiment (6-11, and 38-60 cd/m^2) were not judged gloomy.

In summary, there is plenty of evidence suggesting that low wall luminance may be unacceptable. However, there appears to be no consensus as to which minimum luminance values should be accepted. In this review, the preferred wall luminance ranged from 20-157 cd/m^2 and the minimum wall luminance appeared to be somewhere between 20-100 cd/m^2. However, a minimum luminance value around 30 cd/m^2 has been mentioned by some authors (e.g. Loe, Mansfield & Rowlands, 1994;

Rothwell, Campbell, 1987 in Tiller & Veitch, 1995; van Ooyen, van de Weijgert & Begemann, 1986, 1987). This is approximately the luminance of a white diffusing surface which receives 100 lx of illuminance. Since many lighting standards recommend 100 lx as minimum illuminance value, it makes sense to use 30 cd/m^2 as the minimum acceptable luminance value for the walls. But it is evident that more research is needed in this area to establish minimum acceptable luminance values, especially in situations with daylighting.

2.1.4 Luminance ratios

As mentioned in the previous section, the importance of the luminance of elements located in the visual field is increasingly recognised as a major determinant of visual comfort. Office interiors should be lighted to provide for good visibility with no distracting glare. Thus large luminance variations creating direct and reflected glare should be avoided (Hopkinson, Petherbridge & Longmore, 1966). This is also stated in the ISO Standard 9241-6 (ISO, 2000): “the most important factors for ensuring good lighting is an even distribution of luminance and contrasts in the office room”.

Carter et al. (1994) found that the (lighting) installations rated more even were also rated more acceptable. The most uneven installations were rated most unpleasant and least acceptable. The perception of unevenness appeared to be adversely influenced by both excessive luminance contrasts between adjacent surfaces within the 40° band and by relatively dark surfaces immediately outside the band. The importance of luminance ratios was also pointed out by Loe (1997), who claimed that the visual performance can be enhanced by highlighting the task area with an illuminance ratio of 3:1 between the immediate task area and the surrounding area. Van Ooyen, van de Weijgert & Begemann (1986, 1987) came to an almost equivalent conclusion i.e. if the luminance of a visual task was fixed at 10, then the preferred ratio of task luminance to work plane luminance to wall luminance is 10:4:3.

Two separate phenomena are influenced by the luminance ratios within the field of view: transient adaptation and discomfort glare. To limit transient adaptation and discomfort glare, the IESNA (IES, 1993) recommends that the luminance ratios should not exceed the following:

3:1 or 1:3	between the paper task and adjacent VDT screen;
3:1 or 1:3	between the task and adjacent surroundings;
10:1 or 1:10	between the task and remote (non-adjacent) surfaces;
40:1 or 1:40	between points anywhere in the field of view.

In Sweden, NUTEK (1994) also recommends that the luminance ratios within the work area between the task, the direct surrounding and the remote surrounding do not exceed 10:3:1. Moreover, this norm recommends that the luminance ratios between any points within the field of view should not exceed 20:1, which is stricter than the IESNA recommendation mentioned previously. The CIBSE (1994) has similar recommendations: the luminance ratios should not exceed 3:1 between the task and immediate surroundings and 10:1 between the task and general background.

While large luminance ratios should be avoided, it is not either desirable to create totally even lighting distributions. Dull uniformity in lighting, though not harmful, is not pleasant, and can lead to tiredness and lack of attention (Hopkinson, Petherbridge & Longmore,1966). According to Loe (1997), people prefer an interior to have a measure of “visual lightness” combined with a degree of “visual interest”. The visual interest applies to the non-uniformity of the light pattern. Therefore, according to IES (1993), it is important to provide enough variation in luminance (or colour) to contribute to a stimulating, attractive environment. Small visual areas that exceed the luminance-ratio recommendations are desirable for visual interest and distant eye focus (for periodic eye muscle relaxation throughout the day). Interiors should thus have elements of light and shade rather that the even light pattern provided by regular array of ceiling mounted luminaries (Loe, 1997).

Loe, Mansfield & Rowlands (1994) showed that for a room to be visually interesting, the ratio of the maximum to minimum luminance within a 40°-wide horizontal band, needed to be at least 13:1. Veitch (2000) recommends using meaningful luminance patterns to create interest, to keep vertical surfaces bright, and to use daylighting and windows where possible. She suggests creating interest by integrating luminance variability with architecture to satisfy attention and appraisal processes. However, she also mentions that the acceptable upper limit for luminance contrast that is desirable to provide interest without the maximum value becoming a glare source is still not known. It is also probable that the acceptable luminance ratios are larger for natural than for artificial lighting.

In summary, it is generally acknowledged that large luminance contrasts in the field of view should be avoided. Most standards recommend that the luminance ratios between the task (paper or VDT screen) and immediate surroundings should not exceed 3:1 and that the ratio between the task (paper or VDT screen) and remote surfaces should not exceed 10:1. Moreover, NUTEK (1994) recommends that the luminance ratios between any points within the visual field do not exceed 20:1. While researchers claim that dull, uniform luminance distribution is not either desirable, the acceptable luminance contrast that is desirable to provide interest without the maximum value becoming a glare source is still not known.

2.1.5 Discomfort glare indices

In studies about visual comfort, it has been the custom to use a (discomfort) glare index to assess the degree of visual discomfort in a particular situation. A glare index is simply an empirical formula connecting directly measurable physical quantities (e.g. source luminance, solid angle of the glare source, background luminance, etc.) with the glare experienced by research subjects. Most glare indices are empirical formulas based on research with real human subjects.

While the calculation of the glare index is complex, the important variables are (CIE, 1983; Moore, 1985):

- The luminance (L_s) of the glare source. In the case of windows: the luminance of the sky as seen through the window (the brighter the source or sky, the higher the index);
- The solid angle subtended by the source (ω_s). In the case windows: the apparent size of the visible area of sky at the observer's eyes (the larger the area, the higher the index);
- The angular displacement (ψ) of the source from the observers line of sight. In the case of windows: the position of the visible sky within the field of view (the further from the centre of vision, the lower the index);
- The general field of luminance (L_b) controlling the adaptation levels of the observer's eye (also called the background luminance). In the case of windows: the average luminance of the room excluding the visible sky (the brighter the room, the lower the index).

The subjective sensation of discomfort glare experienced by the observer can thus be related to the four parameters by a general expression of the following type (CIE, 1983):

$$G = \frac{L_s^e \cdot \omega_s^f}{L_b^g \cdot f(\psi)} \tag{2.1}$$

Where *G* is a quantity called the Glare Constant expressing the subjective sensation on a semantic/numerical scale and *e, f* and *g* are suitable weighting exponents while $f(\psi)$ is a complex function of the displacement angle, which takes separate account of its vertical and azimuthal components.

There are so many glare indices that it is difficult to review all of them here. (Glare problems have been studied since the beginning of the second half of the last century). Nevertheless, some of the most common indices are listed and discussed below:

- BRS glare formula (BRS or BGI)
- Cornell formula or Daylight Glare Index (DGI)
- CIE Glare Index (CGI)
- Unified Glare Rating (UGR)
- Guth visual comfort probability (VCP)
- Comfort, satisfaction and performance index (CSP)
- Daylight Glare Perception Scale (DGPS)
- Predicted Glare Sensation Vote (PGSV)
- New Daylight Glare Index ($\mathrm{DGI_N}$)

Note that all but the DGI (and $\mathrm{DGI_N}$) have been developed for electric lighting systems (Osterhaus, 1996) and that the BGI, DGI, CIE, UGR and VCP are supported by the simulation program *Radiance* (see Ward, 1996a), which is the main simulation tool used in the present study.

BRS glare formula (BRS or BGI)

The BRS glare formula was developed by Petherbridge & Hopkinson (1950) at the Building Research Station in England. Petherbridge and Hopkinson examined the effect of source and background characteristics for relatively small sizes of sources and produced formulas that appeared to describe the relationship up to a size, which subtended a solid angle of 0.027 sr. The sensation of glare was evaluated by the following degree of sensations: just noticeable, just acceptable, just uncomfortable and just intolerable. The empirical formula developed had the form:

$$\mathrm{BGI} = 10\log_{10} 0.478 \sum_{i=1}^{n} \frac{L_s^{1.6} \cdot \omega_s^{0.8}}{L_b \cdot P^{1.6}} \tag{2.2}$$

where

P Guth's position index, expressing the change in discomfort glare experienced relative to the azimuth and elevation of the position of the glare source and the observer's line of sight;

n number of glare sources.

The BGI is limited to small sources with solid angles inferior to 0.027 steradians (Osterhaus, 1996). According to Chauvel et al. (1982), the equation produced does not predict glare accurately for larger sources and does not take account of the effect of human eye adaptation. Moreover, Iwata et al. (1992, 1990/91) and Nazzal (2000), mentioned that this formula is mathematically inconsistent: a large glare source cannot be subdivided for the purpose of summing up glare contributions. Iwata et al. (1990/91) demonstrated that the BRS glare formula was the least accurate (compared with the DGI and CGI, see below) in a lighting environment with a wide light source. The BRS glare formula consistently predicted higher i.e. more severe glare votes than what actually occurred. Iwata et al. (1990/91) commented that this was quite normal since this index was originally intended for point-source light rather than wide-source glare.

Cornell formula or Daylight Glare Index (DGI)

The Cornell glare formula (Hopkinson, 1963), which was developed at the Building Research Station (England) and at Cornell University (USA) is a modification of the BRS formula, which has been adapted to large sources. The formula was developed through experiments where a bank of closely packed fluorescent lamps behind an opal diffusing screen was set in a separately illuminated white surround extending to the limits of the observer's view. The formula is expressed as follows:

$$\mathrm{GI} = 10\log_{10} 0.48 \sum_{i=1}^{n} \frac{L_s^{1.6}\,\Omega_s^{0.8}}{L_b + 0.07\,\omega_s^{0.5} L_s} \tag{2.3}$$

where

Ω_s (sr) solid angle subtended by the glare source modified by the effect of the position of its elements in different parts of the visual field in the way put forward by Petherbridge & Longmore (1954).

Validation studies of this formula involving physical measurements both in artificial and daylighting conditions showed that the correlation between observed glare from windows and the predicted calculated glare was not as strong as in the case of artificial lighting and that there was a greater tolerance of mild degrees of glare from the sky seen through the window than from a comparable artificial lighting situation with the same value of glare index, but that this tolerance did not extend to severe degrees of glare (Boubekri & Boyer, 1992; Chauvel et al., 1982). The numerical relationship of the second of these two conclusions was derived from regression curves, which produced an equation for a Daylight Glare Index[2] (DGI) as expressed below (Chauvel et al., 1982; Baker, Fanchiotti & Steemers, 1993):

$$\mathrm{DGI} = \frac{2}{3}(\mathrm{GI} + 14) \tag{2.4}$$

This equation expresses the observed fact that there is a greater tolerance for glare from the sky, as seen through the windows, than from a comparable artificial lighting situation, provided that the glare index is not too high (Baker, Fanchiotti & Steemer, 1993). Chauvel et al. (1982) argued that the weak correlation between the GI and the observed glare from windows is compounded by other visual and aesthetic factors such as the quality of the view out, the appearance of the window as well as the visual and aesthetic interior qualities of the room. Iwata et al. (1991 in Velds, 2000) showed that the perceived glare under real sky conditions was smaller than that predicted by the DGI. However, they mentioned some discrepancies between the real sky and artificial sky evaluations such as different adaptation times, and cultural differences (one experiment with Japanese subjects, the other with Europeans and Americans).

Through experiments with artificial lights, Iwata et al. (1990/91) showed that the Cornell formula was the most accurate (compared with the BGI and CGI, see below) to predict the glare vote from a wide-source glare. However, they maintained that it is inadequate for a range of wide-source glare conditions because it does not include parameters for adaptation and the luminance of the desk surface. They showed that there was a difference between early and late votes showing that adaptation occurs so that the subjects judged the light to be less uncomfortable even after only 30 seconds, suggesting that the most serious glare problems occur during the transition i.e. the time immediately after exposure to the glare source. Also, Osterhaus (1996) observed that the research subjects (32) in his experiment commented on becoming more sensitive to

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[2] Note that the GI is often called the DGI (see for instance Boubekri & Boyer, 1992; Christoffersen, 1995; Iwata et al., 1990/91). This is not without adding to the general confusion about discomfort glare indices.

glare as the experiment progressed (2-2.5 hours) and that this impression was confirmed by experimental data. Osterhaus & Bailey (1992) also pointed out that the DGI does not include a measure of adaptation. In their experiment, they observed that subjects selected higher luminances when high initial presentation luminances preceded the adjustment of luminance for the background. They also observed that when glare severity was assessed immediately following the difficult letter-counting task, the subjects showed less sensitivity to glare. Moreover, they remarked that subjects became more sensitive to glare over the course of the 1.5-hour experiment, a result that agrees with other studies (Hopkinson, 1963 in Osterhaus & Bailey, 1992).

In a more recent study, Osterhaus (1998, 1996) compared subjective glare ratings (SGR) with calculated values derived from the CIE glare index (CGI), the Unified Glare Rating (UGR), the Daylight Glare Index (DGI) as well as measured direct vertical illuminance value at the observers' eye. The subjects were presented with a large glare source of non-uniform luminance pattern. Calculations based on the CGI and UGR showed reasonable correlation with experimental results while the DGI – expected to be more appropriate for the large window-like glare sources – showed a weaker correlation. The best correlation was found for the direct vertical illuminance at the eye or the overall brightness of the visual field. The author concluded that these results suggest that brightness is a fundamental parameter in response to glare discomfort.

Boubekri & Boyer (1992), Iwata et al. (1990/91) and Chauvel et al. (1982) also indicated that the Cornell formula is not directly applicable to a case where the window is parallel to the subject's line of sight. Chauvel et al. (1982) concluded that, for most people, the discomfort glare will be less than that predicted for a window perpendicular to the line of sight. Osterhaus & Bailey (1992) pointed out that currently (as of 1992), no data is available on perceived comfort or discomfort and the relations between comfort and task performance under conditions in which the glare source borders or surrounds a work task, since all previous studies evaluated discomfort glare by directly viewing the glare source rather than focusing on a work task. They concluded that for relevance of today's work environment, it seems important to more carefully consider situations in which the glare source occupies a substantial part of the visual field while the subjects actually perform work tasks.

Waters, Mistrick & Bernecker (1995) also showed that non-uniform surfaces can cause more glare than uniform light sources when positioned perpendicular to the line of sight and less glare when located 10° to 20° from the line of sight. Since the DGI is based on experiments with uniform light sources, it should not be applied when discomfort glare is caused by non-uniform light sources (like in the case of a window with venetian blinds, as an example).

Finally, note that Chauvel et al. (1982) also observed that the discomfort glare resulting from the direct view through windows has been found to vary greatly from observer to observer and also to vary with factors associated with the appearance of the window, the view outside and the surroundings.

CIE glare index (CGI)

The CIE adopted the following formula proposed by Einhorn (1969, 1979) as a unified glare assessment method:

$$\mathrm{CGI} = 8\log_{10} 2 \cdot \frac{\left[1+\frac{E_d}{500}\right]}{E_d + E_i} \cdot \sum_{i=1}^{n} \frac{L_s^2 \omega_s}{P^2} \tag{2.5}$$

where

E_d (lx) direct vertical illuminance at the eye due to all sources;
E_i (lx) indirect illuminance at the eye ($E_i = \pi L_b$).

The CGI was developed in order to correct the mathematical inconsistency of the BRS formula for multiple glare sources. The formula provides the steps of glare sensation corresponding to the BRS scale.

Iwata et al. (1990/91) showed that the CGI was less accurate than the Cornell formula to predict the glare vote from a wide-source glare. They also maintained that this formula is not adequate because it fails to take into consideration the adaptation factor as well.

CIE's Unified Glare Rating system (UGR)

Later, the CIE (1992) proposed a unified glare rating system (UGR), in which Sørensen combined the "best" aspects of the BGI and CGI (Osterhaus, 1996). The UGR incorporates Guth's position index and combines the aspects of the CGI and BGI to evaluate glare sensations for an artificial lighting system, restricted to sources with a solid angle of $3 \cdot 10^{-4}$ to 10^{-1} sr. The formula is expressed as follows:

$$\mathrm{UGR} = 8\log_{10} \frac{0.25}{L_b} \sum_{i=1}^{n} \frac{L_s^2 \omega_s}{P^2} \tag{2.6}$$

This formula is intended for small sources of artificial lighting. However, Iwata et al. (1992) obtained a good correlation between the Glare Sensation Votes (GSV) and the UGR in central vision (centre of window corresponding to line of sight) and a weaker correlation for the peripheral vision in the case of rectangular windows. Note, however, that this experiment involved a simulated window with artificial lighting.

Guth's visual comfort probability (VCP)

The Visual Comfort Probability (VCP) method provides ratings of visual comfort in terms of the percentage of people who will consider a given lighting system to be acceptable (CIE, 1983). It takes into account all the key factors which influence visual comfort and is applicable to all types of interior lighting systems. The VCP is determined from the calculation of another factor called the discomfort glare rating or DGR, which is expressed as:

$$\mathrm{DGR} = \left(\sum_{i=1}^{n} M_i \right)^{n^{-0.0914}} \tag{2.7}$$

$$M = \left(\frac{0.5 \cdot L_s (20.4\omega_s + 1.52\omega_s^{0.2} - 0.075)}{P \cdot F_v^{0.44}} \right) \tag{2.8}$$

$$F_v = \left(\frac{L_w \omega_w + L_f \omega_f + L_c \omega_c + L_s \omega_s}{5} \right) \tag{2.9}$$

where

M	index of sensation for the *i*th glare source;
F_v (cd/m^2)	average luminance for the entire field of view;
L (cd/m^2)	average luminance of the walls (L_w), floor (L_f), ceiling (L_c) and source (L_s);
ω (sr)	solid angle subtended at the observer's eye by the walls (ω_w), floor (ω_f), ceiling (ω_c) and source (ω_s).

The formula

$$\mathrm{VCP} = 279 - 110(\log_{10}\mathrm{DGR}) \tag{2.10}$$

is a very good approximation for the main range of interest: VCP = 20 to 85, respectively DGR = 55 to 200. Beyond this range, the following correction must be added (CIE, 1983):

$$VCP = 279 - 110(\log_{10}DGR) + 350(\log_{10}DGR - 2.08)^5 \qquad (2.11)$$

Equations for the calculation of the VCP were developed by Luckiesh & Guth (1949, 1959, 1961 in IES, 1993) who carried out experiments in simulated rooms using lensed direct fluorescent lighting systems only (IES, 1993). According to IES (1993), the VCP cannot be applied to very small sources such as incandescent and high intensity discharge, to very large sources such as the ceiling in indirect systems, or to non-uniform sources such as parabolic reflectors. The equations are developed for luminaries under standardised conditions of use.

According to Veitch & Newsham (1996), several features of the VCP model limit its applicability as an indicator of discomfort glare. The original model was developed using flat-bottomed recessed luminaries only, and was initially restricted to that application. The validity of the curves for the wide range of luminaries and possible installation is unknown. That is, the model only makes predictions for a given line of sight, and probably does not hold for other viewing positions that occupants might reasonably adopt. Furthermore, Veitch & Newsham (1996) maintain that evidence (Water, Mistrick & Bernecker, 1995) shows that perceptual differences exist between uniform and non-uniform sources that render the VCP model ineffective in predicting glare ratings for non-uniform sources.

Comfort, satisfaction and performance index (CSP)

The CSP index was developed, based upon existing data, current recommendations of the *CIBSE Code for Interior Lighting* (CIBSE, 1994) and detailed studies of over 650 individual workers and their offices. The CSP index is designed to be used in conjunction with the code and takes a value of zero to 100 which relates to the probability that office workers will be satisfied with their visual environment (Bean & Bell, 1992). The CSP is conceptually similar to the VCP system but the development followed a different path (Veitch & Newsham, 1996). The calculation of the CSP is very complicated and is therefore not reported here (see Bean & Bell, 1992 for details). The derivation of the CSP was limited to direct office lighting with or without visual displays. Note that Perry et al. (1995) attempted to replicate Bean & Bell (1992) and obtained a very low correlation between the subjective ratings of lighting acceptability and the photometrically derived CSP index. Even if there was daylighting in the rooms where the experiments were carried out to develop the CSP index, the light from daylight origin was neither recorded nor included in the formula. The CSP index was only intended to deal with artificial lighting. This means that the CSP index is not suitable for problems including daylight or sunlight.

Predicted Glare Sensation Vote (PGSV)

The PGSV is a formula based on experiments with simulated windows with over 200 subjects encompassing 100 different test conditions (Tokura, Iwata & Shukuya, 1996; Tokura et al., 1993). The PGSV is expressed as follows according to Tokura, Iwata & Shukuya (1996):

$$\begin{aligned}\text{PGSV} = {} & 3.2\log_{10} L_{wp} - 0.64\log_{10}\omega_s \\ & +(0.79\log_{10}\omega_s - 0.61)\log_{10} L_b - 8.2\end{aligned} \tag{2.12}$$

where

$$L_b = \left[\frac{\dfrac{E_v}{\pi} - L_{wp}\cdot\Phi_w}{1-\Phi_w}\right] \tag{2.13}$$

where

E_v (lx) vertical illuminance at the eye;
L_{wp} (cd/m^2) luminance visible within the window plane;
Φ_w configuration factor for the window.

The PGSV was based on glare assessments under artificial lighting conditions and uniform light source. Through experiments involving a simulated window with artificial lighting (Tokura, Iwata & Shukuya, 1996; Tokura et al., 1993), it was shown that the PGSV gave more plausible degrees of glare than the DGI, but generally the glare sensations predicted were too high. Moreover, a comparison was made between the glare sensation votes (GSV) and PGSV in two experiments with actual windows oriented towards two different directions. In the first experiment, the subjects were seated directly facing the window while in the second, the subjects were asked either to look up at the window located forward them diagonally or to look up at the other window located just to their left perpendicularly. The results of these experiments indicated that the actual GSV were generally lower than the PGSV and that few people involved in the experiments felt that the actual windows were uncomfortable because of glare. The authors attributed this to the fact that the PGSV cannot cover the effect of the luminance distribution of the window on glare sensation and that the luminance distribution of actual windows or the view out from the windows could bring some psycho-physical comfort to subjects.

Velds (2000) mentioned that the PGSV does not include a position index and therefore only aims at the evaluation of glare from window located in the line of sight. However, in contrast with the DGI, the PGSV takes into consideration the transition of the adaptation luminance level of the eyes and the total amount of light coming into the eyes.

New Daylight Glare Index ($\mathrm{DGI_N}$)

After arguing that there is still no valid glare index for daylighting, Nazzal (2001, 2000) recently proposed a new daylight glare index, which he called $\mathrm{DGI_N}$, where the N stands for "new". The $\mathrm{DGI_N}$ is expressed as:

$$\mathrm{DGI_N} = 8\log_{10} 0.25\left[\frac{\sum_{i=1}^{n}(L_{ext}^2 \Omega_{pN})}{L_{adapt} + 0.07\left(\sum_{i=1}^{n} L_{window}^2 \omega_N\right)^{0.5}}\right] \tag{2.14}$$

where

L_{ext} (cd/m^2)	average vertical unshielded luminance of the outdoors;
L_{window} (cd/m^2)	average vertical shielded luminance of the window;
L_{adapt} (cd/m^2)	average vertical unshielded luminance of the surroundings;
ω_N (sr)	solid angle subtended by the glare source (window) to the point of observation;
Ω_{pN}	position factor depending on the geometry of the window and the distance from the observation place to the centre of the window area.

There was not sufficient evidence at the moment of writing the present report that this daylight glare index could be reliably used for the prediction of discomfort glare from windows. This index promises some improvements for quantitatively assessing daylight and sunlight glare but it does not include performance assessment under such glare conditions (Osterhaus, 2001).

Other indices

Meyer, Francioli & Kerkhoven (1996) introduced the "J" index, which expresses the relationship between the loss of relative visual acuity (*AC*) of a particular operator under given illumination conditions and the maximum possible visual acuity (AC_{max}) that this person can reach. It is expressed as:

$$J = (V^{a}_{max} - V^{a}) / V^{a}_{max} \qquad 0 < J < 1 \qquad (2.15)$$

The input of data may find their origin through direct photometric measurements on the field, simulations in a laboratory, or computer simulations with *Radiance*. The J index is very promising as a way of measuring and computing visual acuity and, perhaps, visual comfort in a space. However, there was little information about this index at the time of designing the present research. Moreover, it is unclear from the publication whether the index can be used as a measure of comfort in the same way as it measures visual acuity.

Another index called the Stationary Virtual Reality (SVR) index was introduced (Sick, 1995; Wienold et al., 1998 in Velds, 2000). The SVR is based on the use of reproductions of scenes using virtual reality in order to offer equivalent test conditions to a number of subjects. The experimental set-up consists of slide projectors and stereo images on slides of a *Radiance* simulated scene. The stereo projection offers the opportunity to create realistic impressions, observed by the subject through magnifying glasses.

According to Velds (2000), both the J and the SVR indices are still in development but are promising. The SVR offers much potential for testing a large number of lighting situations in a short time, including situations with daylighting. However, there was not enough information available at the time of preparing this study to be able to use it as a glare index.

Summary

After reviewing the literature about the discomfort glare indices, it appears that there is currently no glare index which can reliably predict the level of discomfort glare from daylighting in an office room representing a normal working environment in which normal work activities are carried out (i.e. looking at a computer screen for a prolonged period of time).

This opinion is also shared by Velds (2000), who claimed that the majority of existing glare formulas were developed for the evaluation of discomfort glare from small artificial light sources, such as the VCP, the

BGI and the UGR. These formulas cannot be used for the assessment of discomfort glare from windows because the source size mostly subtends a solid angle at the eye that exceeds 0.01 steradians in daylit situation. In the case of daylighting, the glare source occupies a large part of the visual field raising the adaptation level of the eye and thus reducing the sensation of glare and the contrast effect (Hopkinson & Bradley, 1960, in Velds, 2000). Osterhaus (1996) also argued that existing glare evaluation methods primarily target small to medium size ceiling fixtures. For very large glare sources that occupy a substantial part of the visual field, formulae obtained from small source studies have been modified to fit data obtained with large sources, such as luminous ceilings.

At the moment, only the DGI seems to predict the combined effect of the physical values of size and position of windows (large glare source), sky and background (adaptation) luminance, the observer's line of sight, distance and position in relation to the window as showed by the work of Iwata et al. (1990/91). However, the work of Iwata et al. (1990/1991) was performed in a simulated room with an artificial light source. There is much evidence that the spectrum of the light source might have an effect on the tolerated glare (Boubekri & Boyer, 1992; Chauvel et al., 1982). For example, a recent study by Berman et al. (1996) involving only 12 subjects submitted to two spectrally different broad-band sources indicated that the scotopically deficient source (i.e. the source with more energy in the reddish end of the spectrum in this case than the cool-white lamp) elicited a higher level of subjective and objective discomfort. Velds (2000) found that glare sensations with an artificial sky could not be related with glare sensations with an equivalent natural sky concluding that other factors such as the spectrum of light and the view through the window might mitigate the experience of glare.

Boubekri & Boyer (1992) and Nazzal (2000) also mentioned that none of the proposed discomfort glare methods predict discomfort glare from direct sunlight origin. According to Nazzal (2000), a single internationally acceptable phenomenological glare formula and evaluation method has not been attained and no standard monitoring procedure is available.

Osterhaus & Bailey (1992) also pointed out that no data is currently available on perceived comfort or discomfort and the relations between comfort and task performance under conditions in which the glare source borders or surrounds a work task. All existing discomfort glare indices were developed by assessments of subjects directly viewing the glare source rather than focusing on a work task. The study by Osterhaus & Bailey (1992) indicated that subjects tolerated larger changes in glare source luminance when performing a letter-counting task than when just fixating the centre of the VDT screen without actual attention to the task. This identified attention to a work task as a relevant variable in the analysis of discomfort glare (Osterhaus, 1996). Christoffersen (1995) also mentioned that although the recognised empirical models of discomfort glare provide the designer with an indication of advice, they are based on lighting technology current at the time of developments, which reduces their applicability of glare calculations to today's lighting technology, working conditions and activities (computer work). Osterhaus (1996) also suggested to carry out glare experiments with subjects exposed to the daylighting situation for at least the eight hours of a regular work day. Decreasing work performance would be expected due to fatigue and distraction induced by glare discomfort. Sivak & Flannagan (1991) found that task difficulty affected discomfort glare. In their study, smaller gap-sizes in a gap-detection task resulted in more discomfort glare responses concerning a simultaneous presented light source. They concluded that the assessment of discomfort glare requires the inclusion of the relevant visual task the observer is involved in during the presentation of the glare stimulus.

Finally, note that many researchers attribute the lack of strong correlation between glare indices and subjective evaluations to the nature of psychometric studies and to the difference between the human subjects themselves. According to Nunally (1978 in Boubekri & Boyer, 1992), the nature of human beings is far too complex to allow precise prediction, and their visual, emotional and psychological appraisals can be equally complex.

2.2 Potential for daylight utilisation

In this study, the impact of the shading devices on energy use is investigated by calculating the daylight factor as well as the manual switch-on probability.

2.2.1 Daylight factor

The daylight factor can provide some indication of the potential for daylight utilisation of a system. Since the daylight factor is the ratio of indoor to outdoor illuminance, it follows that to obtain a work plane illuminance of at least 100 lx, a daylight factor of at least 1 % must be obtained if an outdoor global illuminance of 10 000 lx is measured. In this case, a daylight factor of 3 % would be preferable since it would produce an interior horizontal illumination of 300 lx under 10 000 lx skies and a daylight factor of 5 % would allow a total daylight autonomy since the horizontal illuminance would be as high as 500 lx, which is the minimum requirement for horizontal illuminance on the task in office rooms. Since overcast skies of around 10 000 lx are common in northern Europe, the daylight factor is a useful number indicating the potential for daylight utilisation of a system.

The daylight factor also has two advantages, outlined by Hopkinson, Petherbridge & Longmore (1966). First of all, it is an expression of the efficiency of the room as a lighting installation i.e. as a means of penetration of available outdoor daylight into the room. Even though the outdoor daylighting may increase or decrease, the daylight factor will remain constant because the interior illumination is also changing with the exterior illumination. The second advantage is associated with the concept of adaptation. The appreciation of brightness is governed not only by the actual luminance of the area at which we are looking at, but also by the brightness of the whole surroundings which govern the level of visual adaptation. As the sky gets brighter the eye will adapt provided that the change takes place slowly. As a result, visual appreciation of the interior of a room will tend not to change radically even though the actual physical luminance will be higher (Hopkinson, Petherbridge & Longmore, 1966).

