Daylight in glazed office buildings

A comparative study of daylight availability, luminance and illumince distribution for an office room with three different glass areas

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Division of Energy and Building Design
Department of Architecture and Built Environment
Lund University
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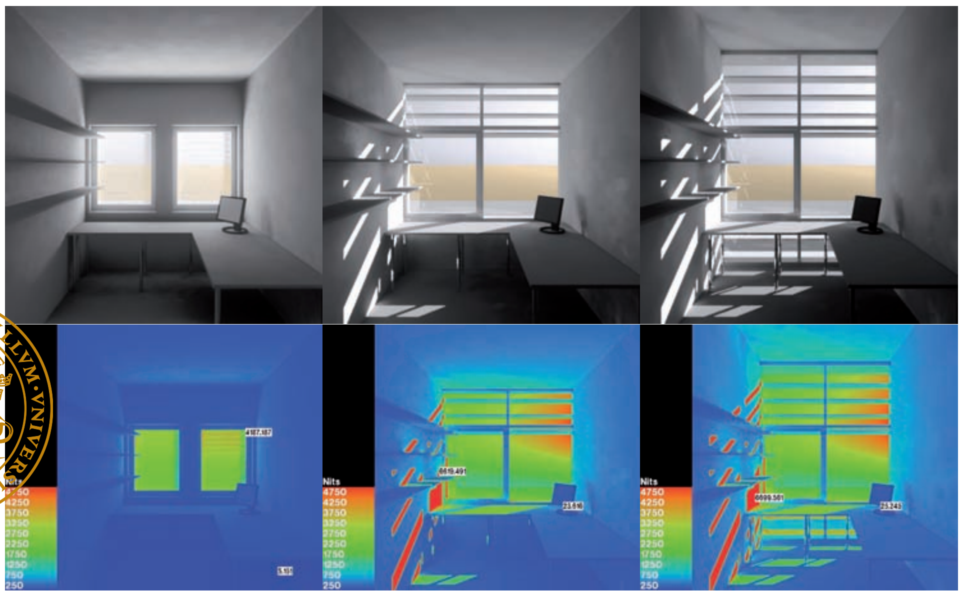

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 105 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 42 500 students attending 90 degree programmes and 1 000 subject courses offered by 74 departments.

Division of Energy and Building Design

Reducing environmental effects of construction and facility management is a central aim of society. Minimising the energy use is an important aspect of this aim. The recently established division of Energy and Building Design belongs to the department of Architecture and Built Environment at the Lund University, Faculty of Engineering LTH in Sweden. The division has a focus on research in the fields of energy use, passive and active solar design, daylight utilisation and shading of buildings. Effects and requirements of occupants on thermal and visual comfort are an essential part of this work. Energy and Building Design also develops guidelines and methods for the planning process.

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Keywords

Blinds, daylight, daylight autonomy, daylight factor, daylight re-direction, electric lighting, glare, glare protection, illuminance, luminance, solar protection, solar shading, windows.

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Abstract

In this project, the light distribution for offices has been studied through computer simulations using the programs Rayfront/Radiance and Daysim. The effect of a few façade alternatives has been compared regarding daylight availability and visual comfort. The study focussed on single-cell offices, but open-plan space has also been studied. Three different façades have been compared, where the windows constituted 30, 60 and 100 percent of the façade area. In the first moderately glazed case windows with a coupled construction (1+2 panes) with an intermediate blind was studied. The light transmittance of the glazing was 73 percent. For the case with 60 percent window area the room was glazed from table height up to a drop-ceiling at 2.7 meters height. In the case with 100 % window area, the room was glazed all the way from the floor to the slab, and no drop-ceiling was used, i. e. the room height was 3.2 m. In these two cases a double-glazing with 66 % light transmittance was used and the windows had a fixed exterior shading system made of 300 mm horizontal aluminium slats, spaced 300 mm apart.

In side-lit rooms, the illuminance is highest close to the facade, and then falls off very quickly as one move further into the room. This is true even for a facade glazed to 100 %. Very close to the window (1–1.5 m) the daylight factor is about 4-5 % for the moderately glazed facade (30% case) without shading, and about the same as for the cases 60 and 100% with exterior louvres. The daylight autonomy in this point is approximately 60 % for these three cases. At 3.5 meters from the facade the daylight autonomy is only about 30 % for the 30% case without blinds. For the case 100% with louvres the daylight autonomy is 50 % while it decreases to 45 % for the case 60% with louvres. A conclusion is that an office glazed to 100 % does not provide significantly more light on the office desk than a 60 % glazed case. This is both with and without the studied shading system.

The proposed exterior shading system with fixed slats only works well between mid-April until the end of August. During the rest of the year the sun is so low in the sky, that direct sunlight hits the office desk, resulting in glare. Glare can be avoided by improving the shading system. In one investigated case, the shading was improved by adding an interior curtain in front of the view window. In another case, the exte-

rior shading system was replaced by 80 mm wide exterior venetian blinds. The high luminance on the window plane is thus reduced, lowering the risk of glare from the window. However, the resulting daylight levels will drop significantly, and will not be much higher than for the moderately glazed case with blinds at 30°.

Fixed shading devices in general have a strong drawback, since sunlight can penetrate through or below them when the solar height is lower than the cut-off angle they are designed for. Further, they always shade more or less of the important diffuse light from the sky. Venetian blinds are much better since they provide a very flexible solution. The slats can always be turned to the right cut-off angle, and can thus respond to the great variations of solar heights that occur during a full year and during the course of the day. The slat angles can also be adjusted to provide the preferred window luminance of the user, in order to avoid glare. During dark and cloudy conditions, they can be retracted fully to provide maximum daylight in the room.

Light re-directing blinds may be an option for tall windows, since this provides more light through the upper part of the blind, which can penetrate to the deep end of the room. However, the risk of introducing more glare should always be considered. Due to low solar heights in the winter at high latitudes, the slat angle difference should be kept low to avoid sunlight penetration through the upper part of the blind. The benefit of such system is therefore somewhat limited in Sweden.

If only the glass area increases while nothing else changes, the daylight factor will increase with increased glazing area. However, it will not increase in direct proportion to the glazed area. One reason is that all light that is transmitted through the (vertical) window plane does not effectively contribute to increasing the daylight factor, which is measured at a horizontal plane 0.8 meters above the floor. Especially light that is transmitted below 0.8 meters will primarily hit the floor, where around 70% will be absorbed. Only a small fraction of the transmitted light will therefore affect the daylight factor.

The conclusion is that very large windows do not mean that the light is automatically better. It can be difficult to achieve a glare free environment without additional measures, for example by adding interior curtains or blinds. Today's computer based work which includes looking at vertical self-luminous surfaces also increases the risk of glare compared to looking down on a piece of paper. The line of sight is raised and the central field of view will most likely include the window, especially in open plan spaces. The larger the window area, the greater is the chance that a window might create glare. In order to further reduce glare risks, the computer screens could be moved further away from the window, and turned away from the window, to a perpendicular position.

Contents

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1 Introduction

The study presented in this report is one of the studies in a larger research project called “Glazed Office Buildings Project”. The main aim of this large project is to examine the effect of increased window surfaces as often seen in modern architecture and to compare highly glazed office buildings to more moderately glazed ones. Therefore, various glass surfaces and construction types have been studied and compared to what the project group defined as a typical Swedish office building from the 1990’s. The project group has consisted of researchers from Lund University and a group of consultants from WSP and SKANSKA. The consultants together represent all major consultants normally taking part in the design of a building: the architect was represented by Christer Blomqvist from WSP Architecture and Design, structural engineering was represented by Bengt Bengtsson, Skanska, HVAC engineering was represented by Lars Sjöberg, Skanska, and cost estimates were performed by Lars Sjödin, WSP Management. Other consultants have also taken part, but to a lesser extent. From the university, the participants were Åke Blomsterberg (project leader), Harris Poirazis, Bengt Hellström, Helena Bülow-Hübe and Maria Wall. Please refer to other project reports (Poirazis, 2005, 2008) and the project home page found under www.ebd.lth.se.

The main issues studied in this project have been the influence of varying glass surfaces on energy use and thermal comfort, daylight availability and visual comfort, initial building cost and life-cycle costs. Therefore, an office building was designed and a virtual 3D building model was made in ArchiCAD. The purpose of using a 3D Cad modeller was to facilitate cost calculations since changes made to the model could easily be estimated. The building designed was about 60 m long, 15 m wide and had 6 stories above ground. A number of parameters where then studied using various other tools, for example energy use and thermal comfort was studied in the energy simulation program IDA-ICE (Poirazis, 2005). The structure of the building was left intact during these various parametric studies, but the façade construction was changed, and also the spatial layout of the floor plan (both cell type offices and open-plan space was studied). This report will present the daylight studies performed on this building.

The glazed office building project is a continuation of previous projects at Energy and Building Design at Lund University. In order to properly design the HVAC system for a building, the effect of shading devices on solar transmittance must for example be well known. A large project was therefore started in 1997, the Solar Shading Project at Lund University, and this has focussed on measuring the performance of shading devices. Another main part has been the development of a computer tool, ParaSol, to estimate the thermal impact of various shading devices which are common on the market. (Wall & Bülow-Hübe, 2001, 2003). One part of the Solar Shading Project was also devoted to daylight studies, and the report presented here is a direct continuation of the work started in the Solar Shading project, see for example the two theses by Dubois (2001a) and Bülow-Hübe (2001) respectively.

2 Background

2.1 General

Today's architectural trend with large glazed surfaces gives fantastic possibilities of view out and is often believed to give abundant daylight in the premises. There are, however, also many problems associated with such solutions: Poor thermal comfort in the winter time is common due to the poor thermal insulation of glazed facades compared to traditional well-insulated walls. This leads to down-draught of cold air and also to radiation losses from the user to the cold glass surface. This imbalance in the thermal climate contributes largely to poor thermal comfort. When the intensity of the solar radiation becomes higher in the spring and summer, the glass surfaces instead become very warm, and overheating can easily occur. Solar control glazing combined with shading devices are usually necessary to help mitigate overheating and decrease cooling loads.

If only the glass area is increased, and no other design parameters are changed, the daylight factor will increase with increased glass area. However, more daylight must not equal better daylight. Although the view out may be impressing, visual comfort may be more difficult to obtain, especially for office work. With the introduction of computers, two major factors have changed compared to paper-based work. Both of these require a more carefully thought out luminous environment. Firstly, the computer screen is a self-luminous surface, a light source, with a certain luminance, so if too much light falls upon it, the contrast on the screen is washed out, and the image cannot be seen. This is very different from paper, which reflects any light falling upon it. The contrast between the paper and the immediate surrounding is thus never higher than the difference between the reflectance of those two surfaces, and for example text printed on paper can be read in many lighting conditions from rather dark indoor environments to sunlight. Secondly, with computers, the view of sight has been raised from looking down on the working table to be almost horizontal, towards the computer screen, see Figure 2.1. The surrounding field of view will thus likely include the window, especially in highly glazed facades and in so called "open landscapes". Today, computers are a natural part of any office work. According to a Danish study, 95 % of 1800 questioned office workers use computers for more than 55 % of their working time. At the same time, more than 70 % of them preferred to sit close to the window. (Christoffersen et al., 1999).

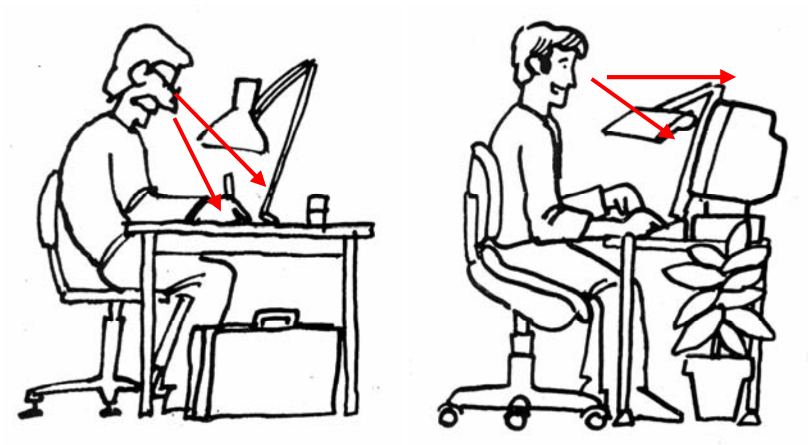


Figure 2.1 *A main difference between paper-based work and computer work is the view of sight, and what becomes part of the surrounding field of view.*

Another factor which is important is the enormous difference in light intensities between indoors and outdoors. Indoors, the illuminance from artificial lighting is often between 100 and 1000 lux, while the outdoor illuminance can be on the order of 10.000 to 100.000 lux. The luminance of the sky can also be very high, up to 100.000 cd/m² around the sun, while a value of 1500 cd/m² is usually considered a maximum value for indoor office environments to avoid glare (NUTEK, 1994). Although a constant light level is not desired in daylit spaces (variation stimulates arousal), it must be kept within some acceptable limits and glare must be avoided. For example, the sky seen through a window is a large potential glare source, and the user must be able to reduce its luminance through manoeuvrable exterior shading devices or interior blinds or curtains. Sunlight penetration should also be avoided (Bülow-Hübe, 2000). On the other hand, it should not be too dark, since daylight also have several beneficial non-visual effects. Light of the right intensity and colour can affect mood, attunes our sleep/wake cycle and the secretion of hormones, and can suppress seasonal affective disorders. (Küller & Küller, 2001; Webb, 2006).