Note also that the Danish Building regulations (Bygningsreglementet, Boligministeriet 1995 in Arbejdstilsynet, 2000) require, for working spaces, that the window area be at least 10 % of the floor area (7 % for skylights). If the access to daylight is reduced compared with this norm, a daylight factor of at least 2 % is required at the working place.

In their large field study, Christoffersen et al. (1999) found a good agreement between measured daylight factors in 20 office buildings and ratings of appropriate levels of daylighting from over 1800 office workers in those buildings. In general, the higher the daylight factor, the higher the ratings of the daylight level. An analysis of the ratings of satisfaction with daylight levels as a function of measured daylight factor showed that the satisfaction increased as the daylight factor increased. In other words, people preferred higher light levels. Only 10 % of the workers interviewed said that the level of daylight was too high during the summer while only 1 % said it was too high during the winter. The measured daylight factor (2 m from window) was 2 % or higher for 20 % of the offices studied but less than 1 % for 25 % of the offices (thus the majority i.e. 55 % had a daylight factor between 1 and 2 %).

2.2.2 Manual switch-on probability

Field work at the Building Research Establishment (Hunt, 1980) allowed to establish that the probability of someone switching on lights in a space correlated with the minimum daylight illuminance on the working plane at the beginning of the day. People tend to switch the lights on – if needed – only at times when entering a space, and they rarely switch them off until the space becomes completely empty. Hunt (1980) derived a probability function from the field data which is expressed as follows:

$$y = [i + k/(1 + \exp(- j(\log_{10}x - m))] \qquad (2.18)$$

where

y	manual switch-on probability
i	constant (= -0.0175)
j	constant (= -4.0835)
k	constant (= 1.0361)
m	constant (= 1.8223)
x (lx)	minimum daylight illuminance in the working area

and

$y = 1$ for $x \leq 0.843$
$y = 0$ for $x \geq 2.818$

This equation can be used to calculate the probability that someone will manually switch-on the lights in the office room, at the beginning of the day. This provides another indication of the potential for daylight utilisation associated with each shading alternative studied.

3 Method

As mentioned in the previous sections, this study was entirely carried out by computer simulations using the program *Radiance*. The room modelled in *Radiance*, was a typical office space, which was identical to the experimental rooms of the Daylight Laboratory at the Danish Building and Urban Research Institute in Hørsholm, Denmark. Modelling this existing experimental room allowed to verify that the results of the simulations were accurate compared with measurements made in the laboratory. Moreover, this allowed to adjust the rendering options in *Radiance* so that a high accuracy could be obtained within reasonable calculation time.

3.1 Office room studied

3.1.1 Geometry

The Daylight Laboratory in Hørsholm consists of two identical experimental rooms raised above the ground to minimise shading from surrounding buildings and trees (Fig. 3.1). The rooms are oriented 7.5° east of the exact south direction. Each room has one window which is 1.78 m wide by 1.42 m high. The window is 0.78 m from the floor and it is centred with respect to lateral walls (Fig. 3.2).

Figure 3.1 *Outside view of the north and west facades of the Daylight Laboratory at the Danish Building and Urban Research Institute, Hørsholm, Denmark (photo Jan Carl Westphall).*

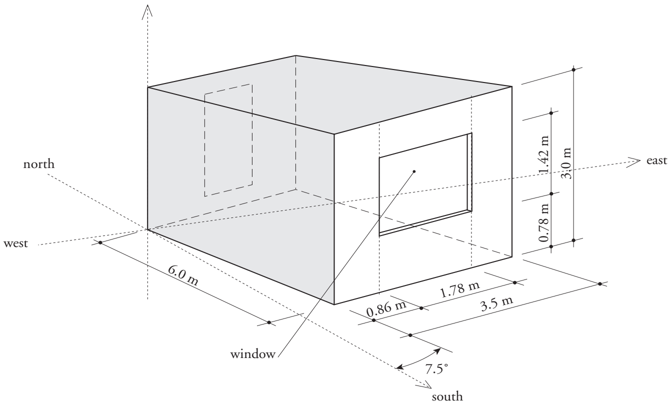


Figure 3.2 *Geometry of the south-oriented office room of the Daylight Laboratory at the Danish Building and Urban Research Institute.*

3.1.2 Surface properties

Walls, floor and ceiling

The reflectance of the inner walls, floor and ceiling of the Daylight Laboratory was estimated by measuring the luminance of the element of unknown reflectance under constant, diffuse lighting conditions and comparing it with the luminance of a sample of known reflectance under the same lighting conditions as explained in Fontoynont (1999) and Hagner (1980). For example, for the walls, the reflectance (ρ_{wall}) was determined as follows:

$$\rho_{wall} = \rho_{ref} \cdot \frac{L_{wall}}{L_{ref}} \tag{3.1}$$

where ρ_{ref} is the reflectance of the reference reflector, L_{wall} is the luminance (cd/m^2) of the wall and L_{ref} is the luminance (cd/m^2) of the reference reflector.

The measured reflectance of each surface in the room is reported in Table 3.1.

Table 3.1 Estimated average reflectance, specularity and roughness of the walls, floor and ceiling of the Daylight Laboratory.

Element	Colour	Material	Reflectance	Specularity	Roughness
Walls	Off-white, matt	Gypsum	0.81	0.03	0.03
Floor	Dark grey, matt	Carpet	0.11	0.03	0.20
Ceiling	White, matt	Suspended tiles	0.88	0.03	0.03

The material primitive (type) used in *Radiance* to model the interior surfaces of the laboratory was “plastic”. This material is defined by its red, green, blue (RGB) reflectance values and a value for specularity and roughness. Since it was irrelevant to model the correct colour in this study as the impact of colour was not investigated, the values of the RGB channels were set to the same reflectance value shown in Table 3.1.

The other properties that must be determined for the “plastic” material type are the specularity and roughness. The specularity is the amount of light reflected (or transmitted) by specular (mirror-like, not diffuse) mechanism (Ward Larson & Shakespeare, 1998). The roughness is the root mean square (RMS) microfacet slope of the surface. It is a measure of the average instantaneous slopes of a polished surface, which determines to what degree a semi-specular highlight will be dispersed (Ward Larson & Shakespeare, 1998). The specularity and roughness control the way light will be reflected off the material. If both are set to zero, the surface is perfectly diffuse and reflects light equally in all directions (Ward Larson & Shakespeare, 1998). On the other hand, if the material is purely specular (high specularity) and has a roughness of zero, it is a mirror

(Larson in Ward, 1996b). If the value for specularity (0.05) is followed with a roughness value of zero, the surface will appear to have the properties of a smooth porcelain plate. By adding a roughness factor (0.03), a diffusing component is mixed in, producing the reflection patterns associated with a satin finish (Ward Larson & Shakespeare, 1998). According to Ward (1996a), specularity fractions greater than 0.1 and roughness greater than 0.2 are not very realistic and the specularity of most non-metallic surfaces rarely exceeds 0.06.

In this study, the specularity and roughness values were determined from the boundaries given in the reference manual (Ward, 1996a) and from values normally used by other researchers (Ward Larson & Shakespeare, 1998). As all material surfaces in the laboratory were rather matt with a smooth surface, a low specularity (0.03) and low roughness (0.03) were assigned, except for the floor where a very high roughness value (0.2) was used to imitate the carpet material. However, according to Ward Larson & Shakespeare (1998), roughness cannot be used to model macro scale roughness–that is, surface imperfections visible to the naked eye and the carpet should thus in this case be modelled as a macro scale surface perturbation. However, during the preparatory tests, it appeared that this parameter had a negligible impact on the illuminance and luminance values examined in this study and the macro scale perturbations were thus discarded from the model since they increased calculation time significantly.

Window

The window of the Daylight Laboratory is a double-pane assembly with a low-emissivity coating and argon fillings from Pilkington (Optitherm S). This window has a U-value of 1.1 W/m^2°C, a light transmittance of 72 % (direct) and 65 % (diffuse), and a reflectance of 15 % (front) and 14 % (back).

The window was modelled in *Radiance* using the “BRTDfunc” material type. This material type allows to correctly model the bi-directional reflectance and transmittance distribution (BRTD) function which characterizes the window. In this case, the BRTD function was described by simple semi-empirical polynomials developed by Karlsson & Roos (2000). These polynomials allow to calculate the angle-dependent transmittance (T_θ) and reflectance (R_θ) of the glazing assembly based on simple inputs like the number of panes (p), the transmittance (T_0) and reflectance (R_0) at normal incidence and a coefficient (q) describing the type of glazing and/or coating:

$$T_\theta = T_0(1 - az^\alpha - bz^\beta - cz^\gamma) \tag{3.2}$$

$$R_\theta = R_0 + (az^\alpha + bz^\beta + dz^\gamma) \tag{3.3}$$

where

$a = 8$;
$b = 0.25/q$;
$c = (1 - a - b)$;
$d = (1 - a - b - R_0)$;
$\alpha = 5.2+0.7q$;
$\beta = 2$;
$\gamma = (5.26 + 0.06p) + (0.73 + 0.04p)q$;
$z = \theta/90$;
θ = angle of incidence with respect to the glazing normal (°).

These polynomial expressions were originally developed to calculate the total solar transmittance (*g* value) of any glazing assembly at any angle of incidence. However, according to Karlsson (2001), the same or similar polynomials can be used to determine the visual properties using slightly higher or lower "*q*" values. In this case, the "*q*" value which best described the angular properties of this window were obtained directly from Karlsson (2001), who also performed exact Fresnel calculations and showed that the polynomial expressions returned accurate values in the visual range compared with detailed calculations.

The transmittance and reflectance obtained using the polynomials are shown in Fig. 3.3 and compared with the properties which would be obtained if a window with an angle dependence similar to that of clear glass was modelled instead. This figure shows that modelling the window as a clear glazing would result in a relative error in the transmittance of up to 5 % at certain angles of incidence (i.e. at 70° from the normal).

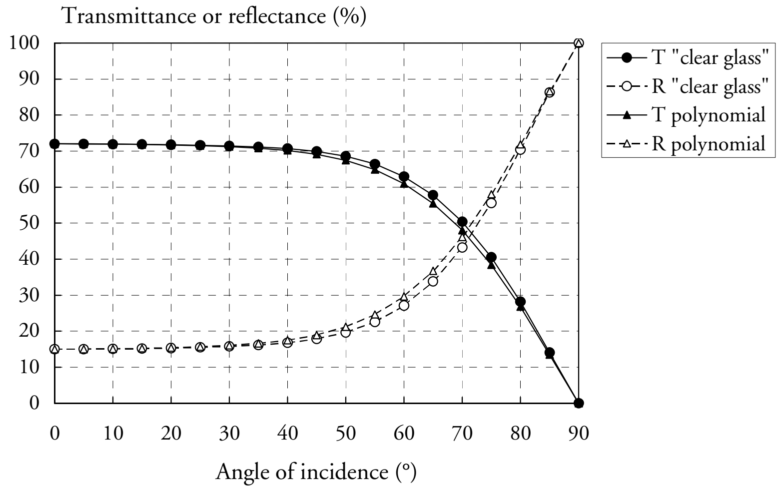


Figure 3.3 *Transmittance (T) and reflectance (R) of the double-pane, low-e coated window at the Daylight Laboratory, calculated according to polynomials by Karlsson & Roos (2000) and compared with the value obtained if the angular dependence function of a clear glass window was used instead.*

Note that *Radiance* uses Fresnel equations to predict the transmitted and reflected light through glass. It would thus be possible to model the window using the "glass" material in *Radiance*. However, this would require that the thickness and optical constant of each layer in the window coating material be known. Since this information is not available, it appeared that the polynomial approach was the most simple and accurate in this case.

3.1.3 Furniture

Before starting the simulations and renderings for all the shading systems, the impact of furniture on the illuminance values in the office room was studied. The work plane illuminance and illuminance on the ceiling and lateral walls were calculated in an empty room and compared with the values obtained in a furnished room, under an overcast sky, and a sunny sky in June (at 09.00 and 12.00 hours) and December (at 09.00 and 12.00 hours). A quick rendering of the furnished room is shown in Fig. 3.4.

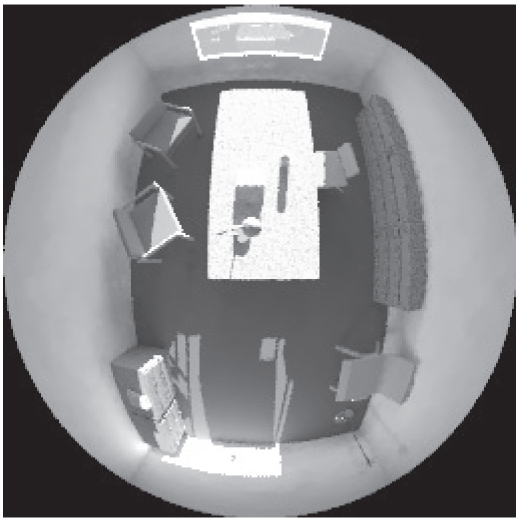


Figure 3.4 Quick rendering of the furnished room modelled in Radiance.

The relative difference (calculated as $RD=100[(E_e-E_f)/ E_e]$) between the empty and furnished room was calculated and is shown in Fig. 3.5 to 3.9.

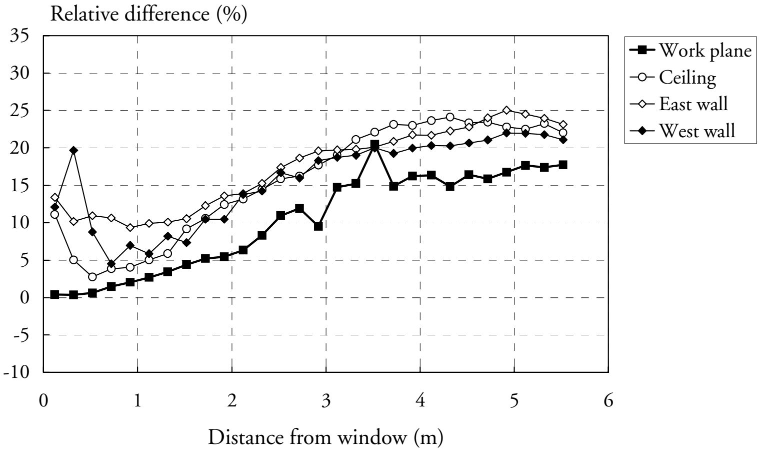


Figure 3.5 Relative difference (%) between the illuminance values obtained in the empty and furnished room, under an overcast sky of 10 000 lx.

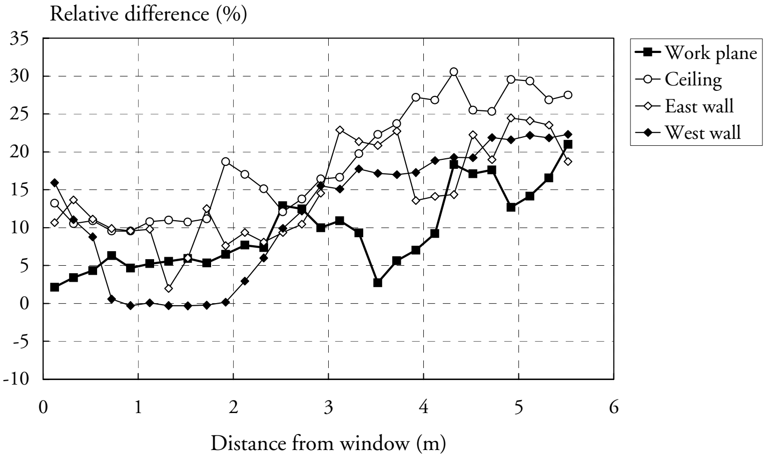


Figure 3.6 *Relative difference (%) between the illuminance values obtained in the empty and furnished room, on December 21 at 09.00 hours.*

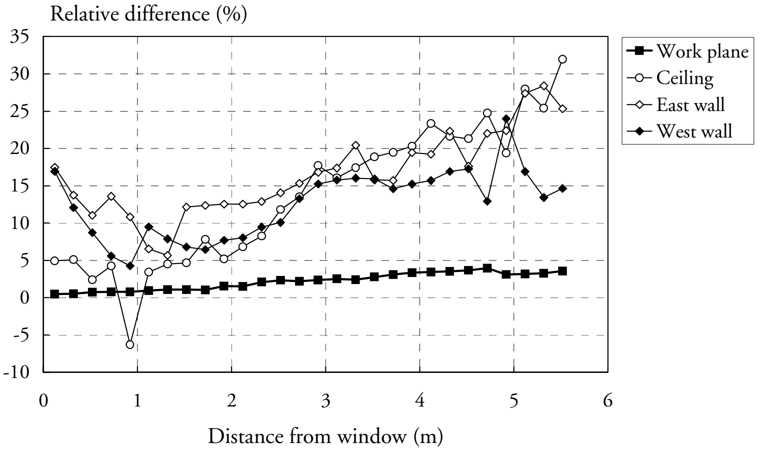


Figure 3.7 *Relative difference (%) between the illuminance values obtained in the empty and furnished room, on December 21 at 12.00 hours.*

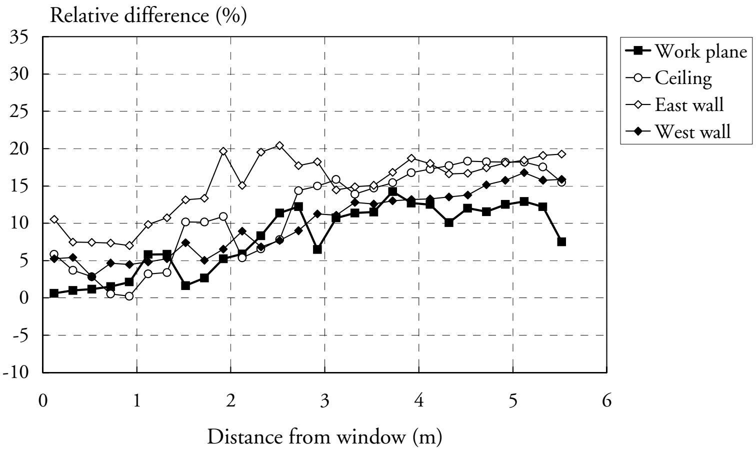


Figure 3.8 *Relative difference (%) between the illuminance values obtained in the empty and furnished room, on June 21 at 09.00 hours.*

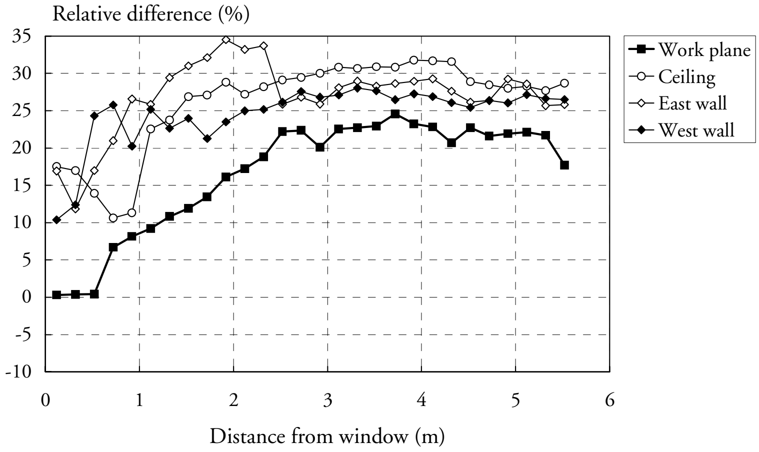
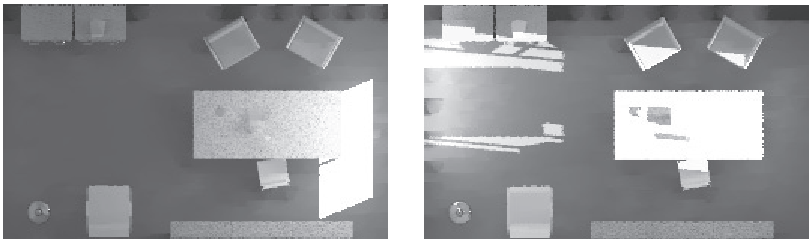


Figure 3.9 *Relative difference (%) between the illuminance values obtained in the empty and furnished room, on June 21 at 12.00 hours.*

Fig. 3.5 to 3.9 show that the illuminance was almost always lower in the furnished than in the empty room (positive values mean that the illuminance was lower in the furnished room). The figures also show that the relative difference between the empty and furnished room was generally higher in the back than in the front of the room and lower on the work plane than on other surfaces. The relative difference was also lower for the overcast conditions and on June 21 at 09.00 hours and higher on June 21 at 12.00 hours.

Fig. 3.5 to 3.9 show that the relative difference between the empty and furnished room is extremely variable across space and time i.e. the relative difference varies as a function of distance from the window but also as a function of the time and date of simulation. On June 21, for example, the relative difference was 7-17 % in the middle of the room at 09.00 hours and 20-30 % at 12.00 hours. A look at the rendering at 12.00 hours reveals that the direct sunlight patch fell somewhere between the desk and the window (Fig. 3.10). Since the desk shaded the room from the direct sunlight patch, the illuminance on walls and ceiling was significantly reduced, which explains the higher relative difference found for this case (Fig. 3.9).

Fig. 3.10 also shows the rendering on December 21 at 12.00 hours. The relative difference between the empty and furnished room was smaller in this case (Fig. 3.7) since the sunlight patch fell directly on the desk top (Fig. 3.10) and the desk reflected light upwards towards the ceiling in the middle of the room.



a) b)

Figure 3.10 *Quick rendering of the furnished room on a) June 21, at 12.00 hours and b) December 21, at 12.00 hours. The rendering shows that the direct sunlight patch falls between the desk and window in June and on the desk top in December.*

This analysis indicates that the relative difference between an empty and furnished room varies as a function of sun angle, distance from the window and also furniture arrangement. The analysis shows that the furniture interacts with the direct sunlight by reflecting it further in the room or shading it from the rest of the room, depending on the position of the furniture in the room and sun angle. Since the illuminance values are affected by the position of the furniture, any single furniture arrangement will results in a specific illuminance distribution. Thus it is necessary to study many furniture arrangements to draw realistic conclusions. Since it is impossible to study all the possible furniture arrangements within the scope of the present study, we decided to leave this aspect for future research and perform the simulations with an empty room, a situation which is further away from reality but may provide more general results.

3.1.4 Landscape

The main floor of the Daylight Laboratory is raised approximately 7 m from the ground on the north side and about 13 m from the ground on the south side to prevent shading from adjacent buildings and trees (Fig. 3.1). The outside scene in front of the laboratory on the south side consists of a 22 m-deep parking lot adjacent to a 55 m-deep football field, which is terminated by a row of approximately 8 m-high trees. There is also a group of trees near the laboratory towards the south-west direction. Fig. 3.11 shows a panoramic (180°) view of the landscape in front of the laboratory.

Figure 3.11 *Panoramic view (180°) of the landscape in front of the south facade of the Daylight Laboratory (photo Jan Carl Westphall).*

As Fig. 3.11 shows, the space in front of the south elevation is essentially empty from obstructions, apart from the distant row of trees at the end of the football field, which obstructs the lower part of the sky towards the south direction, and the group of trees towards the south-west direction (Fig. 3.11, right).

Fig. 3.12 shows a picture of the outside scene from the point of view of a person standing at the back of one of the experimental rooms (eye level at 1.6 m from the floor). This picture shows that the distant row of trees at the end of the football field obstructs the lower part of the sky, which is likely to affect the amount of direct light received in the middle and back of the room. Note that the importance of accurately reproducing the skyline was pointed out by Velds (2000).

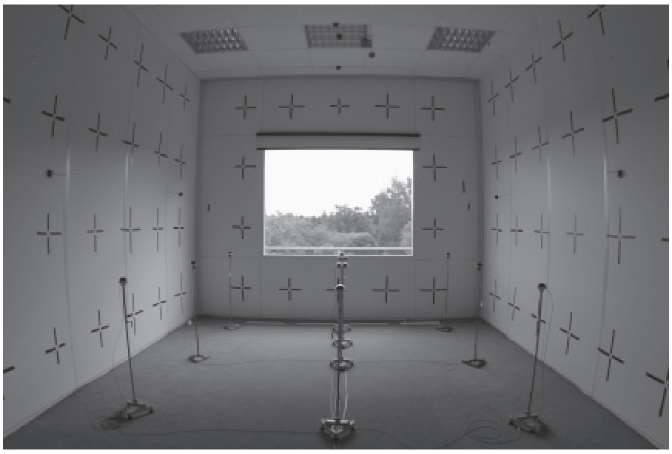


Figure 3.12 View out from the interior of the laboratory from the point of view of a person standing at the back of the room (eye level at 1.6 m from the floor) (photo Jan Carl Westphall).

In order to make sure that the lighting distribution in the model was as close to reality as possible, some of the features of the outside scene in front of the laboratory were added to the model. These elements include: the distant row of trees which was modelled as a simple 8 m-high by 100 m-wide rectangular polygon located 77 m away from the south facade, the football field and parking lot, the foundation wall of the laboratory and gangway. The reflectance attributed to the elements of the landscape (row of trees, football field, parking lot) was determined from the literature (Iqbal, 1983), while the reflectance of the foundation wall and gangway were obtained from staff at the laboratory. These reflectance values are presented in Table 3.2.

Table 3.2 Reflectance of the elements composing the landscape in front of the laboratory (south facade).

Landscape element	Reflectance
Parking lot	0.10
Football field	0.20
Distant row of trees	0.04
Foundation wall	0.60
Gangway	0.60

Fig. 3.13 shows a quick rendering of the laboratory modelled in *Radiance* showing the main elements of the outside landscape included in the model. The group of trees in the south-west direction was not modelled as it was judged almost impossible to determine the geometric shape of these trees. Moreover, even if this would have been possible, this additional geometrical complexity would have overloaded the calculations tremendously.

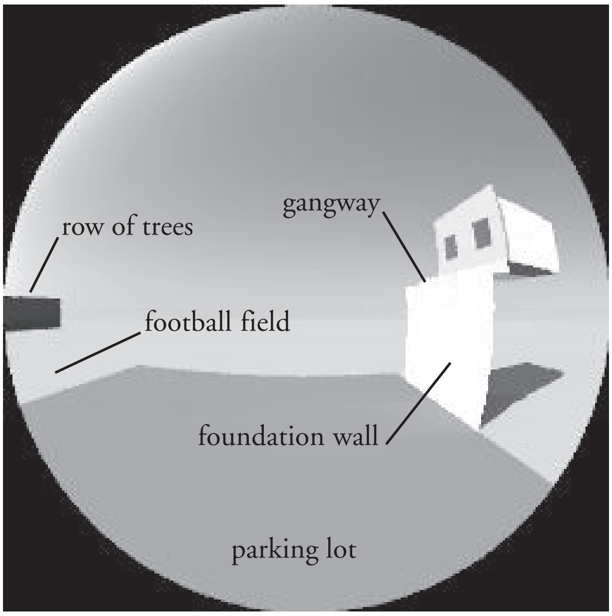


Figure 3.13 Quick rendering of the Daylight Laboratory modelled in Radiance showing the elements of the landscape included in the model.

Fig. 3.14 shows the daylight factors obtained through measurements in the Daylight Laboratory and through calculations with a simple and a detailed landscape layout. The simple landscape consisted of only the ground plane while the detailed landscape included the elements shown in Fig. 3.13. The relative difference (calculated as $RD=100[(D_M-D_S)/D_M])$ between the measured and simulated values is also shown in Fig. 3.15.

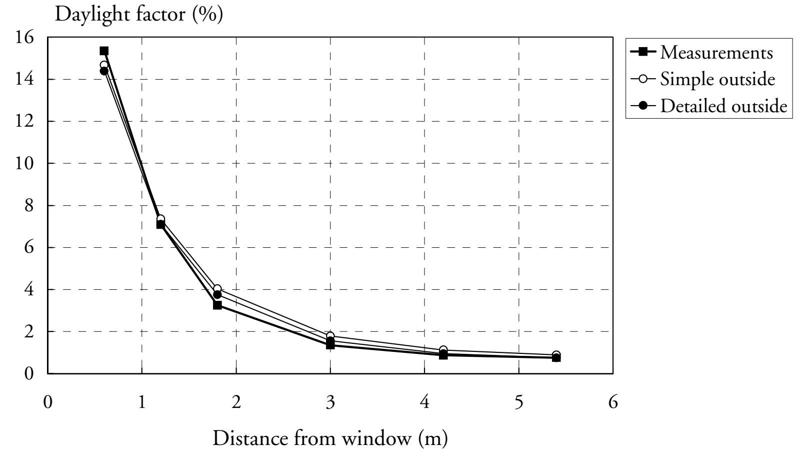


Figure 3.14 *Daylight factors (%) in the Reference room obtained through measurements and simulations with a simple and detailed landscape model.*

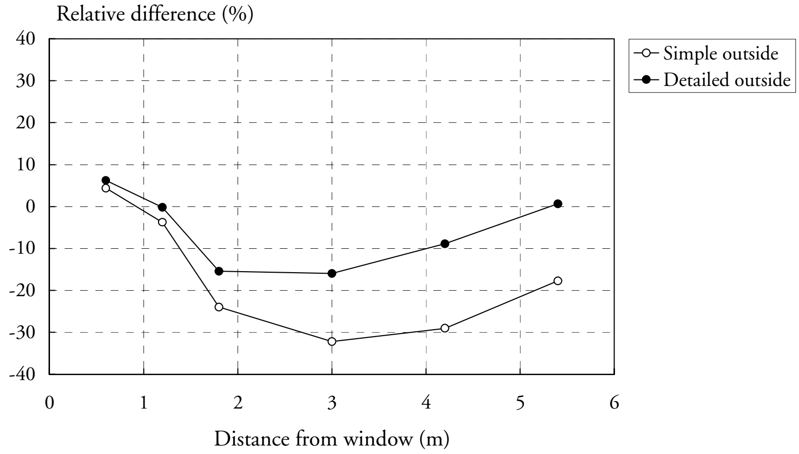


Figure 3.15 *Relative difference (%) between the daylight factors obtained through measurements and simulations with a simple and detailed landscape model.*

Fig. 3.14 shows that the detailed landscape model results in a more similar daylight factor profile in the room compared with the measurements. Fig. 3.15 shows that the relative difference between the measurements and the simulations is greatly reduced by introducing some more detailed landscape features, especially in the middle and back of the room. In the case of the simple lanscape model, there was too much light in the middle and back of the room (negative values mean that the results from the simulations were higher than the results from the measurements). The problem is partially corrected by introducing a distant row of trees, which obstructs the lower part of the sky, thus reducing the direct incident light in the back of the room. The detailed landscape model was therefore used in this study.

3.2 Shading devices studied

Six exterior shading devices were evaluated in this study: one venetian blind, two awnings, two screens and one overhang with slats. These devices were selected from a database of products, that have been characterised within the Solar Shading Project at Lund University (Wall & Bülow-Hübe, 2001). The selected shading devices thus have a known total solar transmittance (*g* value).

3.2.1 Geometry

Venetian blind

The venetian blind was an exterior, 2.02 m-wide blind with 80-mm wide, curved slats. Two different slat angle positions were studied: 0° (horizontal) and 45° as illustrated in Fig. 3.16. The support box and fixtures holding the slats were also modelled so as to reproduce the real blind system as accurately as possible.

Awnings

A white and a dark blue awning were modelled. The awnings were 2.19 m wide and thus overlapped the window by 0.21 m on each side. The support box and arm details were modelled to reproduce the real system as closely as possible as shown in Fig. 3.17. The awning's length was adjusted so that the window would be exactly shaded at 12.00 hours on each day of simulation.

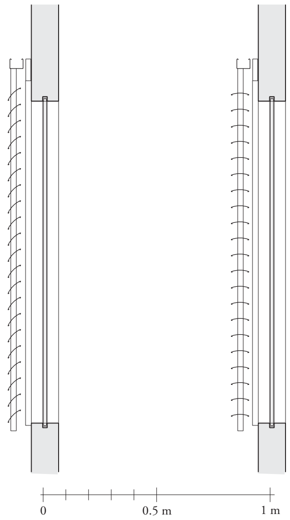


Figure 3.16 *Venetian blind with the two slat angle positions studied: 45° (left) and 0° or horizontal (right).*

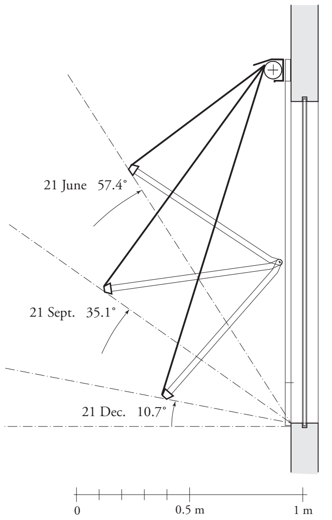


Figure 3.17 *Awning's geometry shading exactly the window at 12.00 hours on June 21, September 21 and December 21.*

Screens

The screens were modelled as a flat sheet of translucent material located 30 mm from the exterior side of the window. The screen was fitted into the window frame and had the same size as the window to prevent light leakage on the side of the window.

Overhang

The overhang was a horizontal structure consisting of a series of slats inclined at 45° as shown in Fig. 3.18. The overhang was 2.56 m wide and thus overlapped the window by approximately 0.4 m on each side. The support system for the slats and arms were all modelled so as to reproduce the real overhang system as closely as possible.

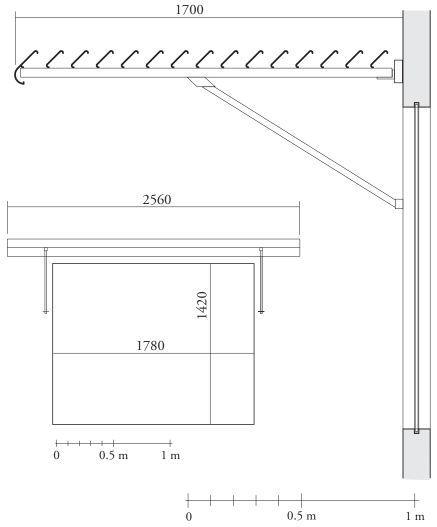


Fig. 3.18 *Overhang with slats.*

3.2.2 Optical properties

The optical properties of the shading fabrics and materials modelled in *Radiance* were determined through measurements in a spectrophotometer at the University of Uppsala by Per Nostrell (2001). Nostrell provided spectral data for the total, specular (direct) and diffuse transmittance and reflectance of each shading material. Since *Radiance* does not calculate spectrally, it was necessary to determine average values from the spectral data. *Radiance* uses red, green, blue (RGB) reflection and transmission values in the input to determine the colour of the material. Since the impact of colour was not investigated in this study, all the materials were assigned the same RGB value. The average transmittance ($\tau_{average}$) and reflectance ($\rho_{average}$) were calculated by weighting the spectral values provided by Nostrell with the photopic luminous efficiency function of the human eye ($V(\lambda)$) and the spectrum power distribution of the illuminant ($I(\lambda)$) in the visual range according to norm D65 as recommended in Cen (1990) as follows:

$$\tau_{average} = \frac{\sum_{\lambda=380nm}^{770nm} I(\lambda)\cdot V(\lambda)\cdot \tau(\lambda)\cdot \Delta\lambda}{\sum_{\lambda=380nm}^{770nm} I(\lambda)\cdot V(\lambda)\cdot \Delta\lambda} \tag{3.4}$$

A similar procedure was used to obtain the average reflectance values ($\rho_{average}$).

The calculated average transmittance and reflectance of each shading material obtained are presented in Table 3.3. This table shows that the venetian blind and overhang were modelled with the same opaque silver painted aluminium material, which had the same optical properties. This table also shows that both the white and dark blue awnings are made of purely diffusing fabrics while the screens had some specular (direct) transmittance. The transmittance of the grey screen was almost totally direct.

Table 3.3 Shading devices investigated and their optical properties.

#	Shading device	Colour, material	T_{tot} (%)	T_{spec} (%)	T_{diff} (%)	R_{tot} (%)	R_{spec} (%)	R_{diff} (%)
1	Venetian blind	Silver painted aluminium	0.0	0.0	0.0	55.9	0.0	55.9
2	Awnings	White fabric	21.7	0.0	21.7	63.5	0.0	63.5
3		Dark blue fabric	0.1	0.0	0.1	2.7	0.0	2.7
4	Screens	Grey fabric	4.1	3.9	0.2	31.3	0.0	31.3
5		White fabric	15.2	3.0	12.2	78.6	0.0	78.6
6	Overhang	Silver painted aluminium	0.0	0.0	0.0	55.9	0.0	55.9

3.3 Simulation tool: *Radiance*

The study was carried out using the *Radiance Lighting Simulation System* (Ward Larson & Shakespeare, 1998) included in the *Adeline 2.0NT* package, which runs on the Windows operating system. *Radiance* is one of the most advanced daylighting/lighting simulation tools available today and it has been fully validated (Mardaljevic, 1999; Aizlewood et al., 1998; Ubbelohde & Humann, 1998; Jarvis & Donn, 1997, etc.).

Radiance uses a backward, recursive ray-tracing method. Backward ray-tracing implies that "view rays" are followed from the virtual focus of a virtual eye or camera through pixels in an imaginary image plane into the environment. Recursive means that the problem is reformulated in terms of a simpler version of the original problem i.e. the final value of a ray is solved by tracing other rays and finding their value. Rays are sent in the space, following each ray until it intersects a surface, where it may spawn more rays until enough rays have been computed. This recursive process halts when one of the following is true:

1. the intersected surface is a light source (for which the reflectance is approximated as zero);
2. the ray has reflected more than a specified number of times;
3. the ray "weight" which is the product of all previous reflectances is below a specified value. (Ward Larson & Shakespeare, 1998).

The ray-tracing rendering technique was introduced by Whitted in 1980 (in Ward Larson & Shakespeare, 1998) and used a strictly deterministic algorithm. Deterministic means that the ray would be sent toward the exact centre of the source every time and that the same result would be obtained for a given rendering when it was repeated. *Radiance* uses a hybrid deterministic-stochastic ray tracing method. A stochastic algorithm employs random processes i.e. it chooses a random direction in which to send the ray. In some cases, the ray reaches the light source, but in other cases it might first intersect the intervening object or go off in a different direction entirely. This non-deterministic behaviour shows up in the rendered image as noise and when repeated will generally give slightly different results. The average of all results thus obtained will be closest to the true answer because the stochastic approach is closer to the way light works in nature: photons are bouncing about randomly, and it is only their enormous number which gives light the appearance of stability at any given point. Stochastic techniques are thus more accurate on the average than purely deterministic approaches (Ward Larson & Shakespeare, 1998). The deterministic approach creates unnaturally sharp shadows and fails to render inter-reflections between surfaces correctly. On the other hand, the stochastic approach takes forever to reach a reasonable noise-free solution. Therefore, by using a mixture of both deterministic and stochastic techniques, *Radiance* yields a high accuracy as a function of the rendering time. (Ward Larson & Shakespeare, 1998).

Radiance is thus well suited for the computation of direct and reflected light distribution in a space (Moeck, Lee & Rubin, 1996). Moreover, *Radiance* has virtually no limitation regarding geometrical input and optical and physical properties of the objects in the scene. *Radiance* takes a three dimensional description of a space and a physical description of its surfaces, such as the bi-directional transmission and reflectance data, colour, and texture. This allows to study the impact on daylighting of detailed objects such as e.g. shading screens with a degree of direct and diffuse transmittance, venetian blinds with specular and diffuse reflectance, etc. *Radiance* also allows to model daylighting at any time of the year and any latitude and longitude and contains a mathematical model for the CIE standard sunny, overcast and intermediate skies. Finally, the program has a virtually unlimited output capacity since it can calculate the radiance/irradiance, luminance/illuminance or the daylight factor of any single point in a scene and can produce highly realistic renderings. The rendering capabilities are supplemented by valuable features such as e.g. the possibility to produce superposed luminance contours and false colour images (see e.g. Plates 1-4), which allow visualisation and luminance (or illuminance) analysis simultaneously.

3.3.1 Rendering options in *Radiance*

One particular feature of *Radiance* is that the user has the possibility to adjust the rendering parameters in order to find the optimum compromise between accuracy and rendering time. This is an essential feature of the program, which demands experience and time to adjust before starting the simulation process. Each rendering option has to be carefully adjusted in order to obtain the maximum accuracy in the calculation in the least possible rendering time. A bad choice of rendering options may also yield low accuracy levels in the results. It is therefore essential to carefully study and adjust the rendering options, especially when lighting analysis is involved.

Much work was performed at the beginning of this research to determine the rendering options which would yield an optimum level of accuracy within a reasonable calculation time. The process to determine the optimum rendering options settings in this case is described in detail in the Appendix (A).

The main outcome of this preliminary work was that high accuracy settings combined with secondary light sources provided the highest accuracy within a reasonable rendering time. The rendering options settings used throughout the simulations were the following:

```
-dt 0.0 -dc 1.0 -dj 0.65 -ds 0.01-st 0.01 -sj 1 -ab 8 -aa 0.08 -ar 512 -ad
2048 -as 512 -lr 8 -lw 0.001.
```

3.4 Data collection

3.4.1 Measured points

Radiance allows to predict the luminance or illuminance value of any point in the simulated scene. These values can be obtained either by performing a complete rendering of the scene (by using the program "rpict") or by calculating specific points using the program "rtrace", which is one of the main tools of *Radiance*. Using "rtrace" instead of performing a rendering with "rpict" allows to obtain the luminance or illuminance value of exact geometric coordinates, without limitation on the amount of coordinates to be calculated. This approach is also generally more effective since rays need only to be sent from the coordinates of interest.

In this study, "rtrace" was used to predict the illuminance and luminance values in the office room and "rpict" was subsequently used to produce a rendering of the window as seen from the interior of the room. The use of "mkillum" and secondary light sources was especially effective in this case since the same "illums" were used by both "rtrace" and "rpict" (see Appendix for further explanations).

Using "rtrace", the work plane illuminance was calculated on 18 points at 0.8 m from the floor. The location of the points was determined by dividing the work plane into six regions along the depth of the office and three regions along the width. This delimited 18 regions of which each middle point was selected as a good approximation of the illuminance for this particular area of the work plane (Fig. 3.18). The illuminance on the roof was also calculated to obtain the global illuminance outside the laboratory, which is needed to determine the daylight factors.

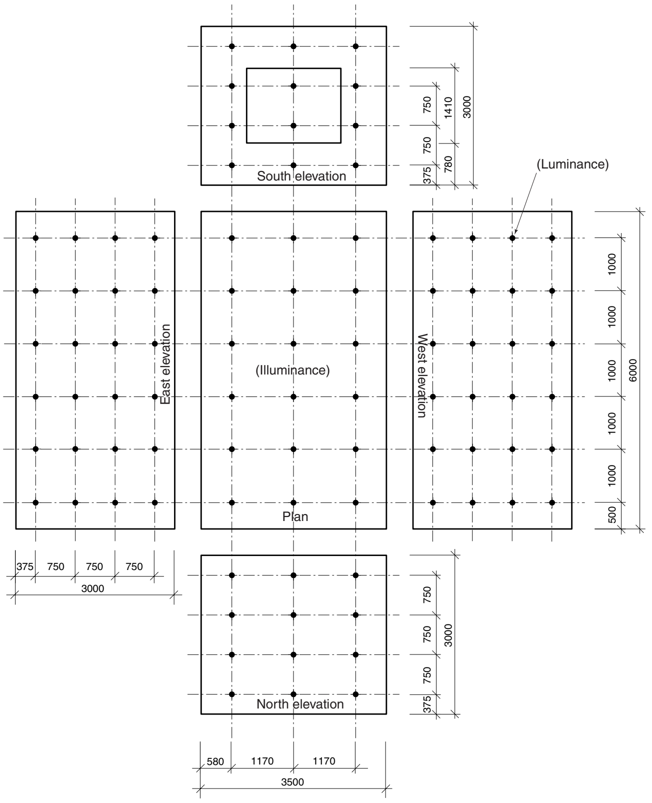


Figure 3.19 Calculated points in the illuminance and luminance calculations.

The areas of interest for the luminance calculations were: the walls, the window and shading device, the floor and ceiling. The luminance of the walls, window and shading device (as seen from the interior of the office) was especially important since walls occupy the largest portion of the field of view of an office worker. The walls (including window and shading devices) were thus divided into four regions along the height, six regions along the depth and three regions along the width of the office room. This delimited 24 sub regions for the side walls and 12 sub regions for the window-wall and back wall, of which each middle point was selected as a good approximation of the luminance of the whole patch. The luminance of the floor and ceiling was calculated at 18 points corresponding to the location of the work plane illuminance measurements. Fig. 3.19 shows the location of the points for the illuminance as well as luminance calculations.

3.4.2 Simulated days and hours

An ideal assessment of daylight quality or availability in a space should take into consideration the transient character of daylighting, which constantly varies throughout the day and year. On the other hand, measuring or even simulating every hour of one year would be an unrealistically time-consuming task.

A more realistic and effective approach consists of choosing some days of the year which represent extreme and average conditions and a few hours during each of these days such that a typical work day in an office is covered. This approach is recommended in some recent international monitoring protocoles for daylighting (Atif, Love & Littlefair, 1997; Velds & Christoffersen, 2000).

In this study, the following days were chosen as representative of extreme and average sky conditions:

- 21 June (summer solstice)
- 21 September (autumn equinox)
- 21 December (winter solstice)
- One overcast day

Most of the simulations were performed under sunny sky conditions since shading devices are usually used under sunny conditions. The overcast sky simulations were performed to determine the daylight factors in the space. The CIE sunny sky model available in *Radiance* was used for the solstice and equinox days (21 June, 21 September and 21 December) while the CIE overcast sky model was used to simulate an overcast sky with an outdoor illuminance of 10 000 lx. No intermediate skies were modelled although shading devices may be used under intermediate skies, especially when bright white clouds are lit by direct sun, which may cause glare problems.

The impact of the shading system on indoor lighting conditions was studied three times a day under sunny conditions: once in the morning (09.00 hours), once at noon time (12.00 hours) and once in the afternoon (15.00). Thus, a total of 80 simulations (eight shading alternatives, ten hours) were carried out. Table 3.4 summarises the simulations which were performed in this study.

Table 3.4 Days and hours studied.

Shading devices	CIE sunny sky			CIE overcast sky
	Summer solstice (21 June)	Autumn equinox (21 September)	Winter solstice (21 December)	
1) Wh. Awn. 2) Bl. Awn. 3) V. B. (h) 4) V. B. (45) 5) Overhang 6) Grey Screen 7) Wh. Screen 8) Window	09.00 hours* 12.00 hours* 15.00 hours*	09.00 hours* 12.00 hours* 15.00 hours*	09.00 hours 12.00 hours 15.00 hours	One hour (10 000 lx)

(*) local summer time.

The local summer time was used since this study aims to evaluate daylighting quality for occupants of real offices who have to work according to the local time. The summer time was thus used for the summer solstice and autumn equinox days, which fall into the summer time period in Scandinavia (from the end of March to the end of October). The summer time has the effect that the clock time is one hour in advance with respect to normal solar time. Thus when the clock shows 12.00 hours during the summer, the sun position is in reality closer to its 11.00 hours position.

3.5 Data analysis

3.5.1 Performance indicators considered

The performance indicators for the evaluation of daylight quality in the office rooms were determined from the literature review presented in Section 2 Daylight quality. All the indicators covered in this review were used except the (daylight) glare index, which was discarded because of the lack of supporting evidence that this indicator can reliably be used in this case. The potential for daylight utilisation was also analysed based on the daylight factors and manual switch-on probability. Table 3.5 gives an overview of the indicators used in this study and the interpretation applied as a function of the values obtained.

Note that for the analysis of the luminance ratios, we used the definition of the ergorama and panorama proposed by Meyer, Francioli & Kerkhoven (1996). According to these authors, maximum luminance ratios of 1:3 should be respected within the ergorama (a cone of 60° centred about the line of sight), while maximum luminance ratios of 1:10 should be respected within the panorama (a cone of 120° centred about the line of sight). In the rest of the field of view, we applied the requirement proposed by NUTEK (1994): a maximum ratios of 1:20 should be respected within the whole field of view.

Table 3.5 Performance indicators considered and interpretation as a function of the data obtained.

#	Performance indicator	Interpretation
1	WORK PLANE ILLUMINANCE	
	< 100 lx	Too dark for paper and computer work
	100-300 lx	Too dark for paper work / acceptable for computer work
	300-500 lx	Acceptable for paper work / ideal for computer work
	> 500 lx	Ideal for paper work / too bright for computer work
2	ILLUMINANCE UNIFORMITY ON THE WORK PLANE	
	$E_{min}/E_{max} > 0.5$	Acceptable
	$E_{min}/E_{max} > 0.7$	Preferable
3	ABSOLUTE LUMINANCE	
	> 2000 cd/m^2	Too bright, anywhere in the room
	> 1000 cd/m^2	Too bright, in the visual field
	< 500 cd/m^2	Preferable
	< 30 cd/m^2	Unacceptably dark
4	LUMINANCE RATIOS	
	$L_{paper\_task}/L_{surroundings} < 0.33$ or > 3	Unacceptable within 60º cone of vision
	$L_{paper\_task}/L_{surroundings} < 0.1$ or > 10	Unacceptable within 120º cone of vision
	$L_{paper\_task}/L_{surroundings} < 0.05$ or > 20	Unacceptable within whole visual field
	$L_{VDT}/L_{surroundings} < 0.33$ or > 3	Unacceptable within 60º cone of vision
	$L_{VDT}/L_{surroundings} < 0.1$ or > 10	Unacceptable within 120º cone of vision
	$L_{VDT}/L_{surroundings} < 0.05$ or > 20	Unacceptable within whole visual field
	$L_{paper\_task}/L_{VDT} < 0.33$ or > 3	Unacceptable
5	DAYLIGHT FACTOR	
	< 1 %	Unacceptably dark, negligible potential for daylight utilisation
	1-2 %	Acceptable, small potential for daylight utilisation
	2-5 %	Preferable, large potential for daylight utilisation
	> 5 %	Ideal for paper work, too bright for computer work, total daylight autonomy
6	MANUAL SWITCH-ON PROBABILITY	
	< 25 %	High potential for daylight utilisation
	25-50 %	Moderate potential for daylight utilisation
	50-75 %	Low potential for daylight utilisation
	> 75 %	Negligible low potential for daylight utilisation

While the absolute illuminance and luminance values and daylight factors could be analysed in a straightforward way, the analysis of the illuminance and luminance ratios and the manual switch-on probability required making a few assumptions and some transformations of the output data from the simulations. These assumptions and transformations are described in the following sections.

3.5.2 Illuminance ratios

To assess the impact of a shading system on the illuminance uniformity on the work plane, the ratio between any two adjacent points of work plane illuminance was calculated. The percentage of illuminance ratios which failed to meet the requirements ($E_{min}/E_{max} > 0.5$ or $E_{min}/E_{max} > 0.7$) were computed. This provided a comparative measure of illuminance uniformity on the work plane.

A total of 43 ratios were analysed in each case (Fig. 3.20). Each ratio corresponded to a possible desk position in the room.

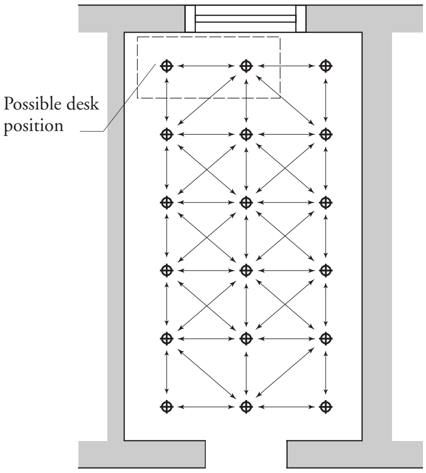


Figure 3.20 The 43 illuminance ratios studied.

3.5.3 Luminance ratios

One of the performance indicators considered in this study was the luminance ratios between the work plane (paper task) and the VDT screen and between the work plane (paper task) and adjacent and remote surfaces (walls, etc.) in the room. Since the room studied was empty and had no desk and no VDT screen, the luminance of the work plane and VDT screen had to be determined indirectly. This was done by making two major assumptions:

1. The background of the VDT screen was white and had a luminance varying between 60 and 120 cd/m^2 (thus an average luminance of 90 cd/m^2);
2. The work plane (paper task) consisted of a perfectly diffusing sheet of white paper with a reflectance of 80 %.

Luminance of the VDT screen

The first assumption regarding the luminance of the VDT was based on values for VDT screens found in the literature and through measurements made on computer screens at the Department of Construction and Architecture, Lund University. Table 3.6 summarises the information found in the literature and through measurements. This table shows that at least two sources (Fontoynont, 2000; IES, 1993) roughly agree with the measured values. These values, which are valid for a VDT screen with a white background, were thus used in the study.

Note that assuming a white background for the VDT screen is reasonable given the fact that most people working with text editors use a white background. A study by Osterhaus (2001) revealed that in nine offices, there were far fewer screens with light letters on dark backgrounds, indicating that the respondents had perhaps chosen the screen contrast settings based on previous experience (i.e. to prevent discomfort glare). Perry (1993) reported that research indicates that positive presentation (i.e. black on white) is preferred by users, despite the increase in problems related to flicker and jitter. Bauer & Cavonius (1980 in Perry, 1993) found an improvement in performance with the use of positive presentation. Van Ooyen, van de Weijgert & Begemann (1987) and Perry & Gardner (1993) also suggested to use white backgrounds and dark characters on VDTs. It is also recommended in many standards to use a white background on the VDT screen since dark backgrounds usually result in more severe reflection and glare problems than white backgrounds. Perry & Gardner (1993) mentioned, however, that positive presentation is sometimes associated with screen instabilities, i.e. flicker and character jitter.

Table 3.6 Luminance of a VDT screen according to the literature and measurements.

	Luminance (cd/m²)	Source
Average value for the entire screen	≥ 35	Norm BS 7179, Part 3 (1990) in Perry (1993)
Average value for the entire screen	65	Osterhaus (1996)
Values for the entire screen	50-120	Fontoynont (2000)
Average value for the entire screen	85	ANSI/IESNA RP-1 VDT Lighting Standard (IES, 1993, in Moeck, Lee & Rubin, 1996)
White characters	140	Moeck, Lee & Rubin (1996)
Black background	2	
Coloured image	38	
Black background	6	Measured
White background, maximum brightness	120	
White background, comfortable brightness and contrast settings	90	
White background, minimum brightness, 50 % contrast	60	

Luminance of the work plane (paper task)

The second assumption regarding the luminance of the paper task (diffuse white sheet of paper) permitted to determine the work plane or paper task luminance (L_{paper_task}) since:

$$L_{paper\_task} = \frac{E_{work\_plane} \cdot \rho}{\pi} \tag{3.5}$$

Where E_{work_plane} is the illuminance (lx) on the work plane and ρ is the reflectance of the surface. This equation is only valid for a perfect Lambertian diffuser.

It is reasonable to use the reflectance of a white sheet of paper since office workers are most of their time either reading or writing on a white sheet of paper and very seldom stare at the surface of their desk. Even when they are not writing or reading a paper or a book, the surface of the desk is often covered with papers (which is an indication that some work is being carried out in the office at some point).

The assumption regarding the diffusing character of this surface is more questionable since paper is not always perfectly diffusing. However, note that a diffusing surface is less likely to result in indirect (i.e. reflected) glare problems. The ISO standard 9241-6 (ISO, 2000) recommends to use work surfaces that are as matt as possible to prevent this particular problem.

Sitting positions and field of view

The analysis of luminance ratios implies that the field of view of the office worker must be known since the criteria for acceptance is that a given maximum luminance ratio be obtained within the field of view. The field of view of a human being is a rather well established fact: 180° horizontally (120° seen by both eyes), 50-55° upwards and 70° downwards. What is not known in this case is the sitting position and viewing direction of the office worker.

The sitting position depends on the furniture available in the room, the location of the door as well as the number of workers in the room. A field study by Christoffersen et al. (1999) revealed that a large number of persons (60 % of males; 73 % of females) share their office with another person. A study by Osterhaus (2001) in nine offices also revealed that most respondents shared their office with at least one other person. In this case, it becomes even more difficult to determine which sitting arrangement is the most common. Fig. 3.21 shows different sitting arrangements in single person offices. This figure shows that there is a large variety of ways to sit in an office room, even for a single person, and that the possible viewing directions are almost infinite.

To avoid limiting the study to only a few specific sitting positions and viewing directions, we determined all possible sitting positions and viewing directions in a systematic way starting from each "measurement" point for the horizontal illuminance. This is illustrated by Fig 3.22, which shows a total of 94 possible viewing directions expressed as viewing vectors. Note that some vectors were eliminated since it appeared unlikely that a person would sit with the back directly leaning against a wall. Moreover, only the vectors forming 90° and 45° angles with respect to the walls were considered to simplify the analysis. This assumption is reasonable considering the fact that the field of view of a person is larger than 45° on each side and thus, that two vectors which are 45° degrees apart will result in overlapping visual fields.

Note that the viewing vectors represented in Fig. 3.22 are essentially horizontal i.e. parallel to the floor. This is perhaps a normal viewing direction for people working with a computer or talking with another person. However, for people achieving more traditional "paper" tasks, the direction of gaze is towards the desk surface or somewhere between the desk surface and the horizontal. In order to account for this, an additional series of viewing vectors pointing downwards (45° from the horizontal) from the eye towards the desk were included in the analysis.

Figure 3.21 *Some sitting arrangements in today's offices (with courtesy of the Danish Building and Urban Research Institute).*

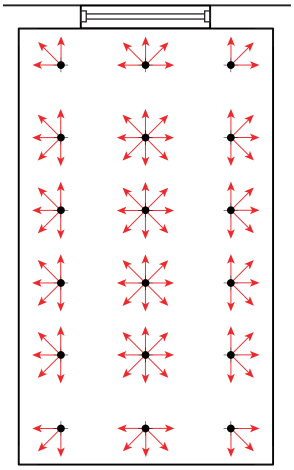


Figure 3.22 *Possible viewing directions from each calculated illuminance point.*

Once the viewing vectors were established, we determined the angle between each viewing vector direction and each point of luminance on the walls, window, floor and ceiling. This was done in the following way:

Suppose that (x_0, y_0, z_0) are the coordinates of the eyes;
and (x_1, y_1, z_1) are the coordinates of the point of luminance on the wall, floor or ceiling that we want to compare. Let us call this point the "target" point;
Let V be a unit (length = 1) vector representing the direction of gaze. This vector is called V for "viewing direction";
Let H be a unit vector perpendicular to the direction of gaze in the plane of V and the vertical. This vector is called H for "head".
Let C be another unit vector perpendicular to V and H. This vector is called C for "cheeks";
Let T be the vector between the eye and the target point;
Together, (C, H, V) form the local coordinate system in which T is to be analysed (Fig. 3.23).

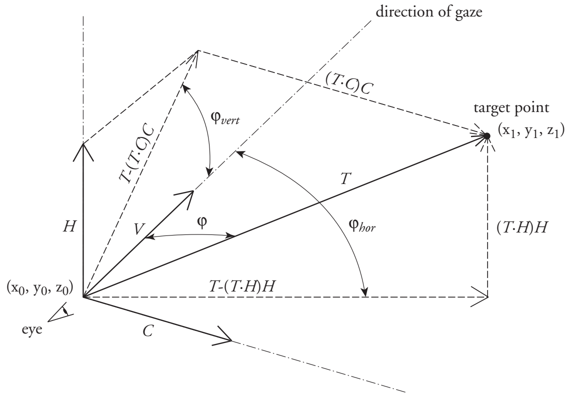


Figure 3.23 Drawing showing the vectors V, H, C and T.

Then, the angle φ between V (direction of gaze) and T can be calculated using scalar (dot) products:

$$\varphi = \arccos\left[\frac{V \cdot T}{|V||T|}\right] \tag{3.6}$$

Then, if $\varphi < 30°$ (cone of 60°), we apply the rule $L_{paper\_task}/L_{target} > 0.33$ and < 3;

And, if $\varphi < 60°$ (cone of 120°), we apply the rule $L_{paper\_task}/L_{target} > 0.1$ and < 10.

Similarly,
If $\varphi < 30°$, then $L_{VDT}/L_{target} > 0.33$ and < 3;
If $\varphi < 60°$, then $L_{VDT}/L_{target} > 0.1$ and < 10.