2.2 The difficult issue of visual comfort

The perhaps most difficult issue to answer is when do people in a lit environment find it comfortable? What criteria govern visual comfort? Surely, absence of glare must be one important parameter. The issue of glare has been studied over a long period, but there still seem to be many unresolved questions. One common finding is however the great variability between individuals as to when they start to perceive a bright surface as disturbing. It is also believed that some glare can be tolerated if the work place contains a view to the outside. (Osterhaus, 2001; Velds, 2000; Wienolds & Christoffersen, 2006).

A common critique towards older work on glare is that it has often been devoted to artificial lighting and small area glare sources. Studies on large area glare sources have often been performed under very controlled circumstances in the laboratory with artificial skies or luminous screens, and the lack of a view out. (Velds, 2000; Osterhaus, 2001). Studies in real environments pose great methodological problems since the daylight varies so rapidly and the individual variation is large. However, one new empirical study performed both in Germany and Denmark shows some promising results towards a new glare rating formula, the daylight glare probability, DGP (Wienold & Christoffersen, 2006). This model uses the concept of a probability that a user is disturbed by glare instead of a fixed glare rating scale. They used well instrumented daylit laboratory rooms, a calibrated camera-based luminance mapping technique (CCD camera) and a larger sample of test persons to try to link glare ratings to measurable light quantities in the work environment. The model is based on the vertical eye illuminance as well as the glare source luminance, its solid angle and its position index. Compared to existing glare models, the DGP showed a very strong correlation with the user's response regarding glare perception. However, if the DGP is to become accepted as a trustworthy prediction model, it must be validated through further studies using the same approach. In their study, Wienold & Christoffersen also developed a glare evaluation tool *evalglare* which automatically detects glare sources and rates them using the Radiance luminance picture format. Radiance is a very advanced lighting simulation program that can accurately predict the luminance and illuminance distribution of both daylit and artificially lit environments (Ward & Shakespeare, 1998).

Other factors for visual comfort are psychological factors, the work task to be performed, and the luminous distribution in the room. But there are still no good prediction methods for visual comfort and glare (Veitch and Newsham, 1996; Osterhaus, 2005). Some issues that have to be fulfilled for lighting installations, like illuminance uniformity, seem ridiculous for daylit environments. In side-lit rooms a smooth gradient is natural. Therefore, if the illuminance decreases slowly when moving away from the light source, and there are no extremely sharp jumps, as between sunlit patches and areas in the shade, this should be just as acceptable as an even carpet of illumination. Other criteria, like the commonly cited rule of thumb of luminance ratios of 1:3:10 has been questioned recently since it is based on studies with very few subjects (Osterhaus, 2001). Even so, it actually seems rather sound, at least as a general guideline. Therefore, before visual comfort is fully understood, we must rely on such and other rules of thumb in our investigations of daylight. (Dubois, 2001b).

Discomfort Glare refers to the sensation of annoyance or pain caused by high or nonuniform distributions of brightness in the field of view. Discomfort glare can be reduced by decreasing the luminance of the light source (windows, skylights, luminaries), diminishing the area of the light source or by increasing the background luminance around the source.

Disability Glare (veiling luminance) refers to reduced visibility of a target due to the presence of a light source elsewhere in the field. It occurs when light from glare source is scattered by the ocular media. This scattered light forms a veil of luminance which reduces the contrast and thus the visibility of the target.

Contrast can be defined as the difference between the luminance of the target and the background relative to the average luminance of the scene.

$$\text{Contrast} = \frac{\text{Target illuminance} - \text{Background illuminance}}{\text{Target illuminance} + \text{Background illuminance}}$$

(Sources: Lighting handbook (IESNA, 1993) and URL: http://sdhawan.com/ophthalmology/glare.html)

2.3 Room perception in glazed rooms

What happens with room perception and the light in the room itself when the opaque façade is replaced by transparent surfaces? Architect and professor in lighting Anders Liljefors seem to be a bit sceptical to what large glass surfaces do to the experience of the architecture itself in a very interesting short essay on space, glass and light: On the positive side he says that glass architecture often provide powerful light experiences where the building or room often gives direct access to the sky, which is exposed in contrasting ways by means of weight-bearing structures, lattice-work or shading devices. But the light in the room itself appears best if sunshine is allowed to enter and be treated by the room's inner surfaces. If the sun is efficiently shaded, the light in a glazed room often seems rather grey. Further, he says that a room is not always perceived as lighter even if the glass area increases. The light in the room will not necessary be more beautiful either.

"Indeed, it is likely that the lighting inside a room will be flatter, the larger the windows are: in that case, the variations between illuminated portions of a room become less marked. … What defines the light in a room is the room itself."

Larger differences between light and shadow apparently give a more distinct description of a room and the distribution of light in a room gets a more obvious character. The smaller the window, the larger is the difference between the light indoors and outdoors which gives us a better reference to the room we are in. A difference between indoors and outdoors is also what creates an interest. Inversely, rooms with larger glass areas will have smaller differences and will be perceived as more flat. (Liljefors, 1998).

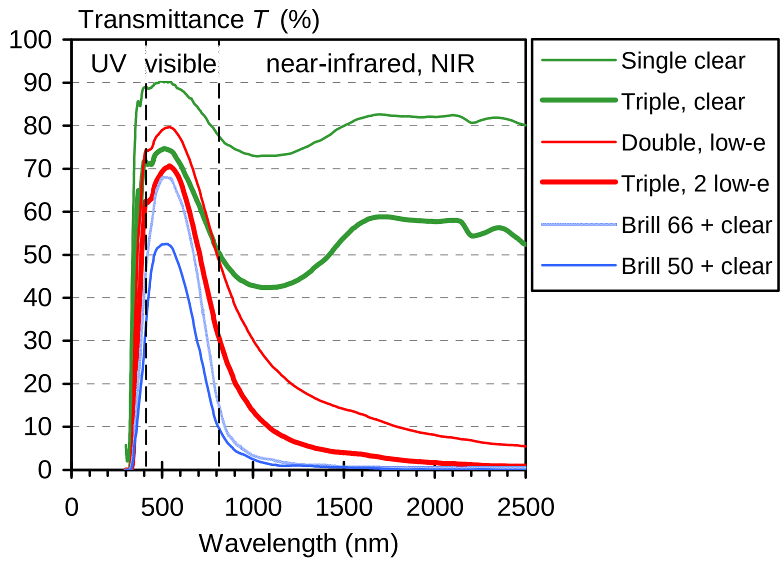
Rooms with glazed surfaces are thus perceived as less enclosed than rooms with moderate glass surfaces when the boundary between indoors and outdoors is gradually dissolved. The light becomes more even; there is less interplay between light and shadow, than in traditional architecture were the window opening is "a hole in the wall". The light might thus be perceived as more dull.