Then, to apply the last requirement (maximum luminance ratio of 1:20 within the whole field of view), we must calculate if the point is located within the visual field. Hellström (2001) provided a general solution to this problem:

The normalized projection of *T* onto plan *V-H* is,

$$T_{V-H} = \frac{T-(T\cdot C)C}{|T-(T\cdot C)C|} \tag{3.7}$$

And the normalized projection of *T* onto plan *C-V* is,

$$T_{C-V} = \frac{T-(T\cdot H)H}{|T-(T\cdot H)H|} \tag{3.8}$$

And the angle φ_{vert} between *V* and the projection of *T* onto *V-H* is:

$$\varphi_{vert} = \arccos\left[\frac{T-(T\cdot C)C}{|T-(T\cdot C)C|}\cdot V\right] \tag{3.9}$$

Similarly, the angle φ_{hor} between *V* and the projection of *T* onto *C-V* is:

$$\varphi_{hor} = \arccos\left[\frac{T-(T\cdot H)H}{|T-(T\cdot H)H|}\cdot V\right] \tag{3.10}$$

Then if $\varphi_{vert} < 60°$ and $\varphi_{hor} < 90°$, then we can assume that the target point falls within the field of view and we can apply the rule $L_{paper\_task}/L_{target} > 0.05$ and < 20.

Similarly,

if $\varphi_{vert} < 60°$ and $\varphi_{hor} < 90°$, then $L_{VDT}/L_{target} > 0.05$ and < 20.

The appropriate luminance requirement was applied for each calculated luminance point on the walls, floor, ceiling (target point) depending on where this point fell within the visual field. Then, the percentage of luminance ratios which failed to meet the requirements were computed for each viewing direction and added up. This provided a comparative measure of the success or failure of a given system to provide adequate luminance ratios in the field of view between the work plane, VDT screen and surroundings (walls, window, ceiling, floor).

4 Results

4.1 Daylight quality

4.1.1 Absolute work plane illuminance

The absolute illuminance on the work plane was calculated for three days (June 21, September 21 and December 21), at three moments (09.00, 12.00 and 15.00 hours) each day. The results obtained for a central row of points along the depth of the room are presented in Fig. 4.1 to 4.9.

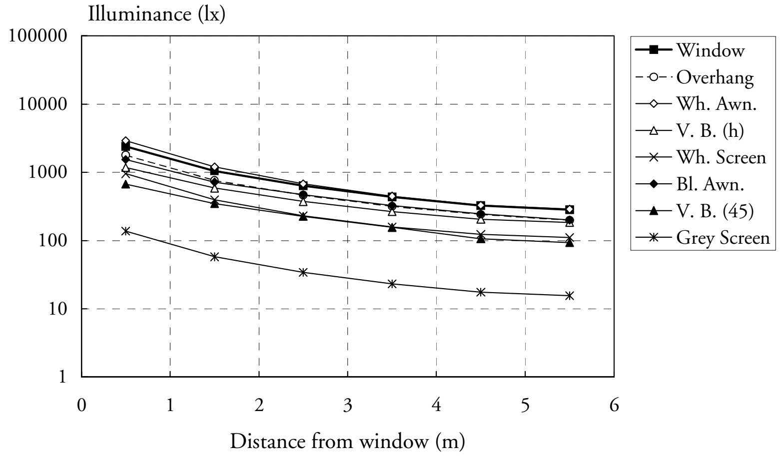


Figure 4.1 *Absolute work plane illuminance (lx) for a central row of points along the depth of the room, June 21, 09.00 hours.*

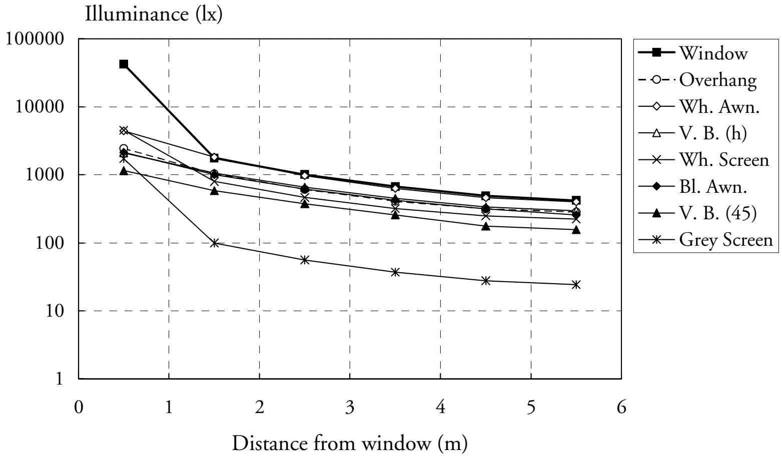


Figure 4.2 *Absolute work plane illuminance (lx) for a central row of points along the depth of the room, June 21, 12.00 hours.*

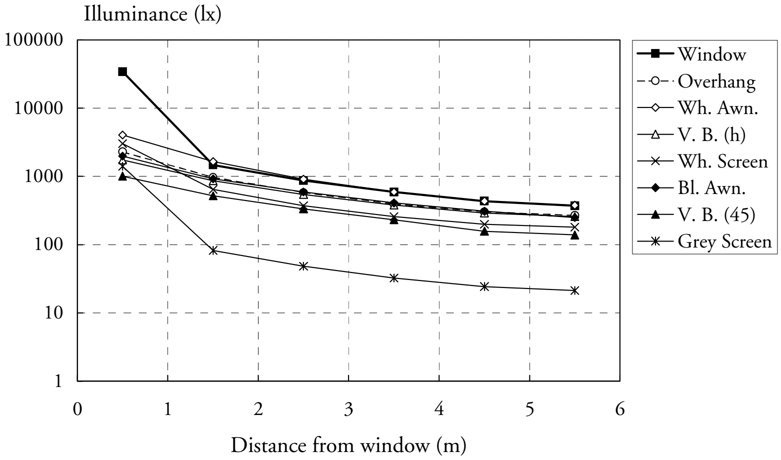


Figure 4.3 *Absolute work plane illuminance (lx) for a central row of points along the depth of the room, June 21, 15.00 hours.*

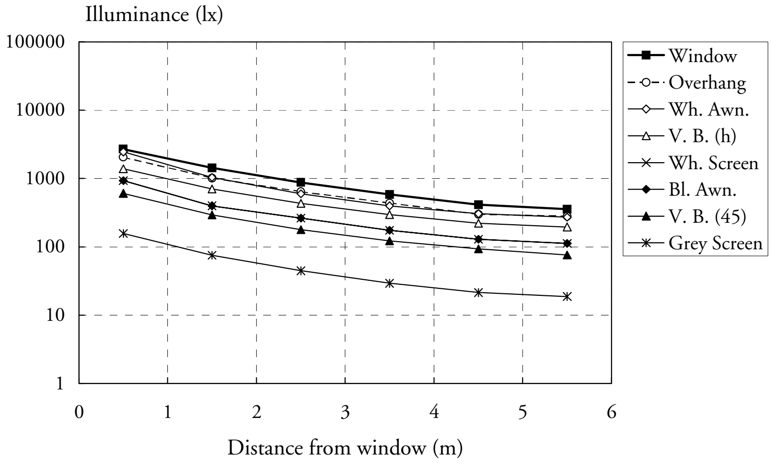


Figure 4.4 *Absolute work plane illuminance (lx) for a central row of points along the depth of the room, September 21, 09.00 hours.*

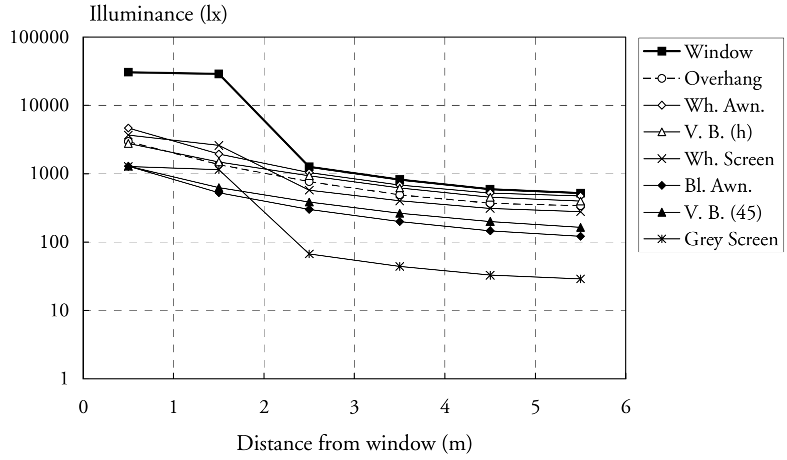


Figure 4.5 *Absolute work plane illuminance (lx) for a central row of points along the depth of the room, September 21, 12.00 hours.*

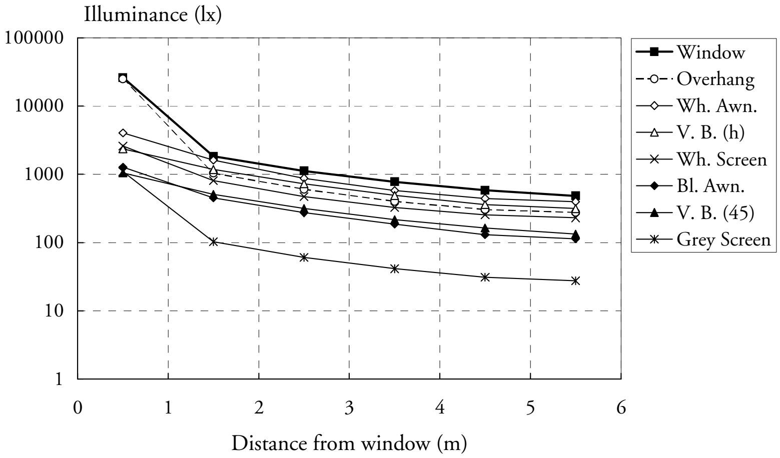


Figure 4.6 *Absolute work plane illuminance (lx) for a central row of points along the depth of the room, September 21, 15.00 hours.*

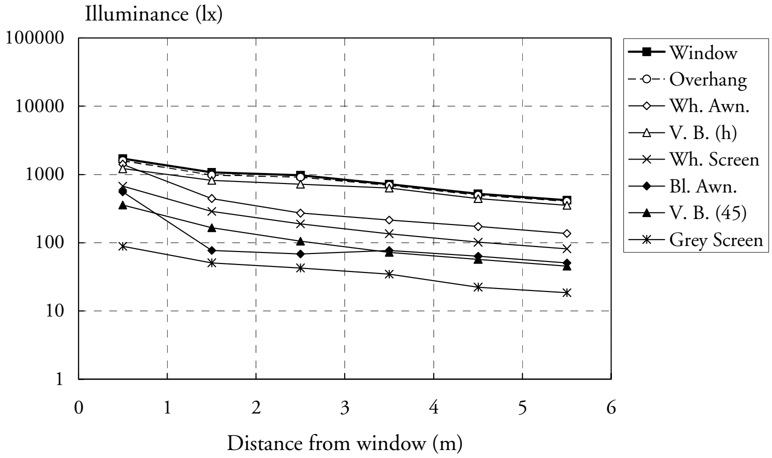


Figure 4.7 *Absolute work plane illuminance (lx) for a central row of points along the depth of the room, December 21, 09.00 hours.*

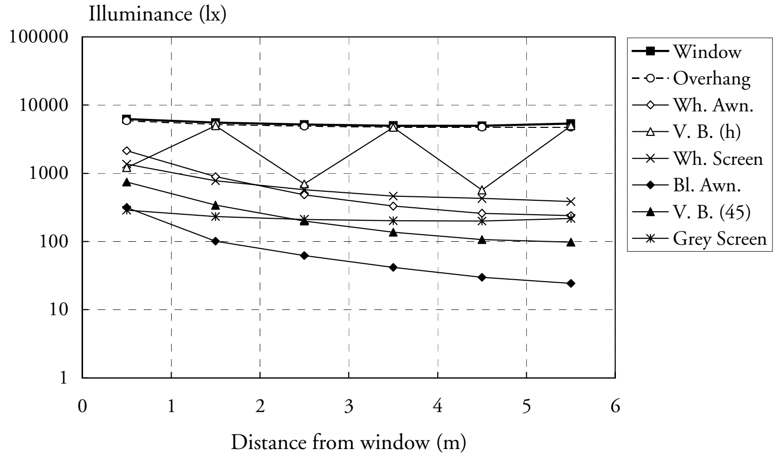


Figure 4.8 *Absolute work plane illuminance (lx) for a central row of points along the depth of the room, December 21, 12.00 hours.*

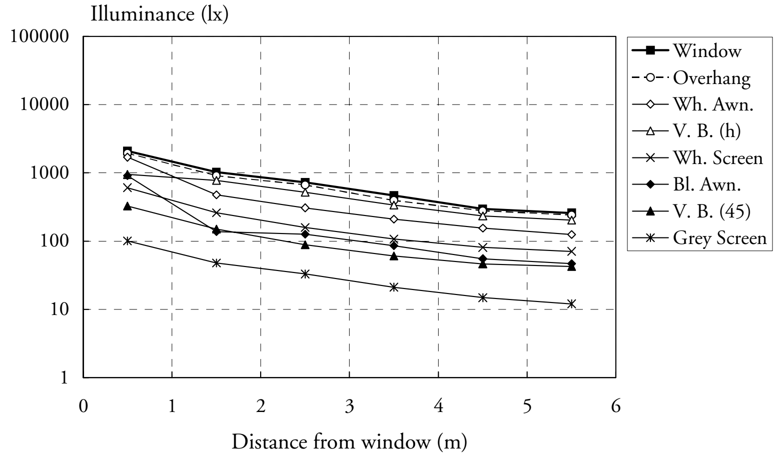


Figure 4.9 *Absolute work plane illuminance (lx) for a central row of points along the depth of the room, December 21, 15.00 hours.*

Fig. 4.1 to 4.9 show that the maximum illuminance was at noon time, as expected, and that there was generally less light in the morning than in the afternoon, except in December. This is an effect of the Danish summer time, which makes people work approximately one hour later with respect to the real solar time. Thus, at 09.00 hours, the real solar time is around 08.00 hours while at 15.00 hours, it is around 14.00 hours. Fig. 4.1 to 4.9 also show that, for the grey screen, the work plane illuminance was almost always well below the values obtained for the other shading devices i.e. below 100 lx, except at 0.5 m from the window. The amount of daylighting was thus generally too low with this device, which means that much extra artificial lighting will be needed in this case.

In June (Fig. 4.1 to 4.3), most shading devices tested prevented direct sunlight patches except for the screens (Wh. Screen and Grey Screen), which had an illuminance profile similar to that of the bare window at noon and in the afternoon. This indicates that there was direct sunlight patches in the room, which is confirmed by the renderings for this day (Plate 1). The grey screen was worse than the white screen (Wh. Screen) since the illuminance at the window was relatively much higher than in the rest of the room. Among the other shading devices, there was little difference between the overhang, the blue awning (Bl. Awn.) and the horizontal venetian blind (V. B.(h)). The illuminance profile of these shading systems was quite similar, although the horizontal venetian blind exhibited a slightly flatter curve, which indicates that light was more evenly distributed in the space in this case.

One surprising result for June (Fig. 4.1 to 4.3) is that the white awning provided as much light in the room as the bare window, except at 0.5 m from the window where the bare window created a direct sunlight patch with high illuminance values. The work plane illuminance was even higher for the white awning than for the bare window in the morning (Fig. 4.1). This is due to the fact that at this time, most of the light was incident diagonally on the window and awning. Since the awning is made of a very diffusing material, it acts like light collector which deviates the direction of the incident light rays towards the window. The rendering at 12.00 hours (June, Plate 1) clearly shows this effect: the luminance of the white awning is higher than the luminance of the sky seen through the window.

There are no fundamental differences between the results obtained in June and those obtained in September, although the direct light patch penetrated further in the room. In the afternoon, the sun penetrated under the overhang (see Plate 2), which shows that this system is not appropriate for shading the low winter or autumn sun.

The profiles for December (Fig. 4.7 to 4.9) are different. First of all, the illuminance was almost constant in the whole room because the sun penetrated deeply into the room. In the morning, the profiles are slightly crooked , especially for the awnings (Bl. Awn. and Wh. Awn.). At noon time, the horizontal venetian blind (V. B. (h)) had an illuminance profile looking like a zigzag, which is normal since the sun penetrated between the slats and made a striped pattern at work plane height (Fig. 4.10). The overhang and window were similar which shows that the shading effect of the overhang was negligible. The grey screen provided more illuminance than at all other times studied and the light was very evenly distributed in the room. A rendering at 12.00 hours shows that the sun was directly in front of the window and that it was directly visible through the screen (Plate 3), which is normal since the screen's transmittance is almost totally specular. Note that the white screen (Wh. Screen) also provided a relatively even light distribution. In the afternoon, the profiles were similar to the ones obtained in the morning, which was expected since the morning and afternoon solar angles studied are symmetrical with respect to the south orientation.

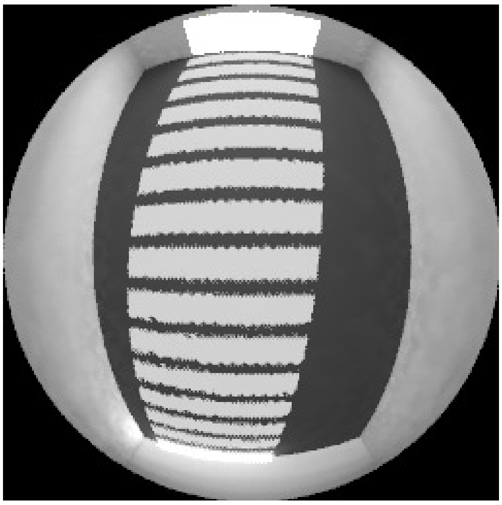


Figure 4.10 *Quick rendering showing the shading pattern produced at work plane height by the horizontal venetian blind.*

Fig. 4.11 to 4.13 show the percentage of calculated points for which the illuminance exceeded a given value, in June, September and December. Each diagram includes the three simulated hours i.e. 09.00, 12.00 and 15.00 hours.

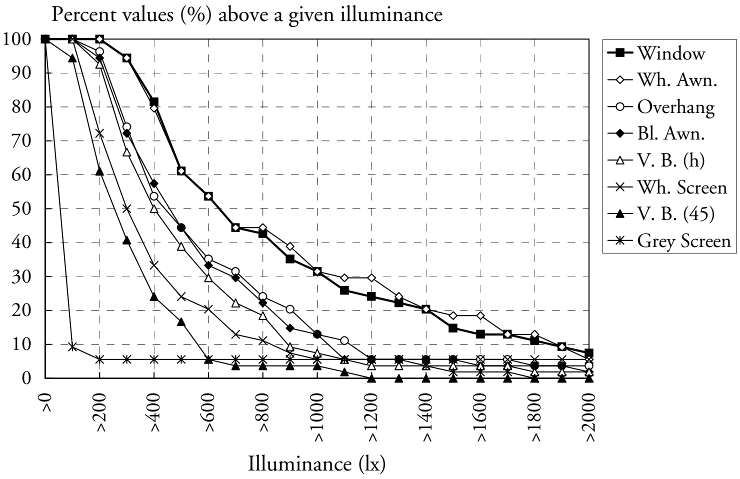


Figure 4.11 *Percentage (%) of calculated points for which the illuminance exceeded a given value, June 21, at 09.00, 12.00 and 15.00 hours.*

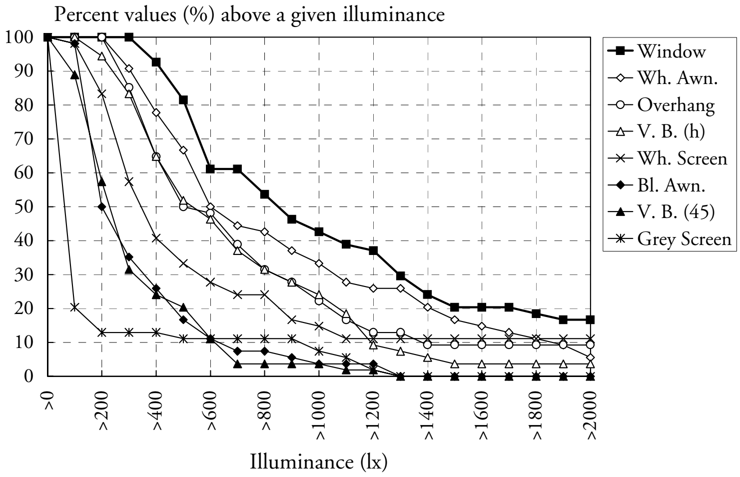


Figure 4.12 *Percentage (%) of calculated points for which the illuminance exceeded a given value, September 21, at 09.00, 12.00 and 15.00 hours.*

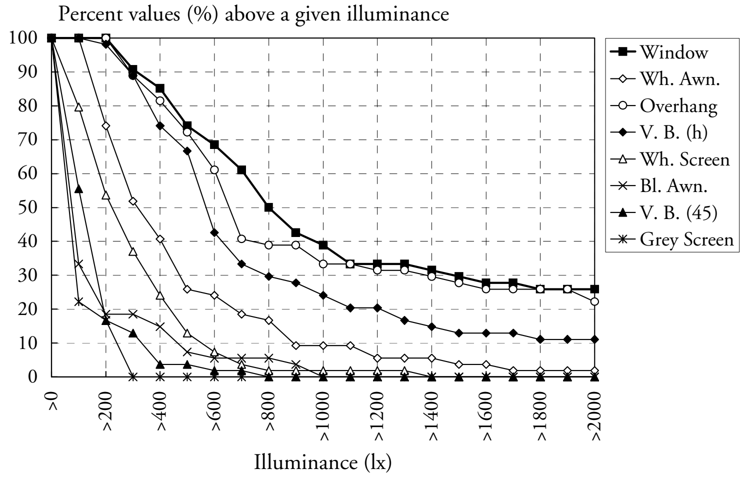


Figure 4.13 *Percentage (%) of calculated points for which the illuminance exceeded a given value, December 21, at 09.00, 12.00 and 15.00 hours.*

Fig. 4.11 to 4.13 show that the grey screen provided too little light with only 10 % of the values calculated above 100 lx in June and only 20 % of the values above 100 lx in September and December. This screen resulted in a very dark interior, with unacceptably low illuminance values.

In June, Fig. 4.11 shows that the 45° venetian blind (V. B. (45)) and white screen (Wh. Screen) had nearly all their values above 100 lx and around 20 % of their values above 500 lx. These shading systems thus provided an illuminance which is ideal for a combination of paper and computer work. The horizontal venetian blind (V. B.(h)), blue awning (Bl. Awn.) and overhang provided a little more light with around 40 % of the calculated values above 500 lx while the bare window and white awning had approximately 60 % of their values above 500 lx. The white awning provided as much light as the window, which is surprising. A closer look at the hourly values reveals that the white awning provided more light than the bare window both in the morning and at noon time and less light in the afternoon. The special diffusing character of this shading device combined with its geometry which turns it into a sunlight collector may explain the curves shown in Fig. 4.11.

In September, Fig. 4.12 shows that the 45° venetian blind (V. B. (45)) and the blue awning (Bl. Awn.) performed similarly with around 20 % of the values measured above 500 lx. Note that the blue awning (Bl. Awn.) provided much less light in September than in June but the awning was also adjusted to a lower position (Fig. 3.17). The white screen (Wh. Screen) had more than 30 % of its illuminance values above 500 lx and the horizontal venetian blind (V. B.(h)) and overhang performed similarly with half of the values above 500 lx. The white awning provided slightly more light in this case than the overhang and horizontal venetian blind but less light than the bare window. Thus the main difference between September and June is that both awnings resulted in lower work plane illuminance values in comparison to the bare window.

In December (Fig. 4.13), the work plane illuminance provided by the awnings was even lower than in September and June in comparison to the bare window. The overhang and horizontal venetian blind (V. B. (h)) had around 70 % of their values above 500 lx, which is more than in June and September. The 45° venetian blind (V. B. (45)) and blue awning (Bl. Awn.) only had around 4-7 % of their values above 500 lx and the white screen (Wh. Screen) had 12 % of the calculated values above 500 lx but 80 % above 100 lx. The white screen thus provided an illuminance range which is ideal for a combination of paper and computer work in this case.

Table 4.1 summarises the results obtained for the work plane illuminance values. Table 4.1 shows that the grey screen yielded too little light both for traditional paper tasks and for computer work. The blue awning (Bl. Awn.) also resulted in much too low illuminance values in December. Apart from this, the values obtained for the bare window, white awning (Wh. Awn.) and horizontal venetian blind (V. B. (h)) indicate that these systems may result in high light levels in the room, which makes these solutions more suitable for traditional paper tasks than for computer work. On the other hand, the 45° venetian blind (V. B. (45)) is more suitable for computer work than for paper work; the white screen may be suitable for a combination of paper and computer work while the overhang risks to result in high illuminance values in December and September. (Plate 4 shows that the overhang provides no shading in December at 15.00 hours). Note that the awnings had a variable performance from June to December but this is due to the fact that their length was adjusted so that complete shading of the window would be provided at noon time for each day of simulation (Fig. 3.17).

Table 4.1 Percentage (%) of points below or above specific illuminance values and corresponding interpretation, for June, September and December.

A= Too dark for computer and paper work
B= Too dark for paper work
C= Too bright for computer work

		Percent points (%) below or above a given illuminance								
System	Period	< 100 lx	< 300 lx	< 500 lx	> 500 lx	Average illum. (lx)	More suitable for:	Other comments.		
Window	June 21	0	6	39	61	2786	Paper			C
Wh. Awn.		0	6	39	61	973	Paper			C
Overhang		0	26	56	44	609	Paper+Computer			
Bl. Awn.		0	28	56	44	579	Paper+Computer			
V. B. (h)		0	33	61	39	529	Paper+Computer			
Wh. Screen		0	50	76	24	506	Paper+Computer			
V. B. (45)		6	59	83	17	308	Computer		B	
Grey Screen		91	94	94	6	125	None	A		
Window	September 21	0	0	19	81	4061	Paper			C
Wh. Awn.		0	9	33	67	959	Paper			C
Overhang		0	15	50	50	1328	Paper+Computer			
Bl. Awn.		2	65	83	17	320	Computer		B	
V. B. (h)		0	17	48	52	701	Paper			C
Wh. Screen		2	43	67	33	634	Paper+Computer			
V. B. (45)		11	69	80	20	301	Computer		B	
Grey Screen		80	87	89	11	176	None	A		
Window	December 21	0	9	26	74	1641	Paper			C
Wh. Awn.		0	48	74	26	461	Paper+Computer			
Overhang		0	11	28	72	1501	Paper			C
Bl. Awn.		67	81	93	7	161	None	A		
V. B. (h)		0	11	33	67	1045	Paper			C
Wh. Screen		20	63	87	13	284	Computer		B	
V. B. (45)		44	87	96	4	149	Computer		B	
Grey Screen		78	100	100	0	72	None	A		

4.1.2 Illuminance uniformity on the work plane

The uniformity of the illuminance on the work plane was also studied by calculating the ratio between 43 adjacent illuminance values corresponding to 43 possible desk positions in the room (Fig. 3.20).

Fig. 4.14 and 4.15 show the average and highest illuminance ratios in the whole room for each shading alternative studied under sunny conditions. (In this case, the illuminance ratio is determined by computing E_{max}/E_{min} between any two adjacent points).

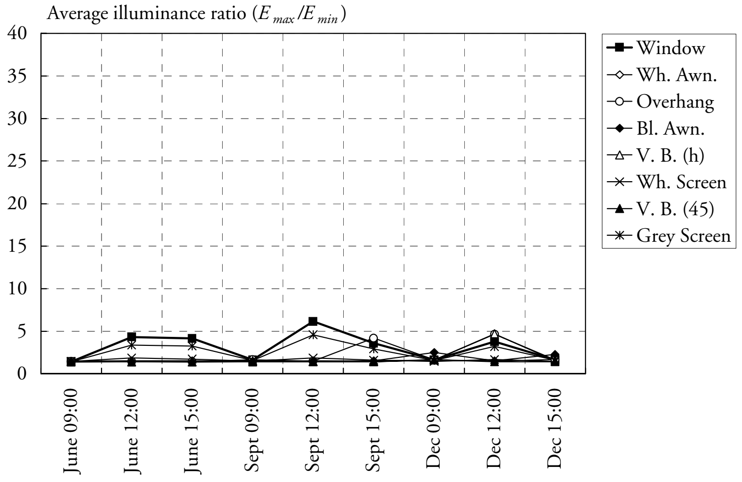


Figure 4.14 *Average illuminance ratios for the whole room under sunny conditions.*

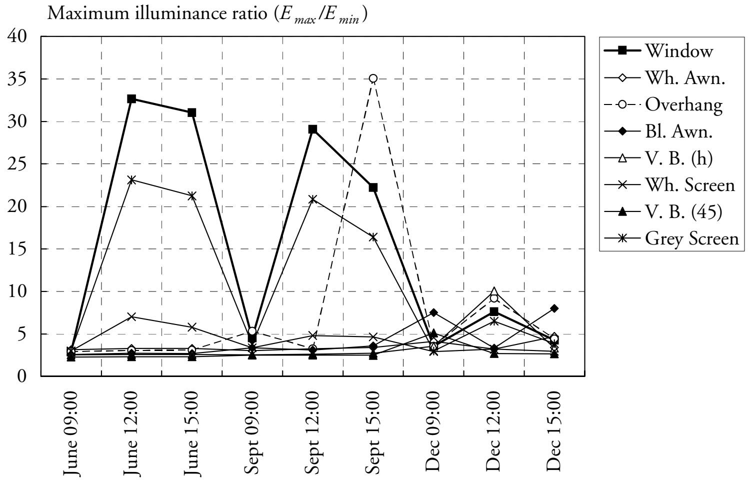


Figure 4.15 *Maximum illuminance ratios for the whole room under sunny conditions.*

Fig. 4.14 and 4.15 show that the average illuminance ratio was around 1.5 i.e. in average there was about 1.5 times more light at one point than at the adjacent point. However, for the bare window, the grey screen, the overhang and the horizontal venetian blind (V. B. (h), Dec.12.00), the average ratio was sometimes between three and six, which is much too high. Fig. 4.14 shows that the bare window and grey screen performed the poorest with many average ratios above four.

Fig. 4.15 shows the maximum ratios for each hour studied. This figure shows that for the bare window, the grey screen, and the overhang, some ratios were very high with 35 for the overhang. Thus, in one case, there was 35 times more light at one point than at the adjacent point. The figure also shows that the problem most often occurred at noon time or in the afternoon.

Fig. 4.16 and 4.17 show the percentage of illuminance ratios which failed to meet the uniformity requirements expressed in Table 3.5 i.e. that $E_{min}/E_{max} > 0.5$ or $E_{min}/E_{max} > 0.7$. Fig. 4.16 shows that most shading systems met the least severe requirement ($E_{min}/E_{max} > 0.5$), most of the time. In average, this requirement was not met for about 5-25 % of the ratios studied except for the bare window, the horizontal venetian blind (V. B. (h)), the grey screen, and the overhang, which had a poorer performance on December 21 at 12.00 hours. It is evident that at this time, the sun penetrated deeply into the room and the shading devices which did not block the direct sun rays resulted in high illuminance variations in the space. The grey screen performed poorly because it transmits light almost totally directly. Thus some points were in the direct sunlight, while others were in the shade. The white screen (Wh. Screen) also performed poorly on December 21 at 12.00 hours, which suggests that even a diffusing screen might yield high illuminance contrasts on the desk when the sun angle is low. Note that the white awning performed better at that time, and this is probably due to the fact that there was more light in the back of the room in this case than for the white screen due to diffuse light leakage from the sides and light reflected from the back of the awning. The blue awning (Bl. Awn.) had 30 % of the ratios not meeting the requirement on December at 09.00 hours, which is an indication that there was light leakage on the side of the awning. It is interesting to observe that the general performance of all shading systems studied was poorer in December than in September and poorer in September than in June. This shows that it is more difficult to provide adequate shading and acceptable visual comfort levels when the sun is low above the horizon.

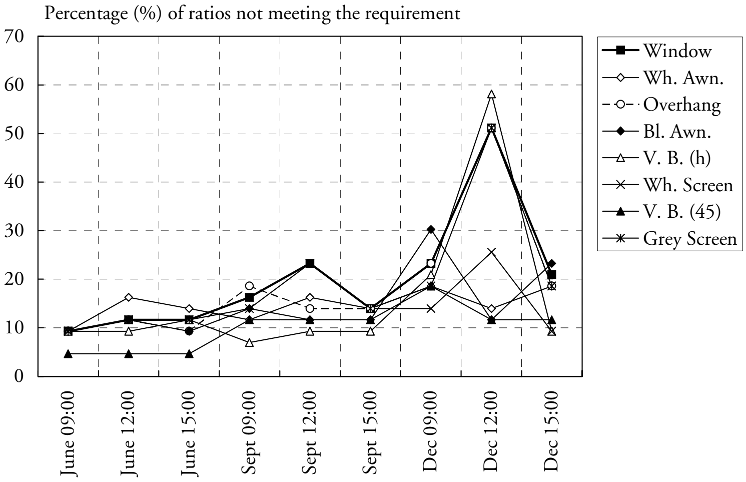


Figure 4.16 *Percentage (%) of ratios studied which failed to meet the requirement E_{min}/E_{max} > 0.5.*

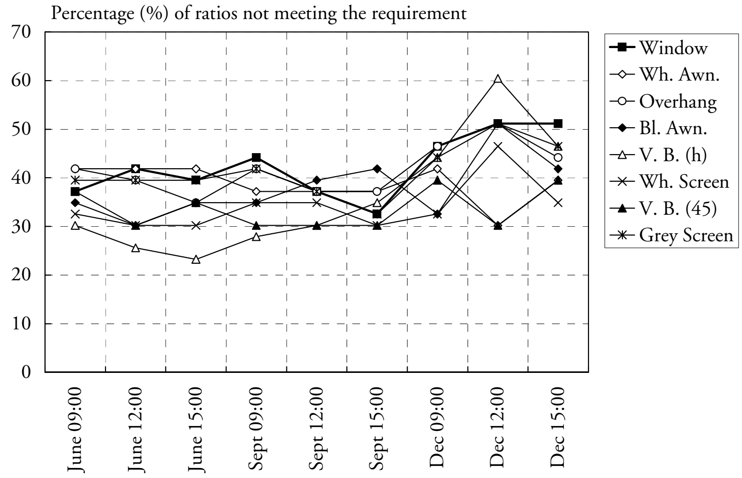


Figure 4.17 *Percentage (%) of ratios studied which failed to meet the requirement E_{min}/E_{max} > 0.7.*

Fig. 4.17 shows that fewer shading devices met the more severe requirement i. e. E_{min}/E_{max} > 0.7. The average was around 30-40 % of the ratios studied not meeting the requirement most of the time except in December where the horizontal venetian blind (V. B. (h)), the bare window, the overhang, the blue awning (Bl. Awn.) and the grey screen had a majority of ratios not meeting the requirement. Note that the 45° venetian blind (V. B. (45)) had a slightly better performance than the other systems.

Finally, we calculated the percentage of ratios which failed to meet the requirements considering all the times studied (June, September, December at 09.00, 12.00 and 15.00 hours), in the whole room and in the third part of the room closest to the window (Fig. 4.18).

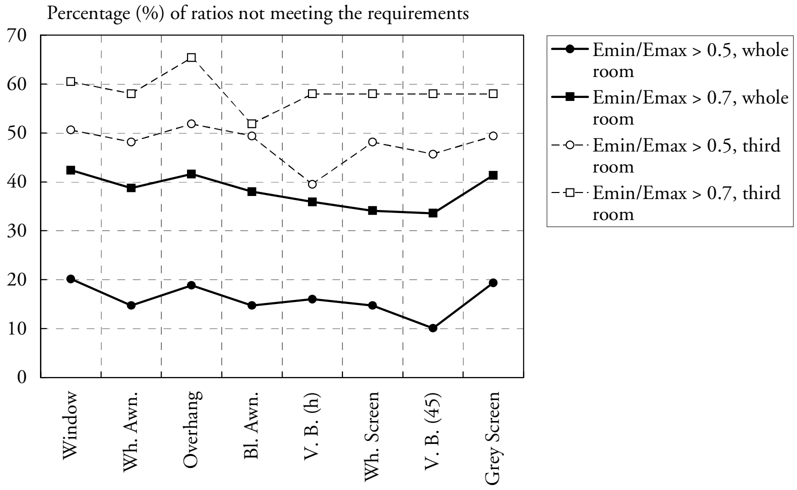


Figure 4.18 *Percentage (%) of ratios which failed to meet the requirements, considering all the times studied (June, September and December, 09.00, 12.00 and 15.00 hours).*

Fig. 4.18 shows that for the whole room, the bare window, the overhang and the grey screen generally had a higher percentage of ratios not meeting both requirements. The 45° venetian blind (V. B. (45)) had a slightly better performance than the other shading systems. However, for the part of the room closest to the window, the overhang had the highest percentage of ratios not meeting the requirements while the horizontal venetian blind performed significantly better for the requirement $E_{min}/E_{max} > 0.5$ and the blue awning (Bl. Awn.) performed better for the most severe requirement ($E_{min}/E_{max} > 0.7$). The figure shows that it is harder to meet the requirements for illuminance uniformity on the desk in the area closest to the window, which was expected. In this case, even the least severe requirement is not met by about half of the illuminance ratios studied, except with the horizontal venetian blind (V. B. (h)).

4.1.3 Absolute luminance of surfaces in the room

Maximum luminance

The absolute luminance values in the room were also calculated for a large number of points (72 on the walls including the window, 18 on the floor, 18 on the ceiling, 18 on the work plane). Fig. 4.19 to 4.21 show the percentage of calculated points for which the luminance exceeded a given value, on June 21, September 21 and December 21. Each diagram includes 09.00, 12.00 and 15.00 hours.

Fig. 4.19 shows that for the bare window, less than 5 % of the calculated points had a luminance above 500 cd/m^2, in June. All the other shading devices had a smaller percentage of points above 500 cd/m^2 compared with the bare window. However, Plate 1 shows that the luminance of the window was generally high with the overhang, horizontal venetian blind (V. B. (h)) and white awning (Wh. Awn.). Also, observe that the bare window created a bright sunlight patch on the floor (> 2000 cd/m^2), which was prevented by all the shading devices except the screens.

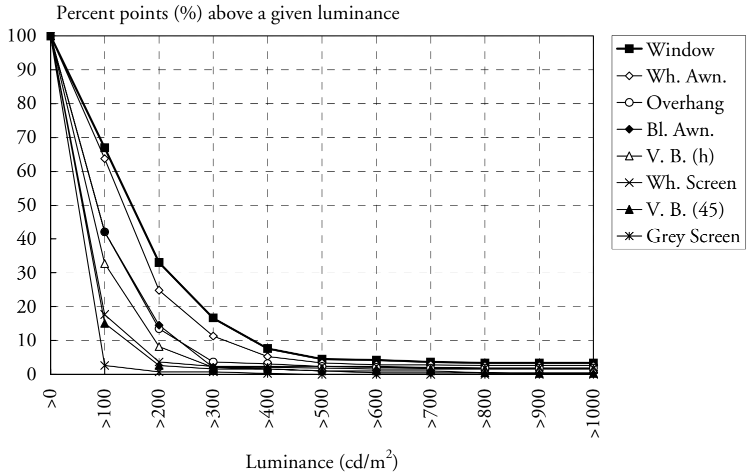


Figure 4.19 *Percentage (%) of calculated points for which the luminance exceeded a given value, in the whole room (including walls, window, work plane, ceiling, floor), June 21, 09.00, 12.00 and 15.00 hours.*

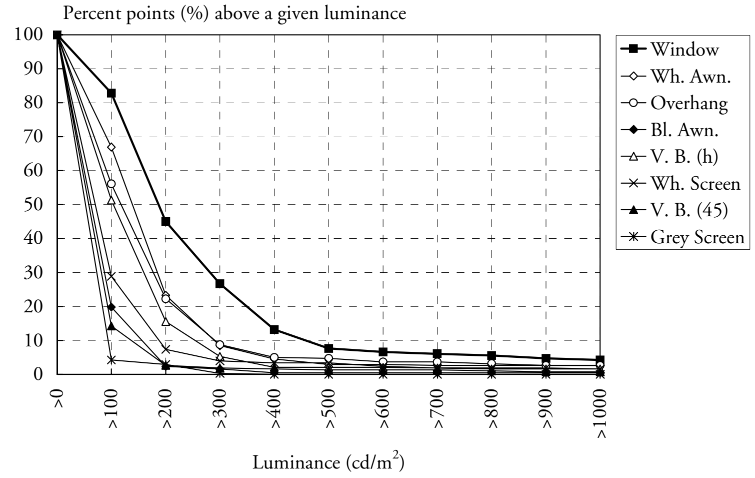


Figure 4.20 *Percentage (%) of calculated points for which the luminance exceeded a given value, in the whole room (including walls, window, work plane, ceiling, floor), September 21, 09.00, 12.00 and 15.00 hours.*

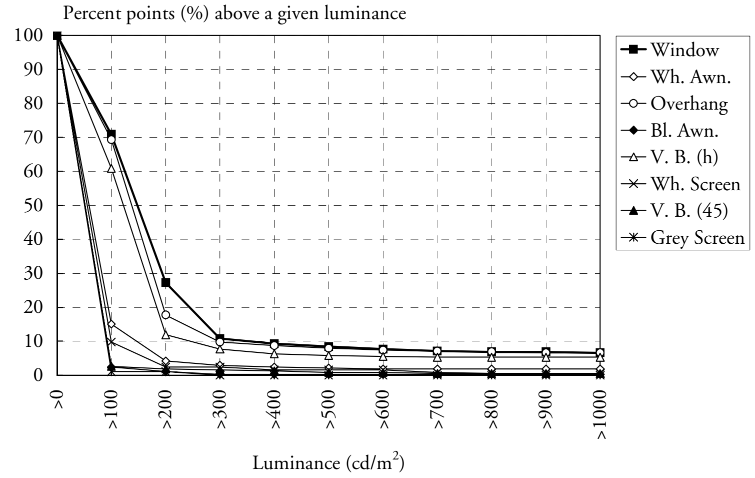


Figure 4.21 *Percentage (%) of calculated points for which the luminance exceeded a given value, in the whole room (including walls, window, work plane, ceiling, floor), December 21, 09.00, 12.00 and 15.00 hours.*

In September (Fig. 4.20), there was a slightly higher percentage of points above 500 cd/m^2, for most shading devices, with around 8 % of the calculated values above 500 cd/m^2 for the bare window, and 5 % for the overhang and white awning (Wh. Awn.). The figure also shows that the luminance values in the room were generally higher for the bare window, the overhang, the horizontal venetian blind (V. B. (h)) and the white screen (Wh. Screen). Plate 2 shows that the luminance of the sky was high and that the overhang and bare window did not prevent sunlight patches. Even the white screen had a relatively high luminance in September as indicated by the renderings (Plate 2).

In December (Fig. 4.21), the percentage of calculated luminance values above 500 cd/m^2 was even higher: 8 % for the bare window and overhang, 6 % for the horizontal venetian blind (V. B. (h)) and 2 % for the white awning (Wh. Awn.). However, Plate 3 shows that the luminance of the sky was higher at that time (compared with June) and that there were sunlight patches on the floor and backwall (reflected in the window) with the bare window, overhang and horizontal venetian blind. Plate 4 also shows that the bare window, overhang, horizontal venetian blind created large sunlight patches on the east wall, which is likely to result in important glare problems and reflections in the computer screen.Fig. 4.19-4.21and the coloured Plates (1-4) clearly show that it is more difficult to keep luminance values below 500 cd/m^2 and ensure visual comfort during the winter (and autumn) than during the summer, due to the low solar altitudes.

The same diagrams were made considering the points located in the third part of the room closest to the window. These diagrams are shown in Fig. 4.22 to 4.24. Fig. 4.22 to 4.24 generally show that if we consider only the part of the room closest to the window, the proportion of luminance values above 500 cd/m^2 is higher. In June, 12 % of the calculated points were above 500 cd/m^2 and 9 % above 1000 cd/m^2 for the bare window. It was worse in September where as much as 20 % of the points were above 500 cd/m^2 and 12 % above 1000 cd/m^2 for the same case. However, the percentage of values above 500 cd/m^2 was relatively low in December if we compare to the percentages calculated for the whole room (Fig. 4.21). This indicates that the percentage of high luminance values obtained in December was mostly due to direct sunlight patches in the room and that high luminance values were not necessarily only in the window area. This is confirmed by the renderings (Plates 3-4). Note that the sunlight patch fell behind the view point of the observation on the renderings at 12.00 hours in December but the reflection of the sunlight patch can be seen in the window.

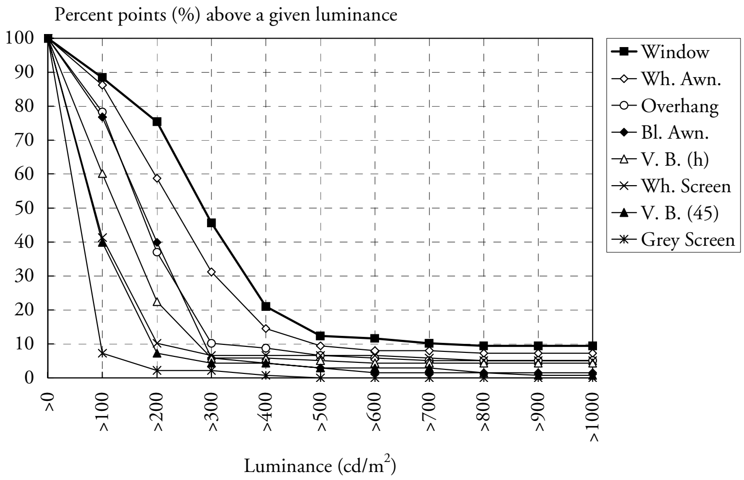


Figure 4.22 *Percentage (%) of calculated points for which the luminance exceeded a given value, in the third part of the room closest to the window (including walls, window, work plane, ceiling, floor), June 21, 09.00, 12.00 and 15.00 hours.*

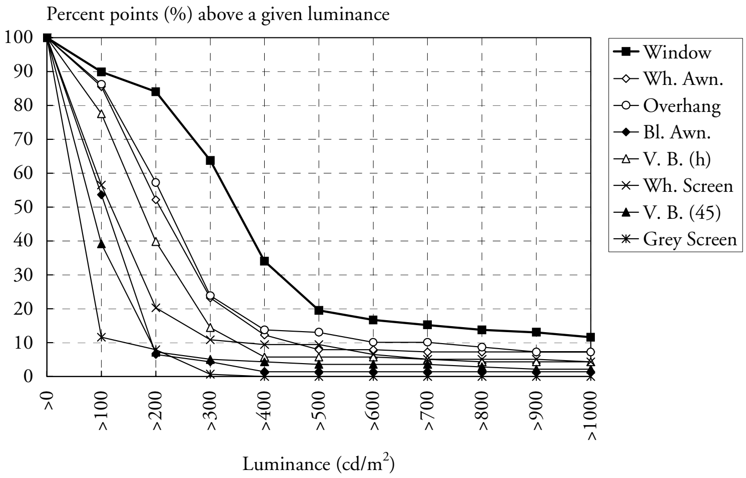


Figure 4.23 *Percentage (%) of calculated points for which the luminance exceeded a given value, in the third part of the room closest to the window (including walls, window, work plane, ceiling, floor), September 21, 09.00, 12.00 and 15.00 hours.*

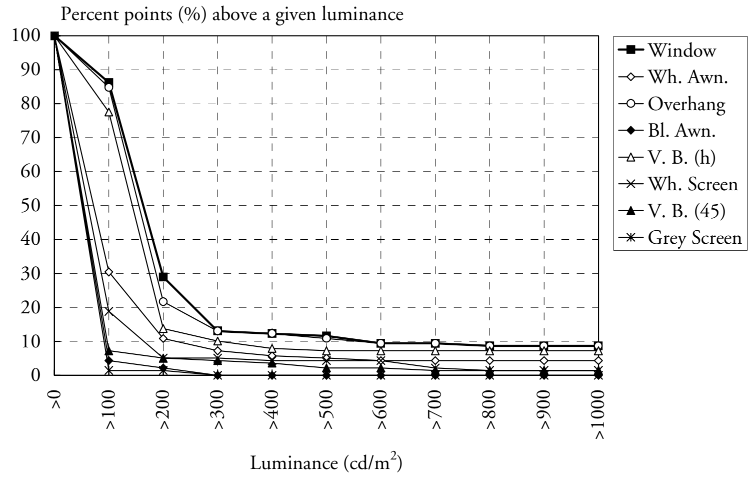


Figure 4.24 Percentage (%) of calculated points for which the luminance exceeded a given value, in the third part of the room closest to the window (including walls, window, work plane, ceiling, floor), December 21, 09.00, 12.00 and 15.00 hours.

These figures also show that the white awning (Wh. Awn.) and overhang also had a relatively high percentage of high luminance values, while the grey screen and 45° venetian blind (V. B. (45)) performed better with only a negligible amount of points above 500 cd/m^2. The renderings (Plates 1-4) clearly show that the 45 venetian blind and grey screen are the only devices that prevented extremely high luminance values at the window, most of the time.

Minimum luminance

It is also essential to examine whether the luminance in the room is too low, since too little light will make the space appear gloomy and unpleasant. This aspect was studied by calculating the percentage of points below a given luminance. In this case, we only considered the luminance of the wall (and window). The results obtained are shown in Fig. 4.24 to 4.26.

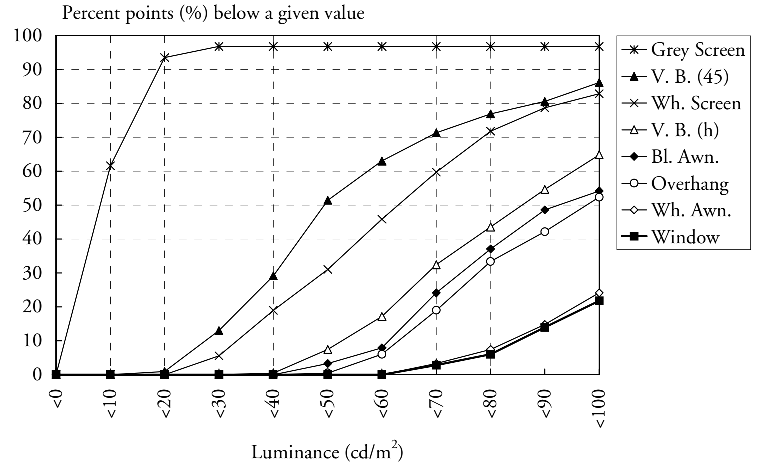


Figure 4.24 *Percentage (%) of calculated points for which the luminance was below a given value, June 21, 09.00, 12.00 and 15.00 hours.*

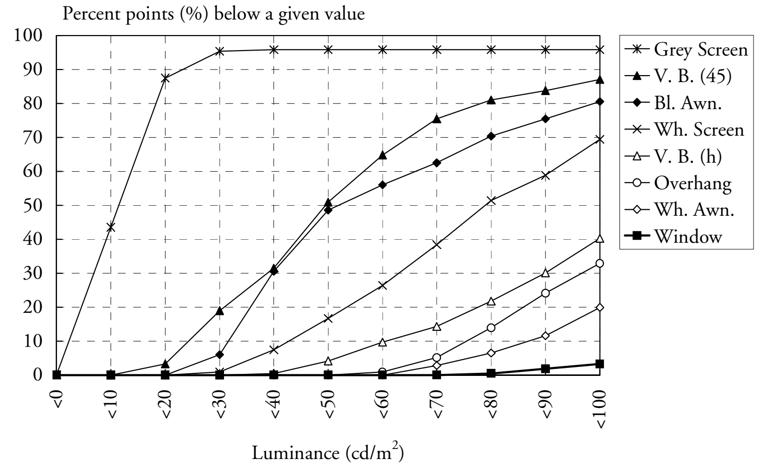


Figure 4.25 *Percentage (%) of calculated points for which the luminance was below a given value, September 21, 09.00, 12.00 and 15.00 hours.*

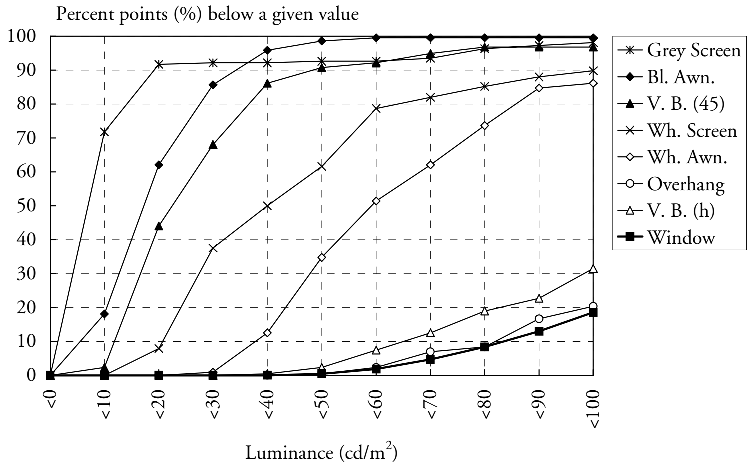


Figure 4.26 Percentage (%) of calculated points for which the luminance was below a given value, December 21, 09.00, 12.00 and 15.00 hours.

Fig. 4.24 shows that in June, the grey screen had unacceptably low luminance values with 97 % of the points below 30 cd/m^2 and 62 % below 10 cd/m^2. The rendering (Plate 1) confirms that the overall luminance levels in the room were very low. In comparison, the 45° venetian blind (V. B. (45)) only had 13 % of the points below 30 cd/m^2, in June. In September, the same trend was repeated although the blue awning (Bl. Awn.) had many more low values compared with June (50 % of the calculated luminance points below 50 cd/m^2). Finally, in December, many systems had a high percentage of low luminance values. Plate 3 clearly shows that for all the shading devices studied, in particular for the blue awning, 45° venetian blind, grey screen, the overall luminance of the room was much lower in December. The percentage of values below 30 cd/m^2 was 86 % for the blue awning (Bl. Awn.), 92 % for the grey screen, 68 % for the 45° venetian blind (V. B. (45)) and 38 % for the white screen (Wh. Screen). Note again, that the awnings–especially the blue awning–resulted in much lower light levels in December because the awning was pulled down so as to shade the entire window at noon time for each simulation day.

4.1.4 Luminance ratios

The luminance ratios between the work plane (paper task), surrounding surfaces (walls, window, floor, ceiling) and VDT screen was studied for 94 possible viewing directions in the room.

Luminance ratios between the work plane and the surrounding surfaces

We studied the luminance ratios between the work plane (paper task) and surrounding surfaces (walls, window, floor, ceiling) for 94 possible viewing directions in the room corresponding to as many sitting positions. For each viewing direction, the ratio between each luminance point in the field of view and the luminance of the task was calculated. The luminance of the task was calculated from the illuminance values assuming a perfectly diffusing white sheet of paper with a reflectance of 80 %. The percentage of ratios which failed to meet the requirements expressed in Table 3.5 were calculated and are shown in Fig. 4.27 to 4.29, for June 21, September 21 and December 21.

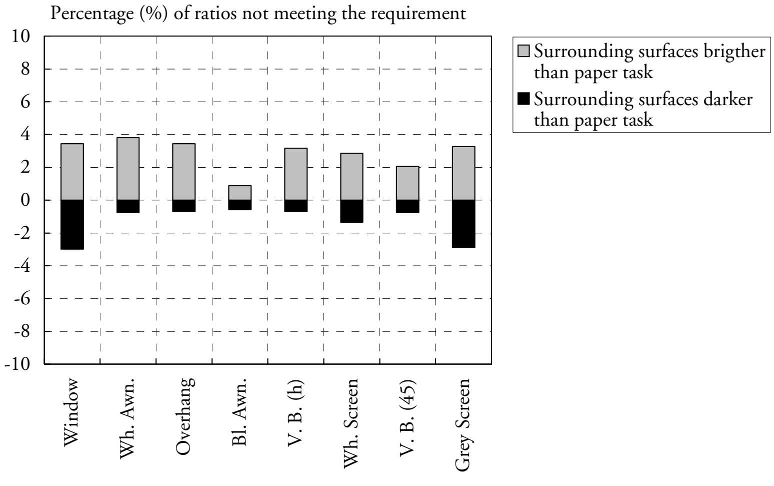


Figure 4.27 *Percentage (%) of luminance ratios between the work plane and the surrounding surfaces (walls, window, floor, ceiling) which failed to meet the requirements, June 21.*

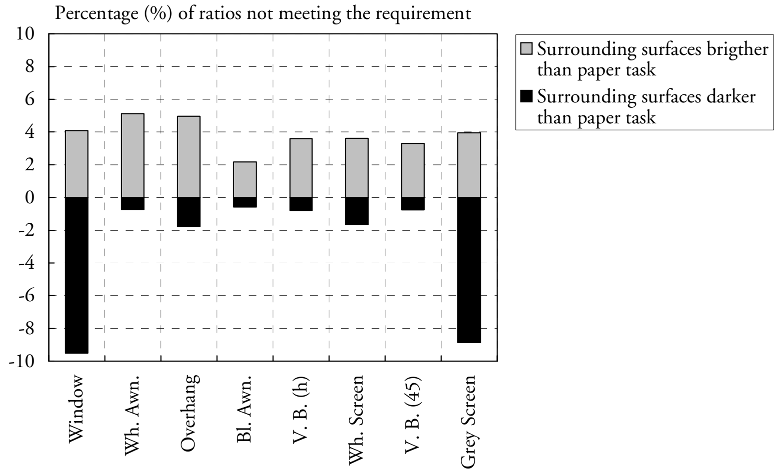


Figure 4.28 *Percentage (%) of luminance ratios between the work plane and the surrounding surfaces (walls, window, floor, ceiling) which failed to meet the requirements, September 21.*

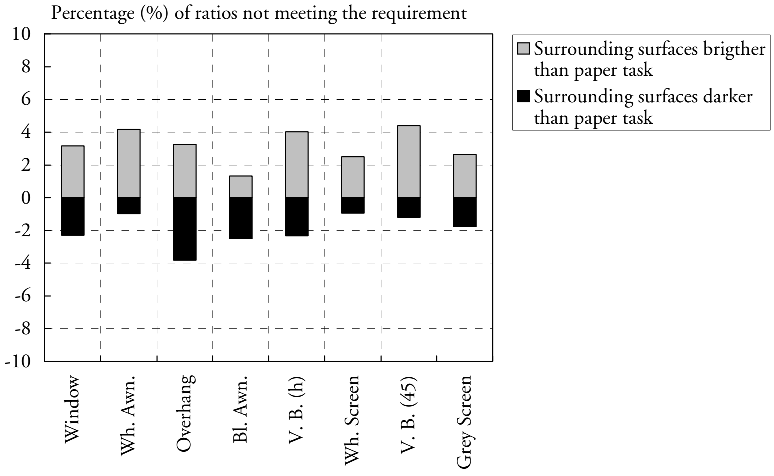


Figure 4.29 *Percentage (%) of luminance ratios between the work plane and the surrounding surfaces (walls, window, floor, ceiling) which failed to meet the requirements, December 21.*

Fig. 4.27 to 4.29 show that in general, there was a small percentage of luminance ratios which failed to meet the requirement, for all the days and shading systems studied. The worst day was September 21, where up to around 14 % of the ratios did not meet the requirements for the bare window. It is possible that the sun angle created sunlight patches on the task for this case, which resulted in unacceptable luminance ratios between the task and the surrounding surfaces. In June and September, the wall was brighter than the task for most shading systems, except for the bare window and the grey screen where the opposite occurred. The blue awning (Bl. Awn.) and 45° venetian blind (V. B. (45)) had a slightly better performance than the other systems with more ratios meeting the requirements. In December, the blue awning (Bl. Awn.) and white screen (Wh. Screen) performed slightly better than the other shading systems.

Luminance ratios between the VDT screen and the surrounding surfaces

The luminance ratios between the VDT screen and the surrounding surfaces (walls, window, floor, ceiling) were studied. We assumed that the luminance of the VDT screen could vary between 60-120 cd/m^2 for a screen with a white background and calculated the ratio between these luminance values and those of surrounding points on the walls and other surfaces in the room. The percentage of ratios which failed to meet the requirements expressed in Table 3.5 were then calculated for each shading alternative and are presented in Fig. 4.30 to 4.32, for June 21, September 21 and December 21.