2.4 Transmittance of coated glazing

A factor which may contribute to dullness of the light is that solar control glass is almost without exception used in highly glazed office buildings. Solar control glass affects both the absolute level of the daylight transmittance, but to a lower or higher extent also the 'colour' of the perceived light. The first kinds of solar control glass were body-tinted glass, where a metal-oxide is used to 'dye' the glass to a desired colour, which gives it a higher absorptance of sunlight and thereby reduces its transmittance. But daylight transmittance is then reduced roughly just as much as the solar transmittance. Later came hard-coated solar control glass, which was often highly reflective when seen from the outside. This glass type also significantly reduces both the daylight and solar energy transmittance. Today, advanced soft coatings are almost exclusively used in modern building projects to control sunlight. These coatings are spectrally selective: they aim to keep the daylight transmittance as high as possible, while blocking sunlight in the UV and near-infrared regions. Further, they also have a low emittance in the long-wave region, giving them much lower U-values than traditional uncoated glazing systems. (Bülow-Hübe, 2001).

What does this filtering through the glazing system do to the perception of the rooms, and potentially even to our health and performance? The first question is to my view unfortunately almost never discussed among architects today, while the second one is starting to generate an interest, mostly among lighting designers and light source manufacturers. This has been spurred after recent findings of a third receptor in the eye that controls our diurnal and seasonal rhythms of hormone secretion (circadian regulation). Exposure to monochromatic light in the range of 446-477 nm seems to be particularly effective for suppressing the sleep hormone melatonin in humans. (Brainard, 2001, Jasser et al, 2006).

Therefore, the effect that tinted or coated glazing may have on the transmitted daylight should be further investigated since it is commonly used for highly glazed buildings. Both effects on room and light perception, and on the biological effects on humans are thus of interest. The often greenish colour in transmission of advanced solar control glazing might create a more subdued and duller indoor environment. In a study I made several years ago (Bülow-Hübe, 1995), 95 persons assessed the indoor environment and daylight in two laboratory rooms furnished as either offices or bedrooms. The only difference between the rooms was the glazing of the window: one room had triple-clear glazing, while the other had quadruple glazing with two low-e coatings. The room with this darker glazing was perceived as more enclosed, and the daylight as darker and more tinted. The effect was attributed to the coatings, and not to the extra clear pane, and resulted in a favour of green light transmission while red light was filtered out. With modern solar control glazing this filtering effect of daylight may be even more pronounced, see Figure 2.2. In these figures single clear and triple clear glazing is compared to double and triple glazing (green curves) with one and two silver-based soft low-e coatings respectively (red curves). The latter alternatives are common in many window types for the residential market. The first one for more standard windows, while the second alternative (with two low-e coatings) is common in windows for so called passive houses, with U-values for the glazed part of 0,6-0,7 W/m^2K (around 0,9 W/m^2K for the whole window). The two blue curves represent modern advanced solar-control coatings of two distinctly different light and solar transmittances, 66 and 50 % light transmittance in a double-glazed window with one clear pane. The region for melatonin suppression is marked out. The transmittance curves for the solar control glazing have a pronounced peak in the middle of the visual spectrum, favouring transmittance of green light. The transmittance curves of the clear glazing have a much flatter shape. This explains why solar control glazing often appears greenish in colour.



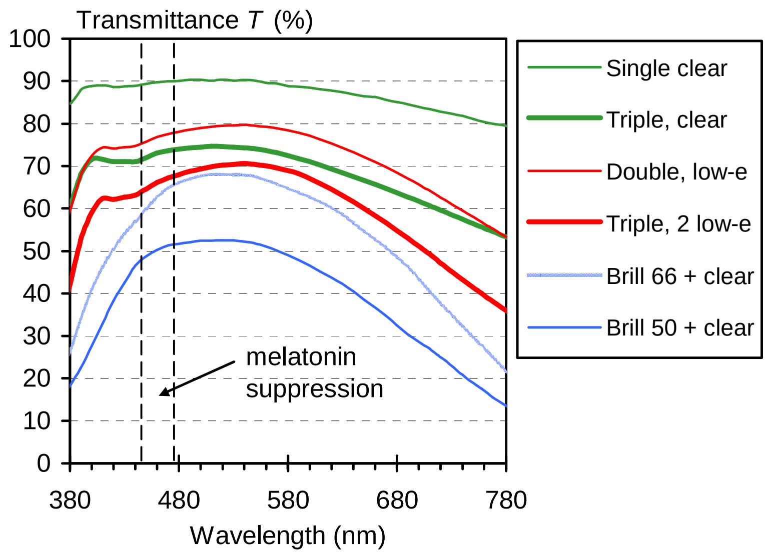


Figure 2.2 *Spectral transmittance for some common glazing systems for the solar spectrum (above) and visual spectrum (below). Single and triple clear glazing. Low-e glazing of two types: (clear + low-e) and (low-e + clear+ low-e). Solar control glazing of two types: (HP Brilliant 66 + clear) and (HP Brilliant 50 + clear).*

3 Aim

The main aim of this study is to investigate the effect of daylight availability and visual comfort when the glass area is increased from a rather moderate window size, via a highly glazed, to a fully glazed façade. Another aim is to estimate potential savings on lighting electricity. A common view among designers and consultants is that an increased glass area will lead to more and perhaps better daylight and also to decreased use of electrical lighting and thus in some way represents an ecological design idea. However, the effect on glare must not be forgotten, and the hypothesis is that increased glass areas lead to more difficult lighting conditions which must be controlled by proper shading devices.

4 Method

A single-person office room has been studied for 3 various glass areas of the façade: 30, 60 and 100 %. First, a comparison of the daylight distribution for sunny conditions was made, both with and without those shading devices that where suggested by the architect in the Glazed Office Buildings project. This was done for three days during the year (summer and winter solstice and equinox). For each day, three times during the day was studied: 9, 12 and 15 hours for summer solstice and equinox and 10, 12 and 14 hours for winter solstice due to the shorter day. Overcast conditions were studied at equinox only.