Fig. 4.30 shows that, in June, most systems had acceptable luminance ratios between the VDT screen and surroundings except the grey screen, for which more than 40 % of the ratios studied were unacceptable since the surrounding surfaces were too dark compared with the VDT screen. In September (Fig. 4.31), the grey screen performed slightly better with approximately 33 % unacceptable ratios. The 45° venetian blind (V. B. (45)) and blue awning (Bl. Awn.) also had a small percentage (around 5 %) of ratios for which the surroundings were darker than the VDT screen, while the opposite problem occurred for the other shading systems. In December (Fig. 4.32), the grey screen, blue awning (Bl. Awn.), 45° venetian blind (V. B. (45)) and even the white screen (Wh. Screen) had a significant amount of luminance ratios for which the surroundings were too dark compared with the VDT screen. On the contrary, the bare window, overhang, and horizontal venetian blind (V. B. (h)) had a small amount of luminance ratios for which the surroundings were brighter than the VDT screen. The grey screen was the device which had the worst performance overall.

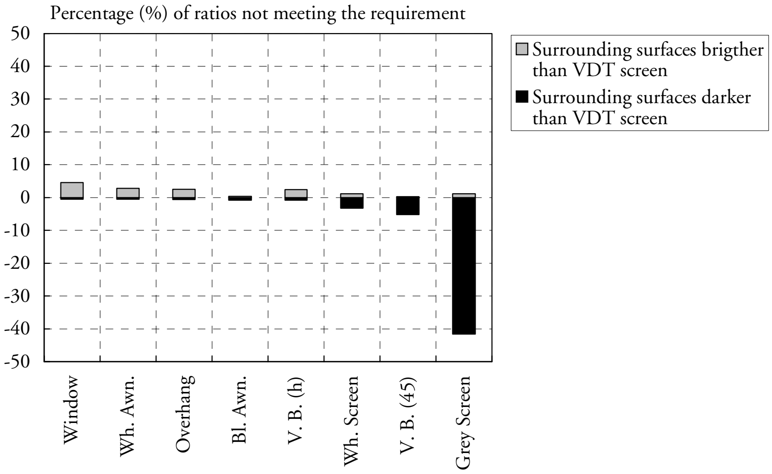


Figure 4.30 *Percentage (%) of luminance ratios between the VDT screen and the surrounding surfaces (walls, window, floor, ceiling) which failed to meet the requirements, June 21.*

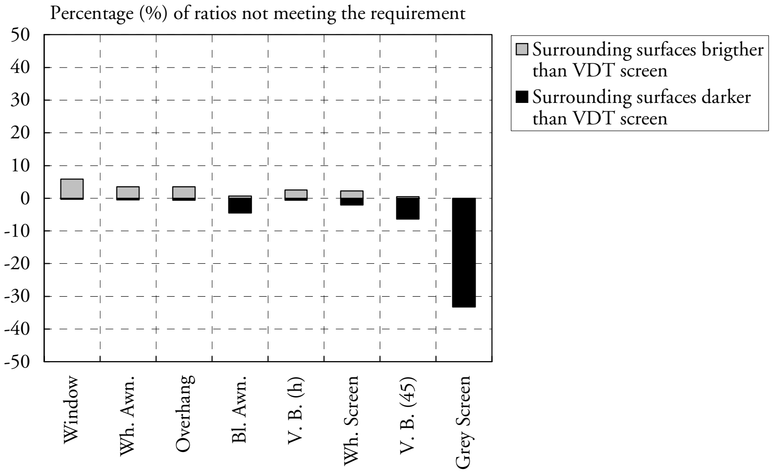


Figure 4.31 *Percentage (%) of luminance ratios between the VDT screen and the surrounding surfaces (walls, window, floor, ceiling) which failed to meet the requirements, September 21.*

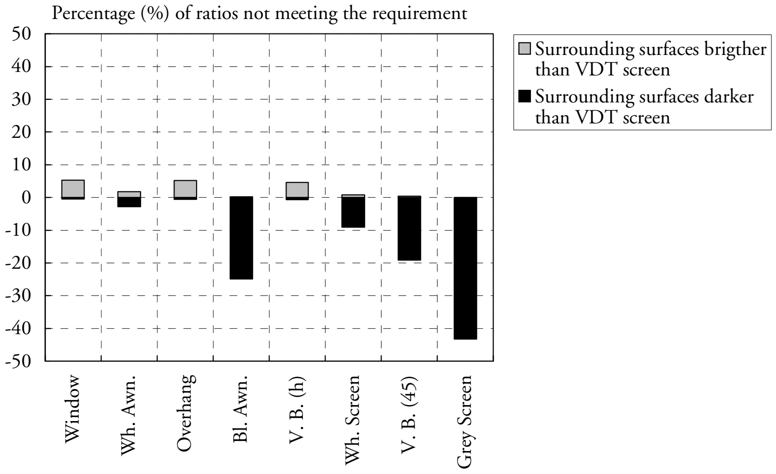


Figure 4.32 *Percentage (%) of luminance ratios between the VDT screen and the surrounding surfaces (walls, window, floor, ceiling) which failed to meet the requirements, December 21.*

Luminance ratios between the VDT screen and the work plane

The luminance ratios between the VDT screen and the work plane (paper task) were also studied. The luminance of the work plane was calculated from the illuminance values, assuming that the task consisted of a sheet of purely diffusing white paper with a reflectance of 80 %. Fig. 4.33 to 4.35 show the percentage of luminance ratios which failed to meet the requirements expressed in Table 3.5, in June, September and December.

Fig. 4.33 shows that, in June, most shading systems met the requirements for most of the ratios studied, except the grey screen, which had as many as 80 % of unacceptable ratios. In this case, the work plane was too dark compared with the VDT screen. The opposite was observed for the bare window and the white awning where about 20 % of the ratios were unacceptable because the work plane was too bright with respect to the VDT screen. The percentage of unacceptable luminance ratios was negligible for the other shading systems.

In September (Fig. 4.34), the same comments as the ones made for June apply but the grey screen performed slightly better with about 74 % of the ratios not meeting the requirement.

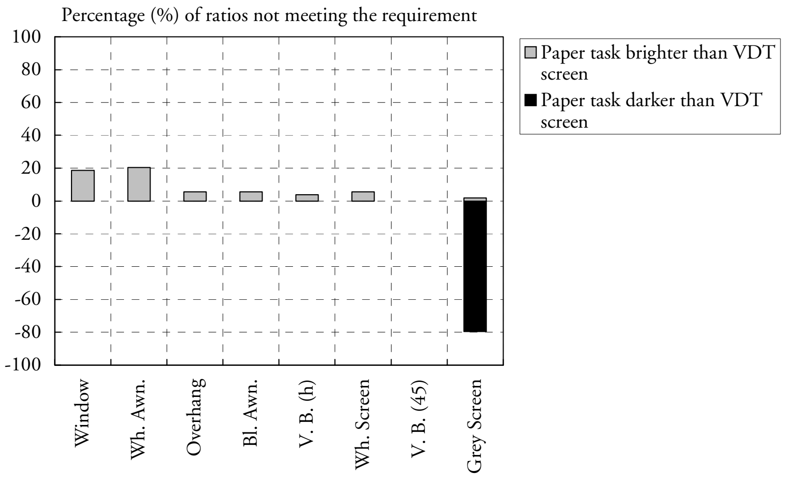


Figure 4.33 *Percentage (%) of luminance ratios between the VDT screen and the work plane which failed to meet the requirements, June 21.*

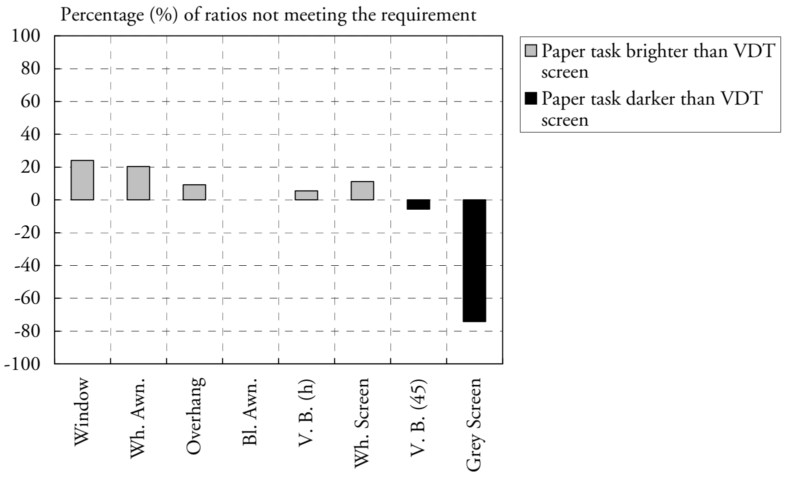


Figure 4.34 *Percentage (%) of luminance ratios between the VDT screen and the work plane which failed to meet the requirements, September 21.*

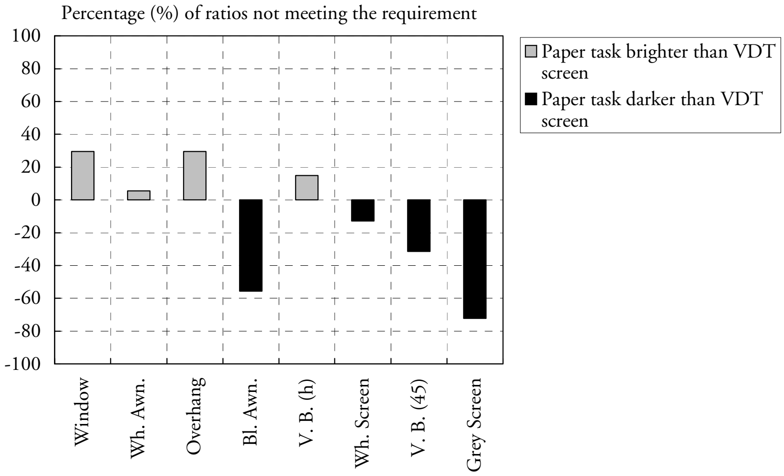


Figure 4.35 *Percentage (%) of luminance ratios between the VDT screen and the work plane which failed to meet the requirements, December 21.*

In December (Fig. 4.35), the performance of most shading systems was poorer. The grey screen, blue awning (Bl. Awn.), 45° venetian blind (V. B. (45)) and white screen (Wh. Screen) had many unacceptable ratios since the work plane was too dark compared with the VDT screen. The opposite occurred for the bare window, the overhang and the horizontal venetian blind (V. B. (h)) while the white awning had a better performance.

4.2 Potential for daylight utilisation

4.2.1 Daylight factor

The daylight factor (*D*) on the work plane was calculated for a central row of points along the depth of the room. The results are shown in Fig. 4.36. Fig. 4.36 shows that the bare window was the only alternative with a *D* nearly above 1 % for all the points along the depth of the room. Even the overhang, white awning (Wh. Awn.) and horizontal venetian blind (V. B. (h)) had a *D* above 1 % from the middle (3 m) of the room to the window. The grey screen yielded a *D* well below 1 % in the whole room, which is unacceptable. Finally, the blue awning (Bl. Awn.) and white screen (Wh. Screen), provided a *D* of around 2 % at 0.5 m from the window, but below 1 % in the rest of the room. The venetian blind yielded *Ds* between 0.2 and 3.4 % depending on the slat angle and distance to the window but exhibited a much flatter curve than all the other devices. Note also that the white screen (Wh. Screen) also had a relatively flat curve, which indicates a relatively even light distribution, similar to that provided by the venetian blind. On the contrary, the curve of the blue awning (Bl. Awn.) indicates a particularly uneven light distribution, with a much higher *D* near the window than in the rest of the room.

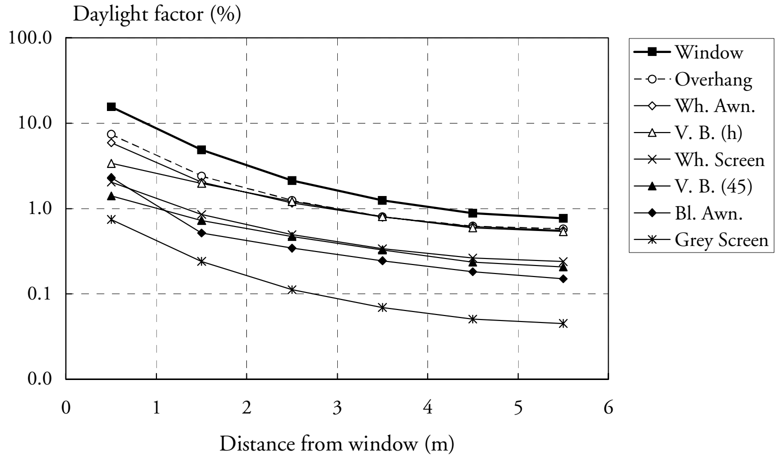


Figure 4.36 Daylight factor (%) for a central row of points along the depth of the room as a function of shading alternative.

Only the bare window, the overhang and the white awning (Wh. Awn.) had a *D* above 5 % in the area closest to the window. These solutions thus allow a certain degree of daylight autonomy in the vicinity of the window. However, there might be too much daylight in these cases to carry out computer work since light levels are likely to be above 500 lx most of the time. Recall that a *D* of 5 % provides a work plane illuminance of 500 lx with an outdoor illuminance of 10 000 lx (overcast conditions). The horizontal venetian blind may have a preferable *D* (above 3 % at 0.5 m from the window) for computer work.

The average *D* in the whole room, and in the third part of the room closest to the window, as well as the value obtained in the middle of the room are shown in Fig. 4.37.

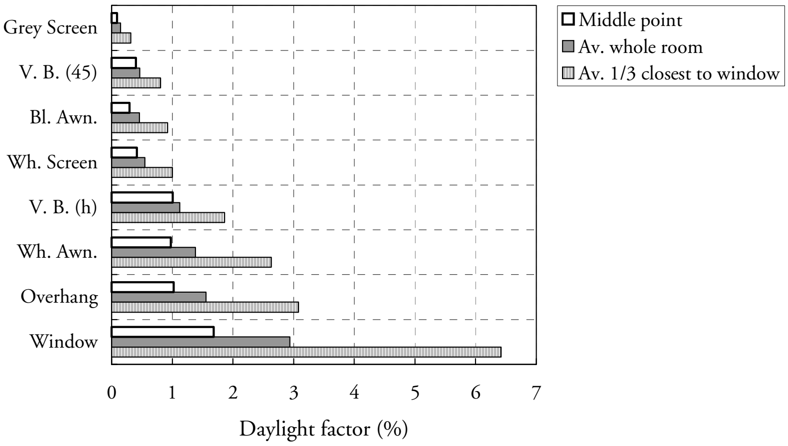


Figure 4.37 *Average daylight factors (%) for the whole room (Av. whole room), for the third part of the room closest to the window (Av. 1/3 closest to the window) and for the middle point.*

Fig. 4.37 shows that the bare window, the white awning (Wh. Awn.), the overhang and the horizontal venetian blind (V. B. (h)) are the only devices which provided acceptable light levels since both average and middle point values were above 1 %. The white screen had an average *D* above 1 % in the area closest to the window but the other values were below 0.5 %. All the other devices (Bl. Awn., V. B. (45) and Grey Screen) had average and middle point values below 1 %, which is unacceptable according to most norms. The bare window had an average *D* well above 5 % near the window, which indicates that no artificial lighting is needed in this case. This solution might provide too much light for computer work in the area closest to the window. However, since the average *D* is around 3 % for the whole room, computer work may be carried out a little further away from the window, while the area closest to the window may be used for traditional paper tasks.

4.2.2 Manual switch-on probability

The probability that someone entering the office room would switch-on the lights was calculated based on Hunt's formula (Hunt, 1980). This formula is based on field work at BRE (Building Research Establishment), which allowed to establish that people tend to switch on the lights

– if needed – only at times when entering a space, and they rarely switch off the lights until the space becomes completely empty. The switch-on probability was calculated for the whole room (Fig. 4.38) as well as for the third part of the room closest to the window (Fig. 4.39).

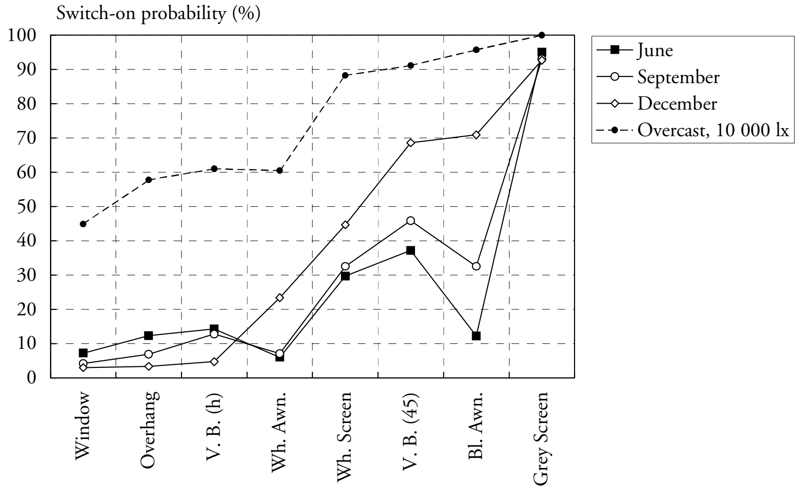


Figure 4.38 *Manual switch-on probability (%) based on Hunt's formula and lowest illuminance values in the whole room, for June, September, December and for an overcast sky of 10 000 lx.*

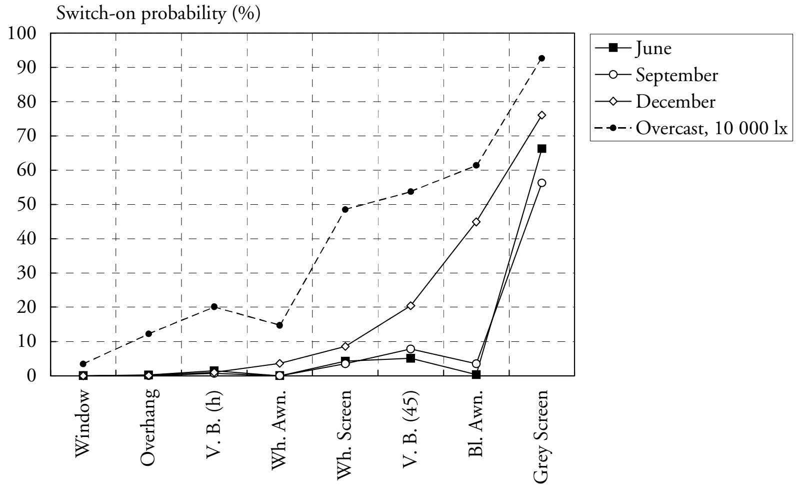


Figure 4.39 *Manual switch-on probability (%) based on Hunt's formula and lowest illuminance values in the third part of the room closest to the window, on June, September, December and for an overcast sky of 10 000 lx.*

Fig. 4.38 and 4.39 show that the probability of switching-on the lights was below 15 % for the bare window, overhang and horizontal venetian blind (V. B. (h)), on all sunny days, in the whole room. The switch-on probability was nearly 0 % for the same systems in the area close to the window, which shows that the potential for daylight utilisation is very high in these cases. In June and September, the switch-on probability was also low for the white awning (Wh. Awn.) both for the whole room and in the area closest to the window. However, the switch-on probability was higher (20 %) for this system in December, when considering the whole room. In June and September, the white screen (Wh. Screen) and 45° venetian blind (V. B. (45)) resulted in approximately the same probability both in the whole room and in the area closest to the window. However, the 45° venetian blind (V. B. (45)) had a significantly higher switch-on probability in December (70 % whole room, 20 % area closest to window). Similarly to the white awning, the blue awning (Bl. Awn.) had a much higher switch-on probability in December than in June and September, with 70 % probability for the whole room and 45 % for the area closest to the window. Finally, the grey screen had the highest switch-on probability of all with over 90 % for the whole room and over 50 % considering the area closest to the window, for all days studied. This means that artificial lighting is necessary in this case, almost all the time.

As expected, the manual switch-on probability was higher for the overcast conditions and also higher if we considered the lowest illuminance values in the whole room. In the area closest to the window, the switch-on probability was very low for most shading systems studied in June and September except for the grey screen. Thus, it is unlikely that artificial lighting will be needed in these cases during the summer, autumn (and probably spring) but artificial lighting may be needed in most cases in December as well as under overcast conditions.

4.3 Overall performance

Table 4.2 summarises some key values obtained in this study. The results suggest that the shading devices may be more or less placed in three groups as indicated in the table.

Work plane illuminance

The values obtained for the work plane illuminance indicate that the shading devices of Group 3 (Window, Wh. Awn., Overhang, V. B. (h)) provided illuminance values on the work plane which might be too high for computer work. These solutions should be preferred in rooms where traditional (paper, meeting) tasks are carried out. Table 4.2 also shows that the grey screen (Group 1) yielded too low illuminance levels on the work plane and therefore is not a valid solution for offices. Finally, the shading devices of Group 2 (Bl. Awn., Wh. Screen, V. B. (45)) are better solutions in offices where a combination of traditional paper and computer work is carried out. The 45° venetian blind is ideal for offices where the work is mostly computer-based while the white screen is ideal for offices where the work consists mainly of paper work with some computer work. Note, however, that the blue awning (Bl. Awn.) resulted in very low work plane illuminance levels in December and did not prevent the view from the bright sky in June and September as illustrated by the renderings (Plates 1-2).

Illuminance uniformity on the work plane

Table 4.2 shows that most shading systems did meet the least severe requirement ($E_{min}/E_{max} > 0.5$), for most of the illuminance ratios studied. The bare window, overhang and grey screen had a significantly poorer performance with 19-20 % of the ratios studied not meeting the requirement while the 45° venetian blind (V. B. (45)) had a significantly better performance with only 10 % of the ratios studied not meeting the requirement. Table 4.2 shows that, as expected, the percentage of ratios which failed to meet the requirement was higher with the more severe requirement (i.e. $E_{min}/E_{max} > 0.7$). Again, the bare window, overhang and grey screen had a poorer performance than the other systems, while the white screen (Wh. Screen) and 45° venetian blind (V. B. (45)) had a slightly better performance than the other systems studied.

Absolute luminance of surfaces in the room

Table 4.2 shows that the grey screen had a majority (95 %) of wall luminance values below 30 cd/m^2, which is unacceptable. The blue awning (Bl. Awn.) and 45° venetian blind (V. B. (45)) also had a relatively high percentage (around 30 %) of wall luminance values below 30 cd/m^2 while the white screen (Wh. Screen) had 15 % of the wall luminance values below 30 cd/m^2. The other alternatives (Group 3) did not generate any values below 30 cd/m^2. Table 4.2 also shows that most shading systems studied only had a small percentage of luminance values above 500 and 1000 cd/m^2. The worst solutions in this repect were the bare window (14 % above 500 cd/m^2; 10 % above 1000 cd/m^2), and the overhang (10 % above 500 cd/m^2; 7 % above 1000 cd/m^2). The white awning (Wh. Awn.), horizontal venetian blind (V. B. (h)) and white screen (Wh. Screen) also had a number of high luminance values (6-7 % above 500 cd/m^2; 4-6 % above 1000 cd/m^2). Note, however, that the renderings (Plate 1) show that the white awning often exacerbated the glare problem from the window because it became extremely bright–often brighter than the sky–under direct sunlight. Finally, the percentage of high luminance values was negligible for the blue awning (Bl. Awn.), the 45° venetian blind (V. B. (45)) and the grey screen. Note however, that the only device which prevented luminance values above 500 cd/m^2 was the grey screen. Note also that the highest luminance value was very high in the case of the bare window and white awning (Wh. Awn.), overhang, blue awning (Bl. Awn.) and horizontal venetian blind (V. B. (h)), which suggests that these devices did not prevent bright sunlight patches in the room or a direct view of the sky.

Table 4.2 Values obtained for each performance indicator considered.

			Group							
			1	2			3			
			Grey Screen	Bl. Awn.	V. B. (45)	Wh. Screen	V. B. (h)	Overhang	Wh. Awn.	Window
WORK PLANE ILLUMINANCE	Percent (%) points below or above a given value	< 100 lx	83	23	20	7	0	0	0	0
		< 300 lx	94	58	72	52	20	17	21	5
		< 500 lx	94	77	86	77	48	44	49	28
		> 500 lx	6	23	14	23	52	56	51	72
		Average illuminance (lx)	124	353	253	475	758	1 146	798	2 829
ILLUMINANCE UNIFORMITY	Percent (%) ratios not meeting the requirement	Emin/Emax > 0.5	19	15	10	15	16	19	15	20
		Emin/Emax > 0.7	41	38	34	34	36	42	39	42
ABSOLUTE LUMINANCE	Percent (%) points below or above a given value	< 30 cd/m^2	95	31	33	15	0	0	0	0
		> 500 cd/m^2	0	1	3	7	6	10	7	14
		> 1000 cd/m^2	0	1	1	4	5	7	6	10
		Maximum luminance (cd/m^2)	441	6 302	1 845	2 921	6 224	6 507	6 535	10 818
LUMINANCE RATIOS	Percent (%) ratios not meeting the requirements	Surroundings brighter than task	3	1	3	3	4	4	4	4
		Surroundings darker than task	5	1	1	1	1	2	1	5
		Surroundings brighter than VDT	0	0	0	1	3	4	3	5
		Surroundings darker than VDT	39	10	10	5	1	1	1	0
		Task brighter than VDT	1	2	0	6	8	15	15	24
		Task darker than VDT	75	19	12	4	0	0	0	0
DAYLIGHT FACTOR	(%)	Average, whole room	0.1	0.5	0.5	0.5	1.1	1.6	1.4	2.9
		Average, 1/3 of room close to window	0.3	0.9	0.8	1.0	1.9	3.1	2.6	6.4
		Middle point	0.1	0.3	0.4	0.4	1.0	1.0	1.0	1.7
SWITCH-ON PROBABILITY	(%)		94	39	51	36	11	8	12	5

Luminance ratios

Table 4.2 shows that the requirements regarding the luminance ratios between the work plane and the surroundings (walls, window, floor, ceiling) was met with most shading systems since the percentage of ratios not meeting the requirements was 5 % in the worst cases (bare window, grey screen). However, the requirements regarding the luminance ratios between the VDT screen and the surroundings, were not met with the grey screen for 39 % of the ratios studied. In this case, the surroundings were too dark with respect to the VDT screen. The 45° venetian blind (V. B. (45)) and blue awning (Bl. Awn.) also had a significantly higher percentage of ratios (10 %) for which the surroundings were too dark compared with the VDT screen. Table 4.2 also shows that the requirements regarding the luminance ratios between the VDT screen and the task were not met for 75 % of the ratios studied for the grey screen where the task was too dark compared with the VDT screen. Again, the blue awning (Bl. Awn.) and 45° venetian blind (V. B. (45)), had a significantly higher percentage of ratios for which the task was too dark compared with the VDT screen. The opposite occurred for the bare window, the overhang and the white awning, which had a number of ratios for which the task was too bright compared with the VDT screen.

Daylight factor and manual switch-on probability

Regarding the daylight factor (*D*), Table 4.2 shows that the shading alternatives of Group 3 (Window, Wh. Awn., Overhang, V. B. (h)) provided an average *D* above 1 % in the whole room and above 2 % in the area closest to the window (except for V. B. (h)), which is fully acceptable. The *Ds* obtained for the bare window and the overhang also indicate that a certain degree of daylight autonomy is even possible, which is confirmed by the values of manual switch-on probability, which were very low (5 and 8 %) in these cases. For the 45° venetian blind (V. B. (45)), the grey screen and the blue awning (Bl. Awn.), the average *D* was below 1 % for the whole room, which is unacceptable according to most norms. The switch-on probability was also quite high for these systems, especially for the grey screen (94 %). The white screen (Wh. Screen) had an average *D* above 1 % in the area near the window, which is acceptable, but the average *D* in the room was only 0.5 % and the manual switch-on probability was 36 % in this case.