For the case 30% (the smallest glass area), a special study was made on the effect of slat angle for an ordinary window blind on the window luminance. Further, an alternative "daylight" venetian blind was studied, which is a blind that is more open at the top than at the bottom.

For the two largest glass areas where the initial design was not considered satisfactory concerning luminance reduction on the window, some alternative designs have been investigated.

While most studies were performed for a singe-person office room of about 9 m², some cases with an open-plan space were also studied. The aim was to study the impact of the absence of dividing walls. Without walls, the visual comfort may become worse, since potentially more glare sources are available.

The tools used have been the lighting simulation software Rayfront for PC environments, and Daysim which runs independent of platform using Java scripts. Both programs are based on an underlying light simulation "engine" called Radiance, which has been called the most reliable software available for accurate daylight prediction (Ward and Shakespeare, 1998) and http://radsite.lbl.gov/. Radiance builds on back-ward ray-tracing; it traces light rays from the observer's eye into the environment and finally to the light source(s). Rayfront is a user friendly menu shell which allows the user to access the Radiance program in the Windows environment and is described further on www.schorsch.com. Daysim extends the normal single-picture simulation to annual estimations of daylight by a smart algorithm, but the underlying light simulation is still performed in Radiance, see further in Chapter 4.6.1. The work behind Daysim is described in a thesis by

Reinhart (2001). The program itself is freely available via http://irc.nrc-cnrc.gc.ca/ie/lighting/daylight/daysim_e.html.

The basic assumptions regarding room sizes, window design and glass types were the same as in the study by Poirazis (2005). The most important design assumptions are described in Sec 4.2 and summarized in Table 4.1.

4.1 Limitations of the study

Despite the powerful tools used in this study, the true nature of daylight is still hard to study theoretically. It is highly variable, from season to season and from second to second. Further, daylight cannot be stored. With most methods available today, simulations can only capture some ideal, momentary weather conditions if they should be performed as high quality renderings without using too much computer time.

The impression of being in a full-size room is also hard to capture in numbers and images. One particular problem is the great difference in experiencing various bright and dark surfaces in real life and in photographs. Where the eye has no problem to see both out through a window and seeing the whole interior as well, a photographer must choose whether to expose the picture for the interior or for the exterior. The difference between different media also vary: Film can capture a wider range of luminances compared to video. In film language this range is called the latitude. Digital video has higher latitude than analogue video, but still not the same as film. With digital images taken by calibrated cameras or from simulations, where the luminance is known in every pixel, this can partly be overcome by using human sensitivity filters as the pcond function in Radiance. This has been used throughout this study, but it is still not exactly the same as being in the environment yourself. Another alternative that exist for digital photography is to merge several photos taken of the same scene with different exposures, see for example (Ward Larsson & Shakespeare, 1998) and the features in Wards software program Photosphere.

Computer screens also vary in the maximum luminance that they can display. Although modern screens seem to have a higher brightness than those a few years ago, it is still very low compared to levels experienced outdoors: A computer screen usually has a luminance of slightly over 100 cd/m² (modern ones up to 400 cd/m²), while the sky luminance can go up to over 100.000 cd/m² close to the sun. Therefore, it is never possible to recreate the glare sensation of a real scene as by looking at an image of it on the screen: white or bright surfaces can only be as bright as the capacity of the screen. The situation is similar for printed pictures, although they actually reflect all incoming light; the brightness thus depends on the illuminance on the picture surface.

The perhaps most difficult issue to answer is when do people in a lit environment find it comfortable? This was discussed in the background chapter. Since we still do not exactly know how to evaluate visual comfort, the study is limited to an estimation of physical, quantitative measures of the environment such as illuminance and luminance, and lighting electricity use. Qualitative factors are not evaluated.

4.2 Room description – cell-type office

The building is assumed to have a story height of 3.5 m with a slab thickness of 300 mm, thus the room height can be 3.2 m at the maximum. The window-to-wall area ratios (WWAR) studied were 30 %, 60 % and 100 %[1]. From here on the case names will be called 30%, 60% and 100% respectively, sometimes with the addition WWAR. The window area ratio was defined as the ratio between the window area and the façade area as seen from the outside, i.e. the story height times the width of an office module (centre to centre), which was 2.4 m. For the cases 30% and 60%, a drop-ceiling was placed at a level of 2.7 m above the floor. In the 100% case there was no drop-ceiling at all, i.e. the room height was 3.2 m.

For the case WWAR 30%, an ordinary 25 mm white venetian blind was used as shading device between two panes of glass in a coupled window (Reflectance, R = 76 %, specularity 0.05). For the two larger areas (60 and 100%), 300 mm grey horizontal fixed external louvers at a vertical spacing of 300 mm were used as shading device (R = 63 %, specularity 0.22). No louvres were placed in front of the view window; instead a 600 mm wide louvre was placed directly above the window, as designed by the architect. A frontal view of the three glass areas can be seen in Figure 4.1.

In the 30% case the window is assumed to be triple glazed in a 1+2 type construction. The blind is placed between the outermost single glass layer and the internal double glazing unit. This construction was very common during the 1990's. All three glass layers are assumed to be clear, which gives a visual transmittance of approx 74 %. This case is equivalent to the reference case in the work by Poirazis (2005).

In the cases 60 and 100%, the glazing is assumed to be a sealed double-glazed unit with a rather clear solar control glass in the outermost layer (type Pilkington Brilliant 66/33 or equivalent), and a clear glazing

[1] The case 100 % was defined in the work of Harris. The façade part covering the slab front was not assumed to be glazed, therefore 91% glazed is actually a more correct name.

as the inner pane. This glazing is equivalent to the building alternative 3 in the work of Poirazis. The visual transmittance of the glazing is thus assumed to be 66 % for the glazing. The data for the glazing system is summarized in Table 4.1.

30 % White blinds — 60 % — 100 % Aluminium louvres

Figure 4.1 *External view of the studied office room for the cases WWAR 30, 60 and 100% respectively (middle two windows).*

Table 4.1 *Data about studied window alternatives and shading devices.*

	WWAR 30%	WWAR 60%	WWAR 100%
Glazing type	Triple, clear (1+2)	Double, solar control + clear	
Shading device, width/spacing	Intermediate white blinds, 25/21 mm	Fixed external louvers. 300/300 mm	
Window area, A_w (m²)	2.60	5.04	7.68
Glass area, A_g (m²)	1.76 (100 %)	3.60 (205 %)	5.36 (305 %)
Light transmittance, LT (%)	73	66	66
Relative transmittance, A_g*LT	1.28 (100 %)	2.38 (186 %)	3.54 (277 %)

The room was sparsely furnished with what was thought as the most important visual elements that interact with the daylight in the room: an office desk was put in a 90 degree corner setup and three simple bookshelves were placed on the side wall. Further, a flat computer screen was modelled with a luminance of approx. 100 cd/m². This means that the screen was actually modelled as a light source which helps the reader to interpret the rendered images because it gives a comparison between the brightness of the screen and the surrounding surfaces. If the screen appears black it will be difficult to read on the screen. When it appears light grey, the luminance in the room is lower, and close to that of the screen. An interior view of the room is seen in Figure 4.2.

The room surface reflectances selected where: $R_{ceiling}$ = 85 %; R_{walls} = 65 %; R_{floor} = 35 %, $R_{furniture}$ = 50 %. This follows the recommendations for office environments established by NUTEK (1994).

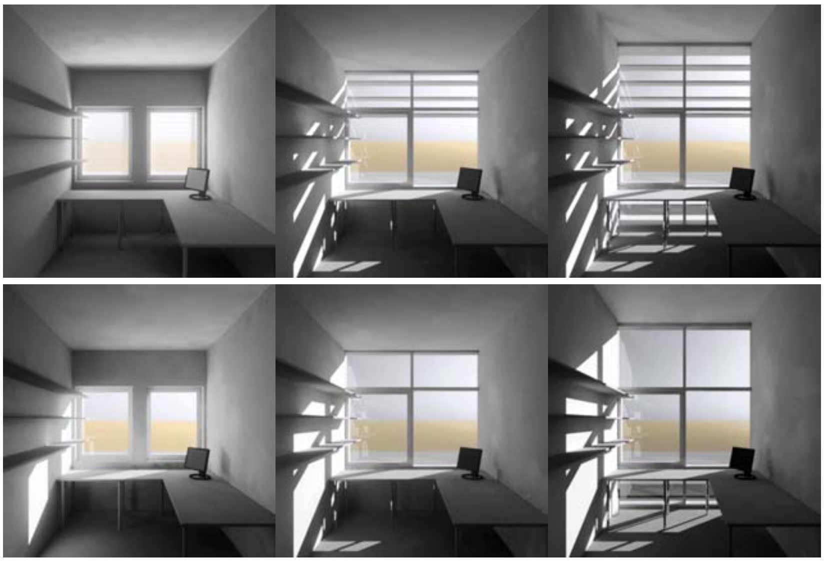


Figure 4.2 Interior view of cases WWAR 30, 60 and 100% with and without shading devices respectively, seen from back wall. March 21st at 15.00.

A view from the top shows the furniture in the room, and the selected position for the observer, see Figure 4.3.

Figure 4.3 *Plan of the room indicating view point and view direction of the observer, and an example of a rendered image (right).*

4.3 Open plan space

An open landscape was created by looking at a space that was 4 cellular office modules wide and one module deep, plus the corridor. The size of the room was thus approx 9.6 x 5.9 m. A view from the top of the room indicates two possible seating positions which were studied, see Figure 4.4. The room was furnished with tables, cabinets and flat computer screens to allow for 8 persons to work in this space. The main office desk in the cell-type office was thus kept the same, while the smaller table was omitted and rather low cabinets were used to replace the bookshelves. The glass façade and the surface reflectances were kept the same as in the cell-type office.

Figure 4.4 *Top view indicating the 2 seating positions studied (1, 2) and the perspective from the back (3).*

4.3 Selection of slat angles for blinds

In order to avoid glare, a first criterion is that direct sunlight should be avoided on the work plane. In cases where venetian blinds are used, these must be tilted so that direct sunlight cannot penetrate the blind. The slat angle when this happens is usually called the cut-off angle. Since blinds are usually operated throughout the day, week or year, either manually or automatically, various slat angles where simulated for the case WWAR 30% at the different times of the year. The goal was to ensure that direct sunlight was always avoided, i.e. that at least the cut-off angle was reached, see Figure 4.5.

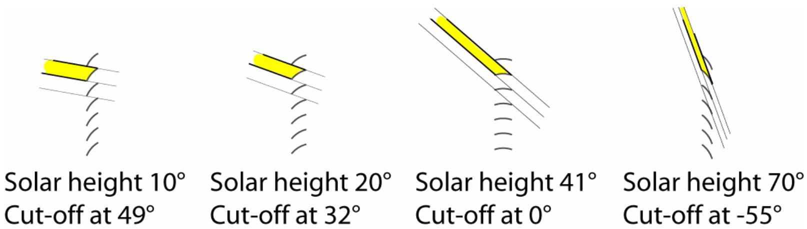


Figure 4.5 *The cut-off angle of the blind is the angle where direct-sunlight penetration is just avoided.*

The cut-off angle for every hour of the day can be calculated quite easily when the concept of effective or projected solar height is introduced. The effective solar height is the solar height projected onto a plane perpendicular to the window plane. To do this, both the solar height and the azimuth angle must be known, see Figure 4.6. During half of the year, from March 21st to September 21st, the effective solar height is lowest at noon and higher in the morning and afternoon for a south-facing window. At equinox, the effective solar height is equal all day. The solar heights for Gothenburg (Lat. 57.7 °N, Long. 12.01 E), where the building was assumed to be located, can be seen in Figure 4.7.

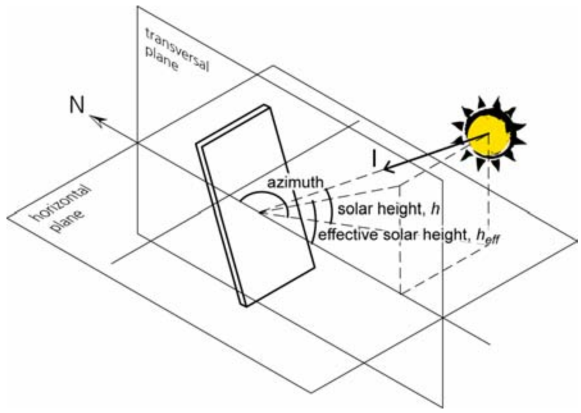


Figure 4.6 *The solar height (h) and the azimuth angle is needed to calculate the effective solar height (h_{eff}). (Original illustration by Andreas Fieber).*

For a blind which is assumed to have 25 mm wide flat slats (which is and adequate approximation of most blinds), at a common vertical spacing of 21.5 mm, the relationship between the cut-off angle and the projected solar height is shown in Figure 4.8.