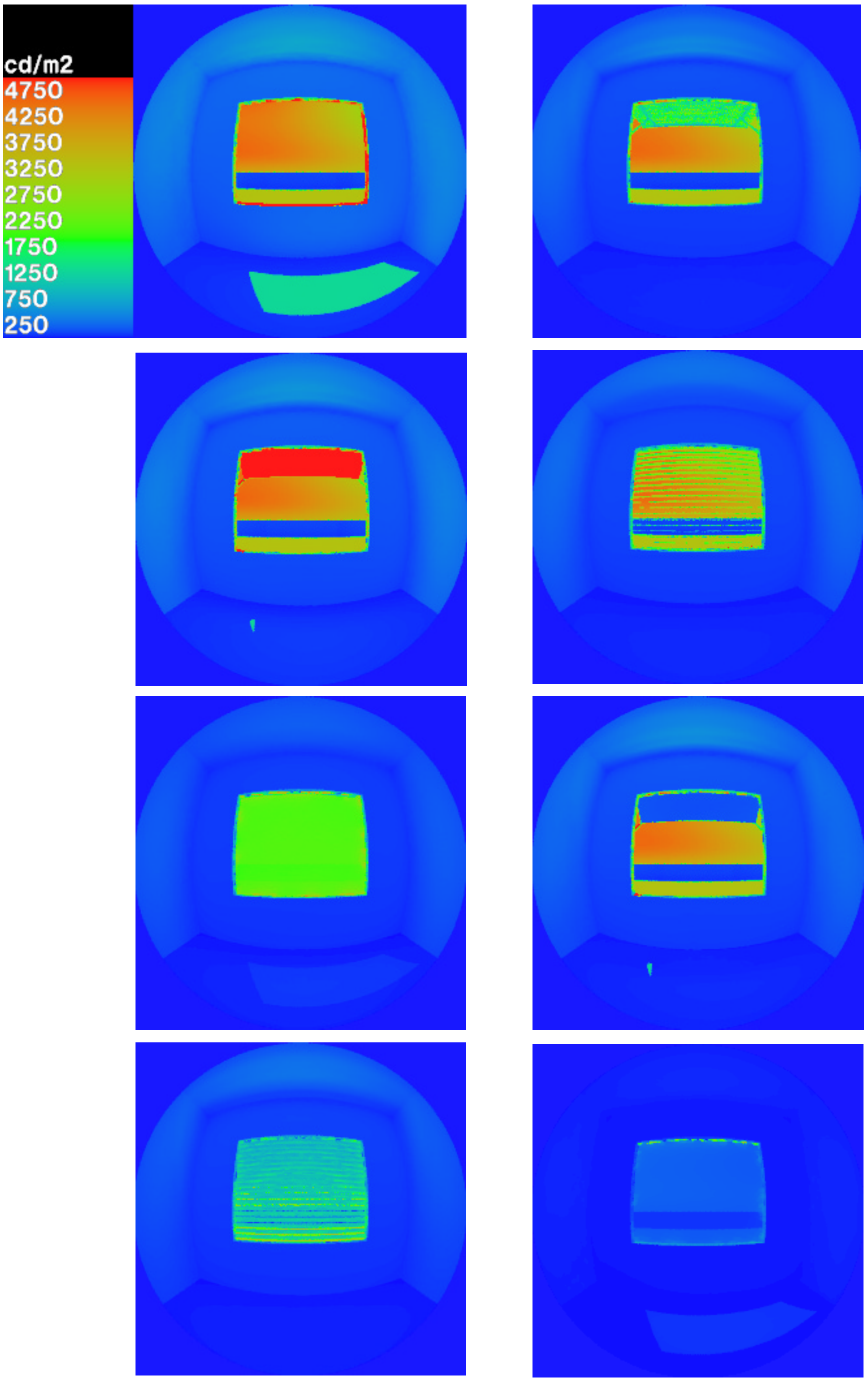


Plate 1 *Renderings of the room with: 1) the bare window, 2) overhang, 3) white awning, 4) horizontal venetian blind, 5) white screen, 6) blue awning, 7) closed venetian blind and 8) grey screen (top left to bottom right), June 21, 12.00 hours.*

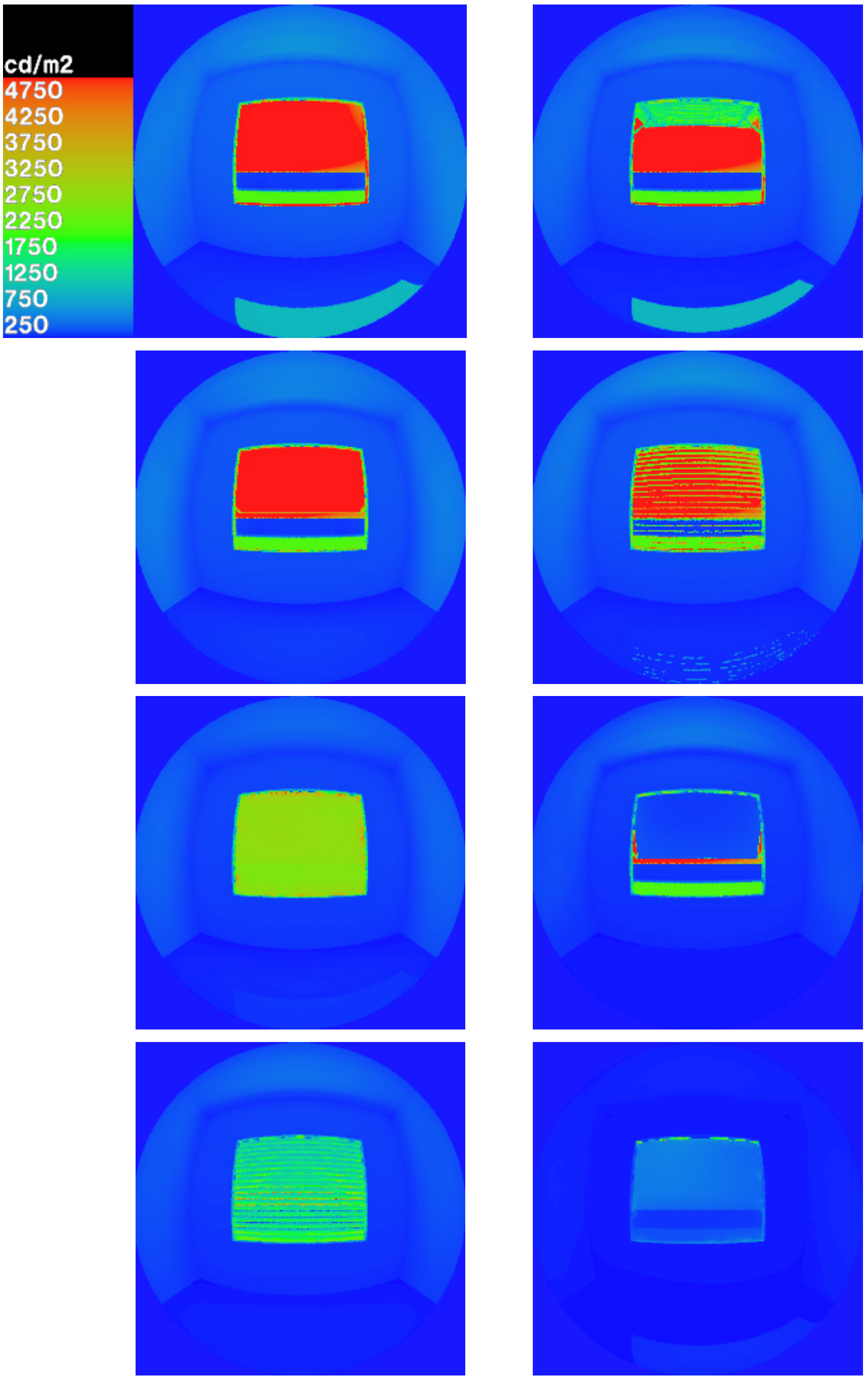


Plate 2 *Renderings of the room with: 1) the bare window, 2) overhang, 3) white awning, 4) horizontal venetian blind, 5) white screen, 6) blue awning, 7) closed venetian blind and 8) grey screen (top left to bottom right), Sept. 21, 12.00 hours.*

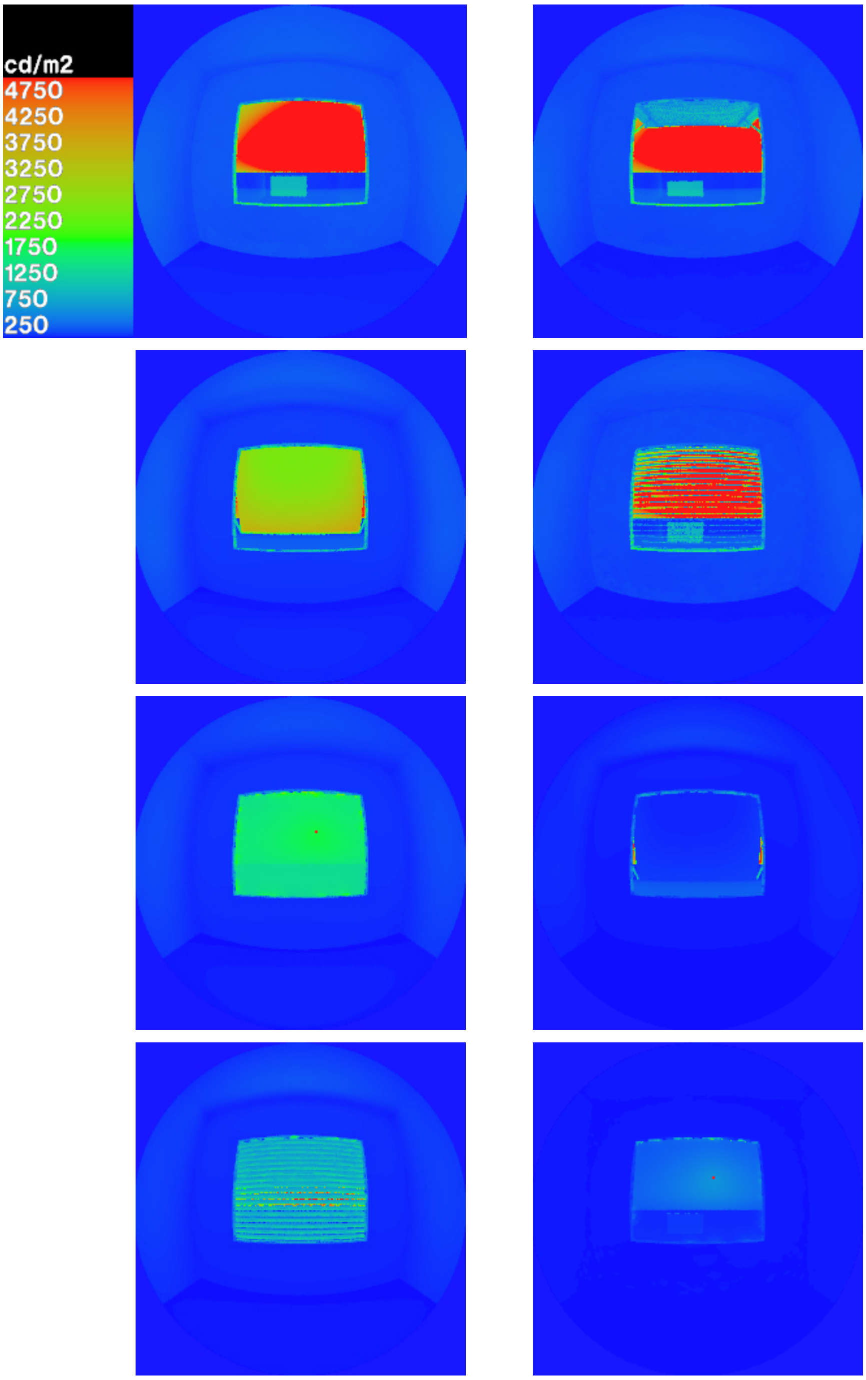


Plate 3 *Renderings of the room with: 1) the bare window, 2) overhang, 3) white awning, 4) horizontal venetian blind, 5) white screen, 6) blue awning, 7) closed venetian blind and 8) grey screen (top left to bottom right), Dec. 21, 12.00 hours.*

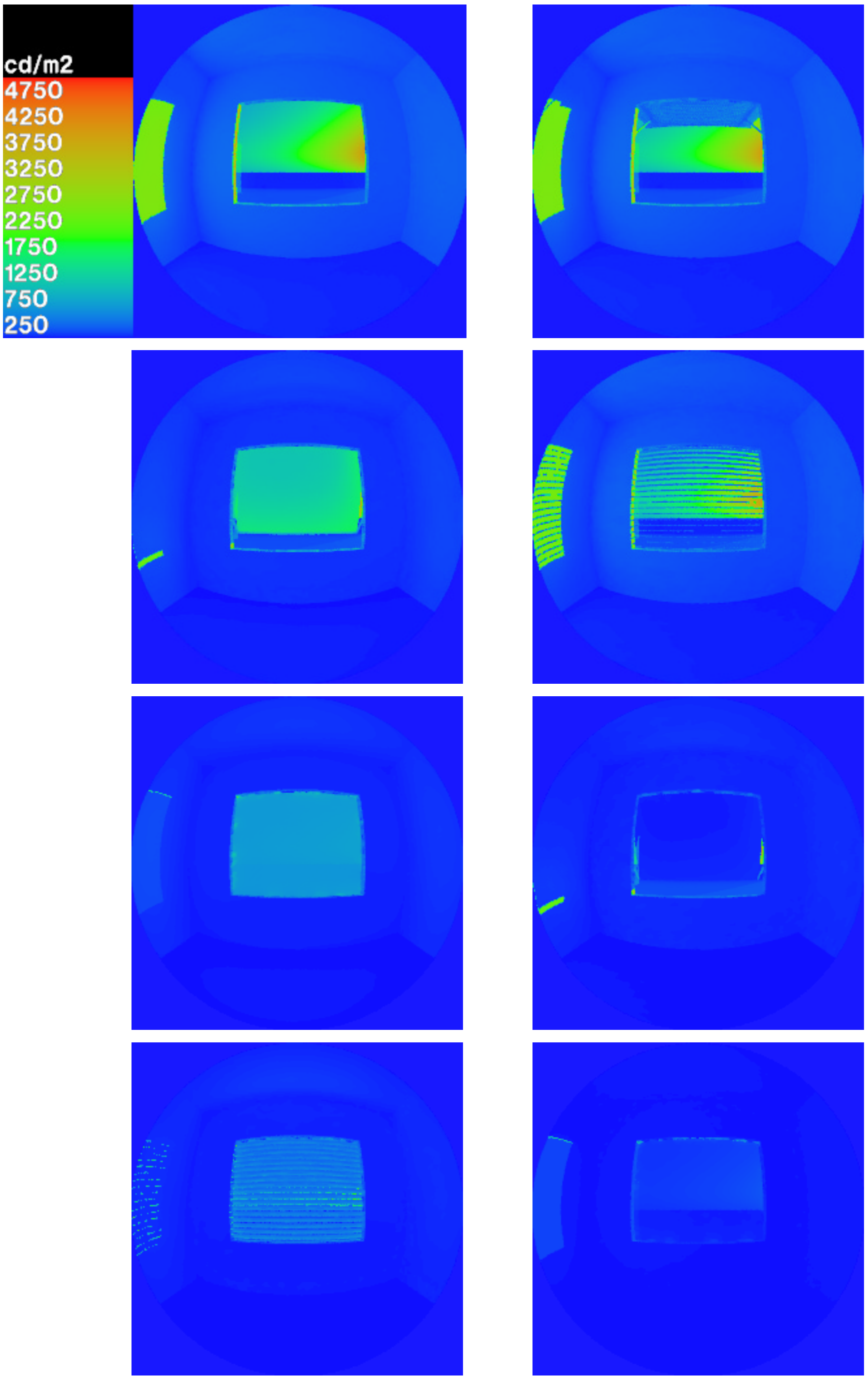


Plate 4 Renderings of the room with: 1) the bare window, 2) overhang, 3) white awning, 4) horizontal venetian blind, 5) white screen, 6) blue awning, 7) closed venetian blind and 8) grey screen (top left to bottom right), Dec. 21, 15.00 hours.

5 Discussion and conclusions

The impact of six shading devices on the daylighting quality and potential for daylight utilisation in a standard office room was investigated using the simulation program *Radiance*. The results of the study indicate that the shading alternatives may be placed in three distinct groups:

Group 1	**Group 2**	**Group 3**
Grey screen	Blue awning	Ven. blind (horizontal)
	Ven. blind (45°)	Overhang
	White screen	White awning
		(Bare window)

The devices of Group 3 provided illuminance levels on the work plane which may be too high for computer work, but are ideal for traditional (paper) tasks. These devices provided acceptable illuminance uniformity with the majority of the illuminance ratios studied meeting the uniformity requirements. The overhang (and bare window) had a slightly poorer performance in this respect since the percentage of illuminance ratios not meeting the uniformity requirement was higher in this case. The shading devices of Group 3 also generated a significantly higher percentage (> 5 %) of luminance values above 500 cd/m^2 compared with the other shading devices studied, which further suggests that these devices should not be used in offices where the work is mainly computer-based. Finally, these devices provided acceptable luminance ratios between the work plane, VDT screen and surrounding surfaces, although there was a small percentage of ratios for which the task was too bright compared with the VDT screen, especially in the case of the white awning and overhang.

The results further indicate that the grey screen (Group 1) produced unacceptably low work plane illuminance levels. This device also resulted in a poorer illuminance uniformity on the work plane than the other devices studied since it failed to block direct sunlight and reduced the overall luminance of the room dramatically, which resulted in sharp luminance contrasts. Moreover, the grey screen yielded a high percentage of unacceptable luminance ratios between the VDT screen and the surrounding surfaces and between the VDT screen and the task. In this case, the task and surroundings were too dark compared with a VDT screen with a luminance of 60-120 cd/m^2. Note, however, that this was the only device among the ones studied that prevented luminances above 500 cd/m^2. Nevertheless, the poor performance of this device for all the other performance indicators suggest that this device should not be used in offices.

The shading devices of Group 2 produced acceptable work plane illuminance values for a combination of traditional office tasks and computer work. The white screen generated higher illuminance values than the blue awning and 45° venetian blind, which suggests that this device is preferable in offices where the work is mostly paper-based and only some computer work is performed. These devices also yielded acceptable illuminance uniformity on the work plane. In this respect, the performance of the 45° venetian blind was significantly better than the other devices. Note also that the illuminance profiles were much flatter with this device (see Section 4.1.1), which indicates a more even light distribution in this case. In comparison, the white screen resulted in much more crooked illuminance profiles following those of the bare window, which indicates that this device produced direct sunlight patches, which was confirmed by the renderings (Plates 1-4).

Both the blue awning and 45° venetian blind yielded around 30 % of the luminance values in the room below 30 cd/m^2, which is rather low, while the white screen had a slightly better performance with only 15 % of the values below 30 cd/m^2. However, this device had more luminance values (4 %) above 500 cd/m^2. The blue awning had few luminance values above 500 cd/m^2 but the maximum luminance in the room was more than twice that obtained with the white screen. This is an indication that the blue awning failed to prevent direct sunlight patches in the room. In general, the blue awning, the 45° venetian blind and the white screen provided acceptable luminance ratios between the work plane, VDT screen and surroundings but the performance of the white screen was the best among all shading devices studied for this performance indicator, probably because the overall light levels were higher in this case.

The results also show that the shading devices of Group 3 were the only alternatives which provided an average and middle point daylight factor (D) above 1 %. The white screen only had an average D of 1 % in the region closest to the window. All the other devices had an average D of 0.5 % except for the grey screen which had a D of only 0.1 %. The manual switch-on probability was very high for this device as well (94 %), which means that the potential for daylight utilisation is marginal in this case. In this respect, the devices of Group 3 had a rather low manual switch-on probability, which suggests a high potential for daylight utilisation. The switch-on probability was moderate for the blue awning and white screen and slightly higher for the 45° venetian blind.

The results thus suggest that the shading devices of Group 3 should be used in offices where traditional tasks (paper, meeting) are carried out while the devices of Group 2 provided work plane illuminance and luminance values which are more suitable for a combination of paper and computer work. However, note that the white screen may yield high luminance values at the window (> 2900 cd/m^2), and care should be taken in this case to avoid placing the workstation so that the window is directly in the field of view of the occupant. Moreover, note that the blue awning did not prevent direct sunlight patches in the room due to light leakage on the sides of the awning and produced unacceptably low illuminance values during the winter, which make it less suitable as a daylight control device. The grey screen scored poorly on all the performance indicators considered and yielded work plane illuminance and luminance values unsuitable both for paper and computer work.

Overall, the 45° venetian blind and white screen performed best. The white screen provided better luminance values in the room than the 45° venetian blind, but the venetian blind offers more flexibility since the slats may be fully opened (horizontal) or fully closed when direct sunlight is incident on the window. The main disadvantage of the white screen is a risk for glare (high luminance values) from the screen itself under direct incident sunlight, in which case the view out is also completely blocked since the screen is transformed into a bright luminous veil which reduces the contrast of the outside scene. Thus the venetian blind may be the only device which allows an adequate control of daylighting and glare over the whole year and which provides adequate illuminance and luminance values for computer work.

The study also shows that it is more difficult to provide adequate shading and acceptable levels of daylight quality during the winter. In December, the sun penetrates all the way in the room, creating bright sunlight patches on the work plane and walls and sharp luminance contrasts. This problem is exacerbated in Scandinavia because the sun is just above the horizon during the winter. Thus shading devices like overhangs and awnings are not appropriate as daylight control devices. Shading devices which allow to block the whole window area like screens and venetian blinds are more suitable, especially in offices with computers.

However, the study indicated that not all types of screens provide daylight quality. In this case, an extremely poor performance was obtained with a specular screen (Grey screen) while an extremely good performance was obtained with a diffusing screen (White screen). The study thus also shows that it is essential that the shading device changes the direction of the incoming light rays, by pure diffusion or by redirection (preferably towards the ceiling) of the direct incident light as in the case of the venetian blinds. Venetian blinds are perhaps even preferable than screens because they are more flexible since the slat angle can be changed as a function of specific daylighting conditions and the view out can be maintained for many slat angle positions. In the case of a white diffusing screen, the view out is totally lost as soon as the sun hits the screen because the screen becomes self luminous and brighter than the outside scene and all the contrast in the outside scene is lost.

5.1 Comparison with measurements

As mentioned at the beginning of this report, the simulations were supplemented with measurements in the full-scale Daylight Laboratory of the Danish Building and Urban Research Institute. These measurements included only interior black, brown and white screens as well as a white venetian blind with 25 mm wide horizontal and closed slats. The results of these measurements are reported in Dubois (2001).

The main conclusions of the measurements were that the white screens provided illuminance and luminance values which were too high for computer work and created a patch of high luminance at the window. On the other hand, the brown and black screens resulted in unacceptably low illuminance and luminance values, which produced unacceptable luminance ratios between the VDT screen, the work plane and the adjacent wall. The best performing device in that study was thus the venetian blind (with the closed slats).

It is interesting to compare the results of the measurements with the ones obtained with the simulations although we did not have the possibility to study the same systems in both cases and the amount of points and days analysed differed slightly.

The first obvious observation is that the results obtained with the *Radiance* simulations appear very reasonable, compared with the results obtained through measurements. For example, the values obtained with *Radiance* for the white screens are systematically lower than the measured values, which is normal since the transmittance of the white screen in the *Radiance* model was lower (15 %) compared with the transmittance of the screens evaluated in the laboratory (27 and 59 %). Moreover, the values obtained with the grey screen (*Radiance*) are very similar to the ones obtained with the screen Plastic (measurements). Both screens had an almost exactly similar weaving structure, and the main difference between the two screens was that one was medium brown (Plastic) while the other one was grey.

The second observation is that both studies yield equivalent conclusions: the venetian blind is a shading device which performs well according to all the performance indicators considered. It allows glare control (prevents high luminance at the window) and provides illuminance levels which are suitable for a combination of traditional office tasks and computer work. This device also results in significantly better illuminance uniformity on the work plane compared with the other devices tested and provides acceptable luminance ratios between the VDT screen, the work plane and the surroundings.

Another conclusion of both studies may be that screens with a transmittance of around 5 % yield unacceptably low illuminance and luminance while screens with a transmittance higher than around 25 % yield too high illuminance and luminance values, which may result in glare and unacceptable illuminance values in offices with computers. The ideal screen transmittance is thus around 15 %, as indicated by the results of both studies. Note however, that in both studies, the white screens produced a bright light patch at the window, which may result in glare.

A comparison with the measurements thus indicate that *Radiance* is a valid tool for investigating the impact of shading systems on daylighting quality. Once *Radiance* is mastered as a simulation tool, it allows to study any shading configuration in any climate, for any number of days and orientations, with moderate efforts compared with measurements.

5.2 Limitations and future research

The conclusions of this study are solely based on the results obtained with the computer simulations. These results bear the limitations and accuracy of the computer program used and should thus be appreciated as a function of this major limitation. Also, Veitch & Newsham (1995) claimed that lighting quality can only be assessed indirectly using behavioural measures. This suggests that this study needs to be supplemented by behavioural studies to confirm the conclusions.

Moreover, the room studied was totally empty, which is not representative of reality. It was shown that the main effect of the furniture was to reduce the light levels in the room and that this effect was significant. This suggests that the illuminance and luminance levels in the room would be much lower for all the shading devices studied, which might improve the performance of the white awning, overhang and horizontal venetian blind and reduce the performance of the other devices studied.

The performance indicators used in this study were selected from a large body of literature about the lighting of offices. Most of the indicators used were originally developed for artificial lighting systems. Since it has been shown that human beings have a higher tolerance for glare of daylight origin than from artificial lighting (Chauvel et al., 1982), it is possible that many of the requirements used in this evaluation were simply too severe. For example, it may turn out that the high luminance values obtained with the white screen would be accepted by the majority of office workers. More fundamental research is needed in this field to determine e.g. the acceptable maximum and minimum luminance values or the acceptable uniformity ratios in situations with daylighting.

More research is also needed to develop a solid protocole to evaluate daylighting quality in offices. In this case, we only chose the most common performance indicators and compared them in a simple way without attributing more importance to one factor than to another. It is possible that the luminance in the field of view plays a major role and should weigh more in the overall assessment of daylight quality than the horizontal illuminance or the illuminance uniformity.

Finally, the reader should be aware of the fact that the interpretation of the data in this study was based on standard accepted values for offices as found in the literature. Many “human factor” researchers have pointed out that one of the difficulties in assessing visual comfort – and in particular discomfort glare – is the large variation of responses usually found when comparing individual subjects (Osterhaus, 2001, 1996). For example, Osterhaus & Bailey (1992) found that the least sensitive subjects required an approximately 100-fold increase in luminance to arrive at the same subjective glare rating of the most sensitive subjects when asked to adjust the luminance of glare sources surrounding a computer screen in order to match the same glare rating. The authors even observed that responses of individual subjects were often inconsistent when assessing the same situation.

Summary

The impact of six shading devices on daylight quality and on the potential for daylight utilisation in a standard office room was investigated using the simulation program *Radiance*. The daylight quality was evaluated by considering four performance indicators: the absolute work plane illuminance, the illuminance uniformity on the work plane, the absolute luminance values in the room, and the luminance ratios between the work plane (paper task), VDT screen and surroundings. The potential for daylight utilisation was assessed by studying the daylight factors and the manual switch-on probability according to a formula introduced by Hunt (1980).

The shading devices studied, which were all located on the exterior side of the window, included:

- a white awning;
- a dark blue awning;
- a fixed overhang with slats;
- an aluminium venetian blind with horizontal and 45° slats;
- a white diffusing screen;
- a grey screen with a dominant specular (direct) transmittance.

The analysis was based on simulations under (CIE) sunny sky conditions (on June 21, September 21 and December 21, at 09.00, 12.00 and 15.00 hours) and under a (CIE) overcast sky. The simulated office room was identical to the experimental rooms of the Daylight Laboratory at the Danish Building and Urban Research Institute in Hørsholm, Denmark. This room is a south-oriented, 3.5 m-wide by 6.0 m-deep office space with a 1.78 m-wide by 1.42 m-high window.

The results of the study showed that the overhang, white awning, horizontal venetian blind (and bare window) provided relatively high work plane illuminance levels, acceptable illuminance uniformity on the work plane, and a significantly higher percentage of high luminance values (> 500 cd/m^2) compared with the other devices studied. These devices were the only ones which provided an acceptable daylight factor (> 1 %)

and they also had a very low manual switch-on probability, which suggests that they offer a high potential for daylight utilisation. These devices also produced acceptable luminance ratios between the paper task, VDT screen and surroundings, although there was a small percentage of ratios for which the task was too bright compared with the VDT screen, especially in the case of the white awning and overhang.

The results further indicated that the grey screen produced unacceptably low work plane illuminance levels and a poorer illuminance uniformity on the work plane compared with the other devices studied. The average daylight factor was also very low (0.1 %) and the manual switch-on probability, very high (94 %), which suggests that this device allows marginal energy savings through daylight utilisation. Moreover, the grey screen yielded a high percentage of unacceptable luminance ratios between the VDT screen and the surroundings and between the VDT screen and the work plane. The task and surroundings were too dark compared with the VDT screen. However, the grey screen was the only device which prevented luminances above 500 cd/m^2.

Finally, the results showed that the blue awning, the white screen and the 45° venetian blind produced acceptable work plane illuminance values for a combination of paper and computer work; they yielded acceptable illuminance uniformity on the work plane and a low percentage of luminance values above 500 cd/m^2. Moreover, these devices also provided acceptable luminance ratios between the work plane, VDT screen and surroundings but the performance of the white screen was the best among all devices studied for this performance indicator. However, the blue awning did not prevent sunlight patches in the room due to light leakage on the sides of the awning. Moreover, this device resulted in very low illuminance levels in December. Note also that the white screen resulted in high luminance values at the window.

The results thus suggest that the overhang, white awning and horizontal venetian blind should preferably be used in offices where traditional office tasks (paper, meeting) are carried out while all the other devices except the grey screen should be used in offices where a combination of paper and computer work is performed. However, since none of these devices but the grey screen totally prevented high luminance values (500 cd/m^2), special care should be taken to avoid placing the workstation so that the window is directly in the field of view of the occupant, especially in the case of the overhang, white awning and white screen. The venetian blind might be the only device which may prevent luminance values above 500 cd/m^2 when the slats are totally closed (but this alternative was not tested here).

Finally, the results of this study showed that it was much more difficult to obtain acceptable levels of daylight quality in December than in June and September. This is due to the low solar altitudes in the winter, which make it difficult to shade the entire window area and prevent bright sunlight patches in the room. These bright sunlight patches produce high contrasts, poor illuminance uniformity, and poorer luminance ratios between the VDT screen and the surroundings and they may result in disturbing reflections in the VDT screen.

Thus, shading devices like overhangs and even awnings are not appropriate as daylight control devices in countries at high latitudes. Devices which allow to shade the entire window area like screens and venetian blinds are more suitable, especially in offices where the work is mostly computer-based. However, it is essential that the screens are made of a diffusing material or a material which changes the direction of the incident light rays. This study clearly showed that a screen with a strong direct transmittance component performs poorly on all the performance indicators and probably offers poorer daylight quality and visual comfort levels than all the other alternatives considered, including the bare window.

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Appendix A

Rendering options in Radiance

The following sections describe briefly each rendering option in *Radiance* and its significance for the simulations. Most of what follows is directly extracted from Ward Larson & Shakespeare (1998). These sections are primarily meant as a support of section A.1 Adjustment of the rendering options. Readers who are interested in developing skills with *Radiance* are urged to consult the book by Ward Larson & Shakespeare (1998).

Direct calculation

In *Radiance*, the identification of light sources (which is called "light source testing" or "shadow testing") is made more efficient by using three special algorithms:

1. Selective Shadow Testing;
2. Adaptive Source Division;
3. Virtual Light Source Calculation.

Selective Shadow Testing

To avoid calculation growth with the number of light sources, *Radiance* sorts all potential direct contributions at each evaluation point and sends shadow rays as necessary to meet a given accuracy. This selective light source testing is mainly controlled by two rendering options:

-dt sets the "direct threshold". If set to zero (0), every non zero light source contribution will be tested for visibility, which disables selective light source testing. The calculation may be slightly more accurate but at high costs in terms of rendering time.

-dc sets the "direct certainty". The certainty affects the "stopping" criterion for the direct threshold. If the certainty value is one (1), the tolerance criterion is based on the full remainder of light sources as defined by -dt. If the certainty value is zero (0), only one source beyond the current sum is taken in the calculation. The -dc setting is thus irrelevant if -dt is set to zero (0).

Adaptive Source Division

Large area sources can cause significant errors in a standard ray-tracing calculation because a large source is more likely to be partially occluded than a small one. In *Radiance*, large area sources are subdivided into smaller ones based on the distance to the test point thus avoiding solid angle and penumbra errors without introducing excessive sampling at more distant points. This action is taken conditionally based on the size of the source relative to the distance to the test point in question. If the maximum side length of a source is greater than a certain fraction of the distance to the source from this point (controlled by the -ds option), the source is subdivided into two sub sources along the long axis. This process is repeated on each sub source until all pieces satisfy the relative size criterion. Two parameters control the adaptive source subdivision:

-ds sets the "direct sub sampling threshold". If a source has a side which is longer than this fraction of the distance between the source and the test sample, the source is subdivided. A setting of zero (0) means that the source will never be subdivided.