The cut-off angles for Gothenburg for various dates and times of the year were calculated. The definition of the cut-off angle allows negative slat angles to be selected in June, see Table 4.2. However, it is not recommended to tilt the blinds this way, since it allows for a view of the bright sky which can lead to glare. Therefore, a second criterion of at least 0 degrees should be used. In the simulations for WWAR 30% with blinds the following slat angles where primarily selected: For summer solstice a slat angle of 0° was chosen, for equinox 30°, and for winter solstice 60 degrees. A special parametric study was also performed on both various slat angles and on an alternative daylight redirection venetian blind where the slats of the upper part of the blind are kept more open.

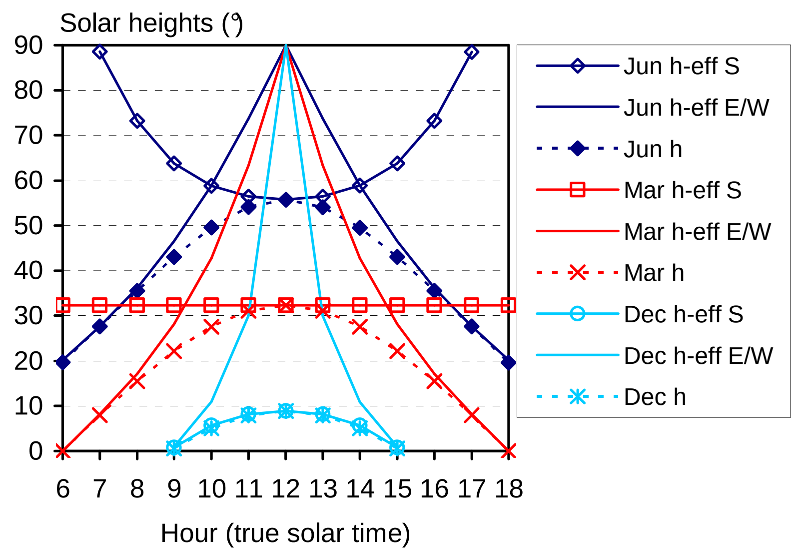


Figure 4.7 *The solar heights h (dotted lines) and effective solar heights h_{eff} (solid lines) for a south (S) facing window and an east and west facing window (E/W) respectively in Gothenburg (Lat. 57.7°N) at the summer and winter solstices and at the equinoxes.*

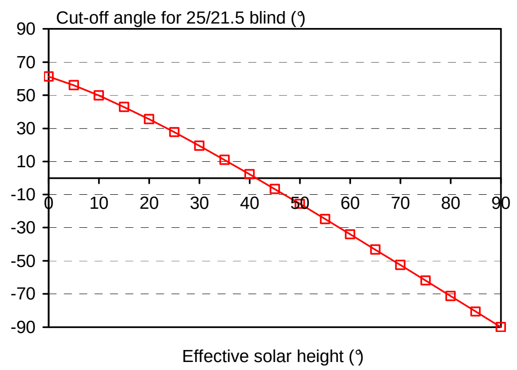


Figure 4.8 *The cut-off angle for a standard 25 mm blind for a south facing window as a function of the effective solar height. (Calculation by Bengt Hellström)*

Table 4.2 *Azimuth angle, solar height, effective solar height, and cut-off angle for blinds 25/21.5 for a south orientated window in Gothenburg. Hours and slat angles used in the study are also shown.*

True solar time	*Azimuth* [°]	*Solar height, h* [°]	*Effective solar height,* h_{eff} [°]	*Cut-off angle* [°]	*Selected hour and slat angle* [°]
21 June					
8	–77.6	35.5	73.3	~–58	
9	–62.7	43.0	63.8	~–41	0
10	–45.1	49.5	58.9	~–32	
12	0.0	55.7	55.7	~–27	0
14	44.8	49.6	58.9	~–32	
15	62.5	43.1	63.8	~–41	0
16	77.5	35.6	73.1	~–58	
21 March					
8	–64.0	15.5	32.3	~16	
9	–49.8	22.2	32.3	~16	30
10	–34.3	27.5	32.3	~16	
12	0.0	32.3	32.3	~16	30
14	34.3	27.5	32.3	~16	
15	49.8	22.2	32.3	~16	30
16	64.0	15.5	32.3	~16	
21 Dec					
9	–40.4	0.6	0.8	~60	
10	–27.4	5.1	5.7	~55	60
12	0.0	8.9	8.9	~51	60
14	27.4	5.1	5.7	~55	60
15	40.5	0.6	0.8	~60	

4.4 Luminance and illuminance simulations

The luminance distribution was simulated by generating rendered images using Radiance via the Rayfront 1.0.4 interface. Sunny conditions (CIE clear sky with sun) were studied for three different days of the year: 21st of June, March and December because these represent the extremes and the midpoint of the year regarding solar heights. Three different hours were studied for each day: 9, 12 and 15 o'clock (winter time), but for December, the hours 10 and 14 were chosen instead, since the high latitude gives very little light for hours 9 and 15 in December, see Table 4.2. Overcast conditions (CIE overcast sky) were simulated in order to calculate the daylight factor. The daylight factor is the ratio of the interior illuminance to the outdoor illuminance from an unobstructed sky. Originally, the daylight factor was only defined for the CIE standard overcast sky condition. This sky is rotationally symmetric which makes the daylight factor independent of orientation and time of year. Therefore, the overcast condition was only simulated for March at 12 o'clock, since the only difference for various overcast hours is the absolute light level. For simplicity, daylight savings time was not simulated. The room was only illuminated with daylight, no electric lighting was included.

Images were generated from the position of an observer sitting down (eye height 1.2 m) at 1 m from the façade wall and 1.05 m from the side wall, and with a view direction facing slightly outwards, towards the corner of the room, see Figure 4.3. The pcond function in Radiance was applied on all rendered images. This is a filter that is used to generate a picture that presents the view according to how the eye would perceive the scene, a kind of human sensitivity filter. This function makes it possible to see for example the view through a window when it would appear white (overexposed) on a normal photograph. Further, false colour images were also generated to display a numeric representation of the luminance in the scene. This is a colour picture where the luminance in each pixel is represented by its colour. The unit is nits or cd/m². The risk of glare can to some extent be interpreted from these pictures. In some cases iso-contour pictures were also generated, where the coloured lines with equal luminance are created.

The images where generated using the following rather high quality settings in Rayfront: Quality=high, Detail=medium, Variability=high, Indirect=medium, Penumbras=false and –ab 8. Depending on which scene that was rendered, an image took between 6 – 24 hrs to calculate.