-dj sets the "degree of jittering"[3]. A value of one (1) forces sampling over the full rectangular source volume but is not recommended because some sources are far enough from rectangular that the corners will be missed (setting of 0.65 or less is recommended). Setting of zero (0) turns direct jittering off.

Virtual Light Source Calculation

Reflecting surfaces like mirrors are a problem with a backward ray-tracing technique since light rays are sent from the observer to the light source (and not the contrary like in reality). The solution to this problem in *Radiance* is to create a "virtual light source" for important specular source paths in the environment. The advantage of using this method instead of a radiosity calculation is that only the light sources need to be repro-

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[3] Jittered sampling is a stochastic process in which values are sampled uniformly over a rectilinear subspace. For example, a ray may be sampled at a random location on a square pixel by choosing random, independent x and y offsets (Ward Larson & Shakespeare, 1998).

duced on the other side of the mirror or glass, not the entire environment. There are two parameters controlling the virtual light source calculation:

-dr sets the maximum number of "direct relays" from redirecting objects. Setting to zero (0) turns off the virtual source calculation. Setting to two (2) means that virtual-virtual (reflection of a reflection) sources will be created.

-dp sets the virtual source "direct pre-test" to the given number of samples per steradians. A setting of zero (0) turns pre sampling off.

Indirect calculation

In *Radiance*, the indirect calculation includes all sources of illumination not found during the direct calculation. This includes light reflected and transmitted in specular directions (see *specular sampling* below) as well as light bouncing diffusely between surfaces in all directions, which belongs to the ambient calculation (see *indirect irradiance caching* below). The basic approach to the treatment of specular and diffuse reflection is to send a small number of rays to sample the specular component, followed by a large number of rays to sample the diffuse component. To avoid geometric growth in the diffuse calculation, values are cached in a specialised data structure for reuse at nearby points (indirect irradiance caching). A weighted average of the cached values is used to compute pixels whose values is not known (Moeck, Lee & Rubin, 1996).

Specular sampling

In *Radiance*, "specular" means basically directional reflection or any non-Lambertian (totally diffuse) component of surface reflection or transmission. This includes e.g. mirror-like reflections from a polished opaque surface or directional scattering from a translucent material. Every material type has at least potentially some specular component. Some materials such as glass are purely specular. Two parameters control the specular sampling in *Radiance*:

-st sets the "specular threshold". Any material whose specular component is above this threshold will have its highlight sampled by tracing a ray distributed about the transmitted or reflected direction. The materials whose specular components are less than or equal to this threshold will have this component added into the diffuse indirect calculation to maintain energy balance but with a loss of directionality. A value of zero (0) means that any nonzero specular component will be sampled. A value of one (1) means that no specular component will be sampled.

-sj sets the amount of "specular jitter". A value of one (1) means that the entire highlight will be sampled. A value of zero (0) means that only the highlight centre will be sampled, creating artificially sharp reflections in rough specular surfaces.

Indirect irradiance caching

The fastest-changing and visually most significant components of the radiance equation have been already captured with the direct calculation and the specular interreflections. Unfortunately, it is not all since light reflects diffusely between surfaces. The effects of diffuse interreflections are critical to the accuracy of the calculation and have an important influence on the appearance of the scenes with little or no direct lighting.

In a standard Monte Carlo (stochastic) evaluation, it would be necessary to sample random ray directions over the hemisphere (or sphere for diffuse transmission) at each pixel. This is impossible to achieve since it would require between 100 and 1000 rays to adequately sample the hemisphere at a given point. The approach taken in *Radiance* is to sample the hemisphere at selected points and interpolate values between these points. This works because the diffuse indirect component tends to change slowly over surfaces so it is not necessary to compute it at every pixel. Several parameters control the "ambient" (diffuse, indirect) calculation:

-av sets the constant "ambient value" to a given RGB (red, green, blue) radiance. This is useful for improving the appearance of a rendering but introduces errors in illuminance predictions where absolute accuracy is required. Mardaljevic (in Ward Larson & Shakespeare, 1998) recommends to set this option to zero (0) for accurate illuminance predictions.

-aw sets the "ambient weight". If enabled (> 0), this option modifies the default ambient value in a moving average as new indirect irradiances are computed. This does not produce accurate rendering in scenes with daylight and it is usually safest to disable this option setting (i.e. by using -aw 0).

-ab sets the number of "ambient bounces" to the specified integer. This many diffuse interreflections will be calculated before the constant ambient value will replace a hemispherical sampling and/or interpolation.

-ad sets the number of "ambient divisions", i.e. how many initial samples are sent out to the divided hemisphere. Increasing this value improves the accuracy of the calculated indirect irradiances and is necessary in a scene with a lot of luminance variation.

-as sets the number of "ambient super samples" i.e. the number of extra rays used to sample areas in the divided hemisphere that appear to have a high variability. Super sampling improves accuracy significantly in scenes with large bright and dark regions by carefully sampling the shadow boundaries. Super samples (-as) should be set to about 1/4 or 1/2 of the ambient division (-ad) value.

-aa sets "ambient accuracy" to a fraction i.e. the maximum error permitted in the indirect irradiance interpolation and is generally less than 0.3 (i.e. allowing up to 30 % error in the indirect calculation). Smaller values result in closer spacing of indirect calculation at a commensurate cost in rendering time.

-ar sets the "ambient resolution". The accuracy of the indirect calculation will start to relax at distances less than the maximum scene size divided by this number. This setting avoids to overkill the program on unimportant geometric details (small objects).

A.1 Adjustment of the rendering options

Before starting the simulation process, a sensitivity analysis was achieved to analyse the impact of the rendering options in *Radiance* on the accuracy of the results. This allowed to determine the optimal rendering options settings to obtain the highest possible accuracy in an acceptable rendering time.

The rendering options were first all set to the "medium accuracy" level suggested in Ward Larson & Shakespeare (1998) and Ward (1996a) and reproduced in Table A.1 below. The work plane illuminance was then calculated at six points along a single row centred about the window, for the empty room with a bare window and a 10 000 lux CIE overcast sky. Each rendering option was then increased to a higher level (high accuracy) one at a time and the time for performing the calculation was noted. This is reported in Table A.2.

Table A.1 Rendering options settings for medium and high accuracy (from Ward Larson & Shakespeare, 1998 and Ward, 1996a).

Rendering option	Medium accuracy	High accuracy	Comments
-dt	0.1	0.0	Max value disables optimisation and can be very expensive
-dc	0.5	1.0	Irrelevant if -dt = 0.0
-dj	0.5	0.65	
-ds	0.2	0.01	
-dr	0	0	Irrelevant if there are no virtual sources
-dp	32	32	Irrelevant if there are no virtual sources
-st	0.15	0.01	Max value disables optimisation and can be very expensive
-sj	0.7	1	Does not affect rendering time
-ab	4	8	
-aa	0.15	0.08	Max value disables optimisation and can be very expensive
-ar	128	512	Max value disables optimisation and can be very expensive
-ad	400	2048	
-as	64	512	Should be ½ or ¼ of -ad
-lr	6	8	
-lw	0.004	0.001	

Table A.2 shows that increasing the accuracy level in the direct (-d… options) calculation did not have any impact on rendering time. This is probably due to the fact that there was only one light source in the scene (the sky). However, increasing the accuracy of the indirect calculation (-s… and -a… options) did have an effect on rendering time, especially for the ambient (-a…) calculation options. The options which had the most dramatic impact on rendering time were the ambient accuracy and ambient resolution (-aa and -ar) as well as the ambient divisions and ambient super sampling (-ad and -as) options.

The relative difference between the daylight factors obtained through simulations and the ones obtained through measurements in the Daylight Laboratory are presented in the Fig. A.1. The relative difference was calculated as $RD = 100[(D_M\text{-}D_S/\ D_M]$ where D_M is the measured daylight factor and D_S is the simulated daylight factor (with *Radiance*).

Table A.2 Rendering time as a function of rendering settings.

Basic settings	Variation	Rendering time (seconds)
Medium accuracy		12
Medium accuracy	-dt 0.0	12
Medium accuracy	-dc 1.0	12
Medium accuracy	-dj 0.65	12
Medium accuracy	-ds 0.01	12
Medium accuracy	-d high accuracy	12
Medium accuracy	-st 0.01	20
Medium accuracy	-sj 1	12
Medium accuracy	-d and -s high accuracy	23
Medium accuracy	-ab 8	16
Medium accuracy	-aa 0.04	180
Medium accuracy	-ar 1028	65
Medium accuracy	-aa 0.04 -ar 1028	> 600
Medium accuracy	-aa 0.08 -ar 512	100
Medium accuracy	-ad 1024	50
Medium accuracy	-ad 2048 -as 1024	130
Medium accuracy	-ad 1024 -as 512	50
Medium accuracy	-a high accuracy	> 600
	High accuracy	1020

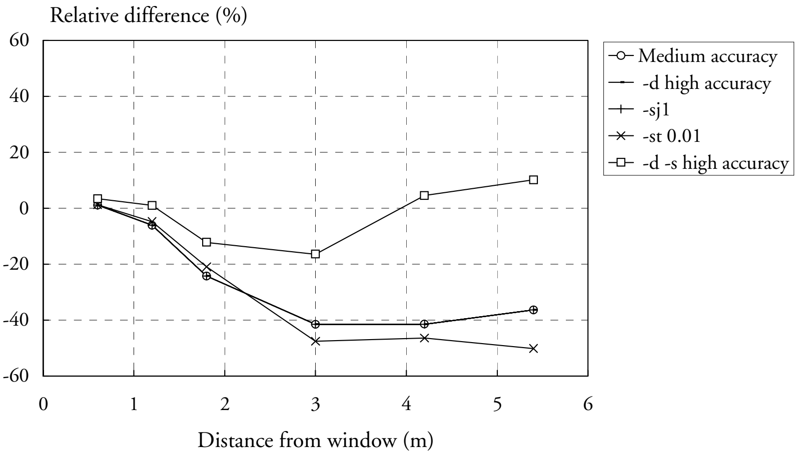

Figure A.1 *Relative difference (%) between the daylight factors obtained through measurements and the ones obtained through simulations with various direct (-d…) and indirect specular (-s…) calculation options settings.*

Fig. A.1 shows that increasing the accuracy of the direct calculation did not generally increase the overall accuracy. This is normal since the sky was the only light source in the scene in this case. Moreover, since most of the light at the back of the room comes from the indirect component in the case of an overcast sky, it is unlikely that increasing the accuracy in the direct calculation will have much effect on the accuracy of the results in the back of the room. To obtain a high accuracy, it is necessary to improve the ambient calculation.

Increasing the specular threshold and jitter separately did not either have a large impact on the overall accuracy. However, an increase in the accuracy of both parameters (-d -s high accuracy) did improve the overall accuracy significantly as shown in Fig. A.1. Note that the extra cost in rendering time was not very high in this case (see Table A.2).

The ambient calculation options (-a… options) were also varied and the relative difference between the daylight factors obtained through measurements and the ones obtained through simulations with different ambient calculation options settings is shown in Fig. A.2.

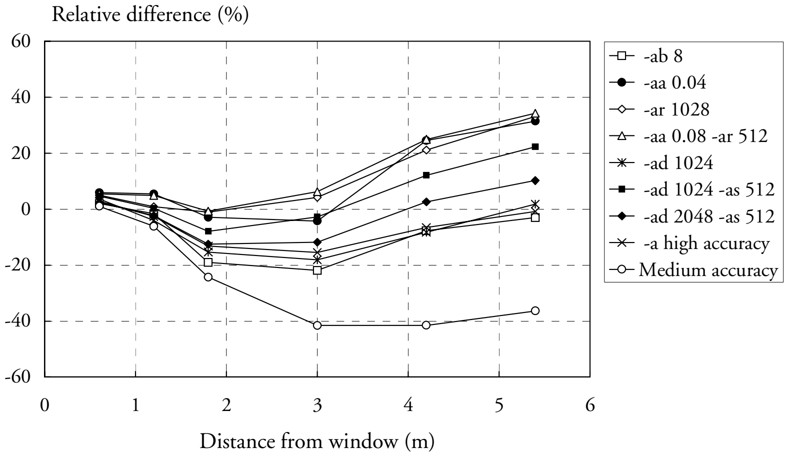

Figure A.2 *Relative difference (%) between the daylight factors obtained through measurements and the ones obtained through simulations with various ambient calculation options settings (-a…options).*

Fig. A.2 shows that an increase in the ambient bounces (-ab) from 4 to 8 greatly improved the accuracy of the results in the middle and back of the room. In the back of the room, almost all the incident light is reflected from other surfaces; it is thus normal that more ambient bounces are needed to achieve a higher accuracy in this region of the scene. Fig. A.2

also shows that an increase in the ambient divisions and super samples (-ad -as) further improved the accuracy of the results in the middle of the room. Overall, the greatest accuracy was obtained by combining high accuracy settings (-a high accuracy) for all the ambient options. In this case, the largest relative error was 15 %, at 3 m from the window. However, the relative difference near the window and at the back of the room was negligible. Note that the difference in the middle of the room may as well be attributed to differences in the sky luminance distribution or in the landscape in front of the window.

The last figures (Fig. A.3, A.4) show the results obtained with the "high accuracy" settings of Table A.1 for all the rendering options. These figures show that the results are greatly improved compared wirh the "medium accuracy" settings, especially at the back of the room. The prediction is also slightly better in the middle of the room, although there is still too much light in the simulations compared with the measurements (a negative relative difference means that there was more light in the simulations than in reality). A better accuracy could be obtained by setting better values for the ambient accuracy and resolution (-aa and -ar) but this was too costly (the rendering took more than one day to be completed). Here a compromise had to be made between accuracy and calculation time and thus, the high accuracy options settings of Table A.1 were chosen.

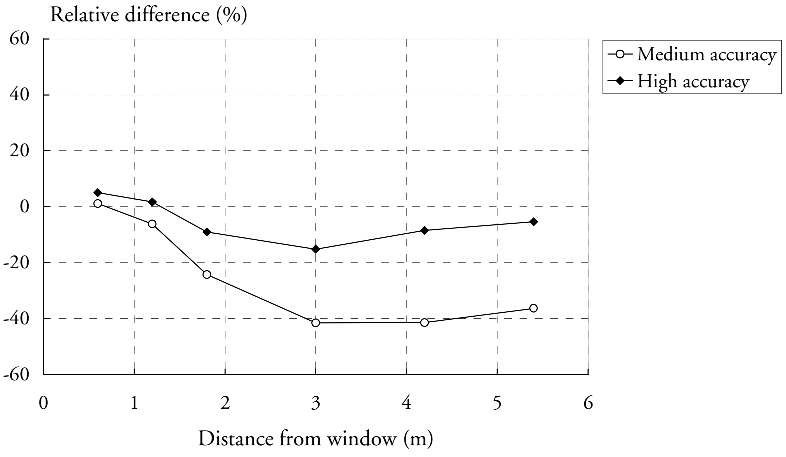

Figure A.3 *Relative difference (%) between the daylight factors obtained through measurements and the ones obtained through simulations with the medium and high accuracy rendering options settings.*

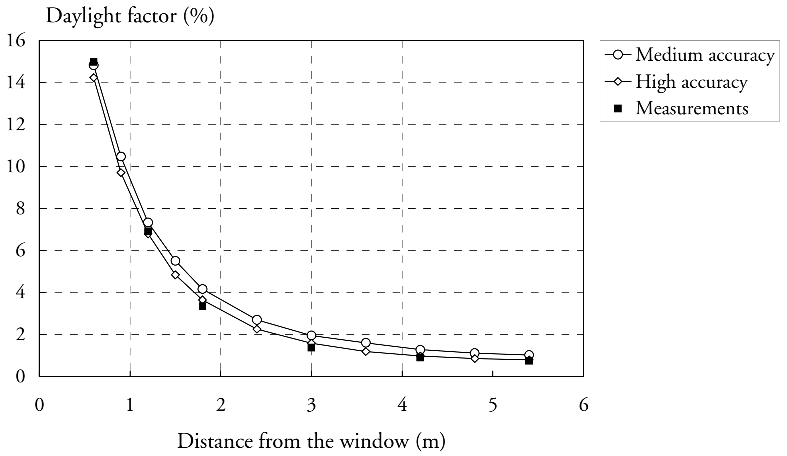

Figure A.4 *Impact of medium and high accuracy rendering options on the simulated daylight factor (%) compared to the measured values.*

Additional tests were made to verify whether the rendering options chosen would still be valid under different conditions i.e.

1. with a more complex scene like a furnished office room with venetian blinds under overcast conditions;
2. under sunny sky conditions.

In those cases, no measurements were available for comparison but we analysed the impact of rendering parameters in a relative way and could make some valid deductions.

For the room with furniture and venetian blinds in aluminium, the results of the simulations are presented in Fig. A.5 as a function of all the rendering options settings tested. The figure shows, as previously, that setting the direct calculation options (-d…) to "high accuracy" has no effect on the results. However, a higher setting for the indirect specular (-s…) options produces either a higher (-st 0.01) or lower (-sj 1) daylight factor. This is obviously due to the fact that the venetian blind (and other objects in the room) have a specular component. Setting -st to 0.01 means that the specular component's direction is accounted for. (Note that it does not make much sense then to have a low -sj setting with a high -st setting).

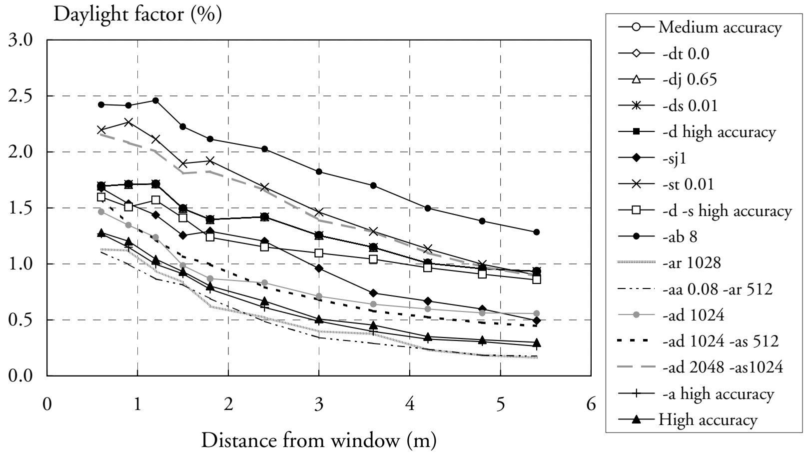

Figure A.5 *Impact of the rendering options on the calculated daylight factor (%) for a furnished room with a venetian blind in alumimium, under overcast conditions.*

As shown previously, increasing the accuracy for the ambient calculation generally reduces the daylight factor in the room. One exception in this case is for the ambient bounces (-ab 8), which resulted in more light overall if we only increased the accuracy of this parameter alone. In this case, it was necessary to combine this option with more ambient divisions, super sampling and a higher ambient accuracy and resolution since the scene contained many small objects. It is no use to have many ambient bounces if the accuracy, resolution and divisions have a low setting. Fig. A.5 shows that when the ambient divisions and super samples and the ambient accuracy and resolution are increased, the results more or less converge in the lower part of the diagram. Moreover, the curves are smoother than in the other cases, which suggests that the results are more realistic. This analysis indicates that it is necessary to use high accuracy options settings. In this case, setting a higher accuracy value for the indirect calculation options (-s… and -a… options) had a large impact on the predicted daylight factor. In fact, the error on the illuminance prediction was up to around 125 lx (1.25 % of 10 000 lx), meaning that the predicted daylight factor could be more than twice too high (or less than half as high) depending on the rendering options settings.

The last test consisted of studying the same furnished office room with venetian blinds but under sunny conditions. For this test, a CIE sunny sky was modelled for June 21 at 12.00 hours (standard time) in Hørsholm (Denmark, latitude 55.4° N, longitude 12.35° E).

The impact of some direct (-d…) rendering options on the calculated illuminance is illustrated in Fig. A.6. The figure shows that, for the first time, changing some settings in the direct rendering options did have an impact on the predicted illuminance. The figure also shows that increasing the direct threshold (-dt) or direct sub sampling (-ds) independently changed the illuminance but that increasing the accuracy of all the direct options together (-d high accuracy) had no effect compared to the medium accuracy settings.

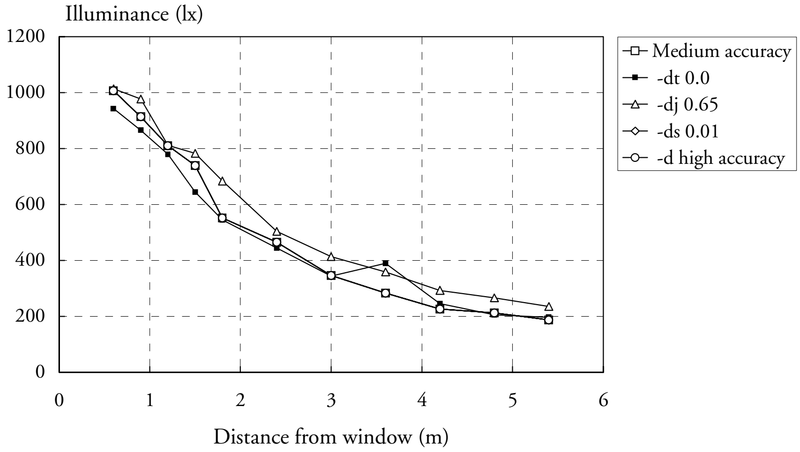

Figure A.6 *Impact of the direct (-d…) rendering options on the illuminance (lx) in a furnished room with a venetian blind in alumimium, under CIE sunny sky conditions (June 21, 12.00 hours).*

The impact of the indirect specular (-s…) options on illuminance is illustrated in Fig. A.7. This figure shows that setting a higher accuracy for the specular threshold (-st) and for the specular jitter (-sj) independently resulted in more overall difference in illuminance than using high accuracy for both options (-d -s high accuracy). Higher accuracy settings resulted in a less even illuminance curve, especially at the front of the room, which might be due to the specular component of the venetian blind. This shows the importance of using high accuracy settings when some objects in the scene have a strong specularity. This effect will be extremely important with e. g. reflective or glossy venetian blinds.

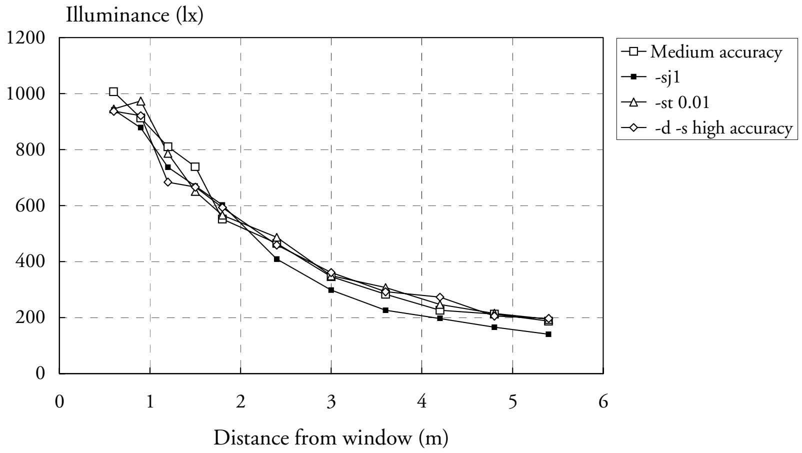

Figure A.7 *Impact of the indirect specular (-s…) rendering options on the illuminance (lx) in a furnished room with a venetian blind in aluminium, under CIE sunny sky conditions (June 21, 12.00 hours).*

The impact of the ambient (-a…) options on the illuminance is illustrated in Fig. A.8.

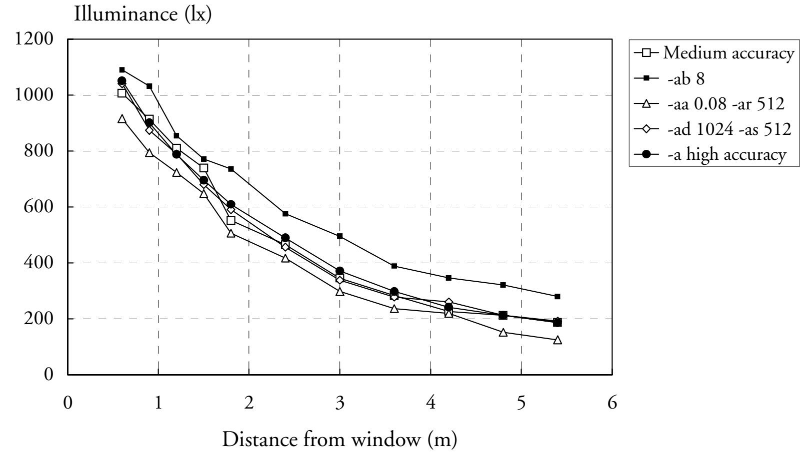

Figure A.8 *Impact of the indirect ambient (-a…) rendering options on the illuminance (lx) in a furnished room with a venetian blind in aluminium, under CIE sunny sky conditions (June 21, 12.00 hours).*

Fig. A.8. shows a similar trend as for the calculations under overcast conditions although the impact of the ambient calculation options on the illuminance is relatively less important. This is normal since a large part of the illumination is provided in this case by the direct component. Another difference is that the high accuracy settings result in more overall illumination than the medium settings. In the previous case (overcast sky), the opposite occurred.

The rendering tests performed suggest that it is necessary to use high accuracy settings in the calculations since this study will evaluate shading systems both under overcast and sunny sky conditions in rooms with a certain level of complexity due to the shading device in the window. The direct (-d…) calculation options are not so important under overcast conditions but they do have some influence on the results under sunny conditions. Since they did not increase rendering time dramatically in most cases, it is preferable to set these options to high accuracy. The specular (-s…) calculation options must be set to higher accuracy to account for the directionality of the specular reflections and transmissions from the shading systems. Finally, the ambient (-a…) calculation options are the ones having the largest effect on the results, especially under overcast conditions and in the back of the room. The tests showed that it is important to select high accuracy settings of these options although this increases rendering time dramatically. A compromise must be made between accuracy and rendering time. In this case, the rendering options settings which produced optimum results in an acceptable calculation time were:

```
-dt 0.0 -dc 1.0 -dj 0.65 -ds 0.01-st 0.01 -sj 1 -ab 8 -aa 0.08 -ar 512 -ad
2048 -as 512 -lr 8 -lw 0.001.
```

A.2 Secondary light sources

In this study, the window is the most complex object in the room (assuming an empty room) and it is also the only light source. Since a large part of the light coming through the window from the sun and sky will be interreflected by or transmitted through the shading device before coming into the room, high accuracy in the indirect calculation options settings will be necessary to properly sample and represent the distribution of light coming from the window. This is unfortunate since the indirect calculation is the most demanding part of the whole calculation as shown in the previous sections.

Fortunately, *Radiance* contains special algorithms allowing to move parts of the indirect calculation to the direct calculation, which makes the whole calculation process much more effective. This is done by using the program "mkillum", which transforms surfaces in the room, e.g. the window, into "illum" surfaces or "secondary light source (SLS)" emitters. SLS are simply light sources with a defined, specific radiance distribution. In our case, transforming the window into SLS means that all the light coming from the window in an indirect way (i.e. reflected at least once by one surface outside the room) will be added up and represented as a series of vectors located at the window surface. This is equivalent to moving a large part of the calculation from the indirect to the direct calculation since no indirect light ray will be needed outside the room.

The "mkillum" program was used in this study as a pre-processor to the calculations. The window was divided into nine parts to capture the changing light distribution over its area as suggested in Ward Larson & Shakespeare (1998). In all the cases, "mkillum" was applied to the scene and the window was transformed into SLS, which greatly reduced calculation time. This also allowed to repeat renderings or e.g. change the view point in one rendering without having to perform long calculations each time, since the most demanding part of the calculation (i.e. making SLS) was already done.

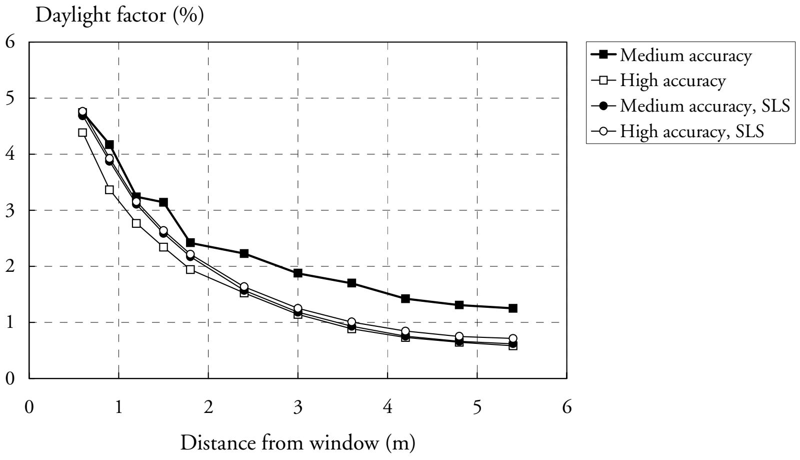

Figure A.9 *Daylight factors (%) in an empty room with horizontal venetian blinds in aluminium. The calculations were performed with medium and high accuracy rendering options settings with and without using the "mkillum" program (SLS).*

The use of "mkillum" greatly reduced calculation time. Fig. A.9 shows the daylight factors obtained in an empty room with horizontal venetian blinds, using medium and high accuracy rendering options of Table A.1 with and without the use of secondary light sources (SLS).

Fig. A.9 shows that the use of SLS allows to reach an accurate solution with only medium accuracy rendering options settings. In this case, only a few ambient bounces, ambient divisions and super samples are necessary since the scene outside the room is not being sampled (in the indirect calculation). Moreover, the difference in calculation time between the medium and high accuracy settings was much less than when the "mkillum" program was not used.

Since the most demanding part of the simulation process consisted of creating the "illums" (running "mkillum"), and that little extra additional time was required for running the final calculations using the high accuracy rendering options settings, we used the high accuracy rendering option settings in the simulations although Fig. A.9 suggests that medium accuracy settings were sufficient.

The calculations were performed on a Pentium III (733 MHz) or equivalent. It took approximately eight hours to compute the illums for the eight shading alternatives (including the bare window case) tested, for each hour (total of ten hours) studied and approximately the same amount of time to perform the final calculations (illuminance and luminance). Thus a total of about 160 hours were needed to complete all the calculations. This process was greatly facilitated by running the calculations on four computers in parallel. Thus all the calculations could be achieved within a two week period (no calculations could be performed during daytime since the computers were used by hard-working PhD students at that time).