The numeric calculation of illuminance distribution in the room was done using the same quality parameters in Rayfront as for the renderings. All illuminance values in this report are calculated for points on a plane 0.8 m above the floor.

4.5 Evaluation of glare

The guideline by NUTEK for Swedish energy-efficient offices (1994) say that the maximum allowed luminance is 1000 cd/m² within the field of view and 2000 cd/m² outside the field of view. The guideline was made to promote energy-efficient lighting, and this value is probably taken to ensure that the lighting installation does not create glare in the room. If these values should apply also to the window surface is not actually stated, but if so, it is a very strict criteria. The luminance of the sky can vary between say 5.000 cd/m² on a cloudy day to more than 100.000 cd/m² around the sun on a sunny day. Thus, a window and a shading system with a variable transmittance down to a few percent is needed in order to always comply with the luminance criterion.

In order to be able to estimate if the luminance of the window surface would create glare, false colour images were created where the scale had a maximum value of 2000 cd/m². Anything that is red in these images thus has a luminance above 2000 cd/m², and can potentially create glare. Although this is a bit simplistic, not taking into account how far from the visual task that the glare source is positioned, it still gives and indication for glare risks. In some pictures the scale was set to either 5000 or 10.000 cd/m², in order to see how much higher the luminance of the window was.

4.6 Daylight autonomy and electric lighting use

A program called Daysim was used to calculate the daylight factor, daylight autonomy and the use of electric lighting (Reinhart, 2005). The features of Daysim are described briefly in the following section.

4.6.1 Short description of Daysim

The possibilities and strengths of Daysim is that it links a detailed simulation of light distribution performed in Radiance with a yearly calculation of interior daylight levels. Finally, it can calculate the annual use of lighting electricity for various lighting control strategies.

The time-consuming part of the calculation is to establish a set of daylight coefficients for selected measurement points in the room using Radiance. The simulation time strongly depends on the quality of the simulation, but can be substantial for high quality simulations. Once the daylight coefficients are established, the annual illuminance profile is calculated. This is simply the illuminance in user selected measurement points in the room for every time-step of the climate file covering a whole year. (The calculation is based on a special climate file, starting typically with a standard climate file with one-hour time steps, which is synthetically broken down to shorter time steps, e.g. 5-minute steps). This annual illumination profile is then used to calculate the daylight autonomy for the year, which is the fraction of the working time where daylight alone can provide all the necessary lighting. The approach to this is rather simple: If the daylight level for a certain time step is above a desired light level (say 500 lux) on the work task sensors, then daylight is assumed to be satisfactory, and can alone provide the lighting.

When daylight fails to provide the lighting, electric lighting can be used to top-up to the desired light level. Thus, a third calculation step is also performed in Daysim: The use of electricity for artificial lighting. An annual occupancy profile is established and used together with the annual illuminance profile. This is combined with a behaviour model to calculate lighting electricity use for various light strategies. Six various light control strategies can be simulated in Daysim.

Research behind the development of Daysim has identified two types of users: active and passive (Reinhart, 2004). Active users are more opt to turning the lights on and off during the day in relation to ambient daylight conditions, while passive users are assumed to turn on the light upon arrival in the morning, and turn it off when leaving the office in the evening. The behavioural models implemented in Daysim are these two, as well as an even mix of the two types (called 'mix of both'). Thus, as many as 18 results may be obtained when combining the 6 light strategies with the 3 user types, although for some cases, the behaviour model does not influence the final result. For further reading about Daysim, see the tutorial (Reinhart, 2005).

4.6.2 Assumptions for Daysim calculations

In the calculations of electricity use for lighting four light control strategies were studied: Manual on/off switch near the door, Switch on/off occupancy sensor, Photo-sensor controlled dimming system and a combination on/off occupancy & dimming system. For all cases the behaviour model was "mix of both" which is a mean value of active and passive users.

In all cases, the basic assumptions were that the office is occupied between 8-17 and that the user leaves the office for lunch and for two intermediate breaks. These breaks are randomly put (i.e. at different times on different days). Daylight savings time is used.

Manual light switching builds on the assumption that the user leaves and returns to the work place a certain number of times per day as just described, and each time he/she returns, makes a choice whether the lights should be switched on or not (if he is an active light user). The choice is based on the ambient daylight level upon return.

The switch on/off occupancy sensor assumes that the lights are controlled both on and off by a presence detector. Lights are turned off when the office is empty after a specified time delay (5 minutes in this study).

The photo-sensor controlled dimming system dims the electric light to the desired light level (here 500 lux) taking the available daylight into account. However, the power reduction is less than the light reduction for normal light systems, which depend on the fact that the light source is less effective when dimmed. Assuming a fluorescent light system, the so-called ballast loss factor was set to 24 %, which means that the power when fully dimmed is 24 % of the installed power. A modern luminaire would usually turn off the light completely after some time of being fully dimmed, but this is not possible to simulate in Daysim. However, with an active user, the lights may be switched off during the day.

Therefore, the electric lighting use for this case may be slightly overestimated.

The combined on/off occupancy & dimming system assumes both a presence and a daylight sensor. Thus, the lighting use can be lower than for the previous case, since the lights are turned off when the room is empty.

The daylight factor in this study is calculated in two different ways; first using the CIE overcast sky model in Rayfront and secondly using the Perez sky model in Daysim. The results will differ slightly because of the two slightly different light distributions: In the CIE overcast sky model, the sky is completely overcast and three times brighter at the zenith than at the horizon. The Perez sky model has three components: a uniform sky, the sun and an area around the sun which is brighter than the surrounding sky. The light distribution for a real sky varies constantly between different extremes like the CIE clear sky and the CIE overcast sky, depending on weather conditions, especially cloud cover. The Perez sky model is attractive to model since it facilitates the calculation of light distribution for a whole year, for both sunny and cloudy conditions. It can easily be linked to actual weather data from a climate file with direct and diffuse components, and this is the feature that Daysim is built on.

In this study, a synthetic climate file with hourly values for Landvetter, Gothenburg, generated by Meteonorm, was used to generate a Daysim climate file with 5 minute time-steps. The work task was defined by 6 sensor points placed in a 3*2 grid, 1.0 and 1.5 m behind the window, and 0.8 metres above the floor. The estimation of electric lighting use is thus based on the illuminance level rather close to the window, at least for the cellular offices. Further, the daylight factor and daylight autonomy was calculated for points along the centre-line of the room, also at 0.8 m. See Figure 4.9.

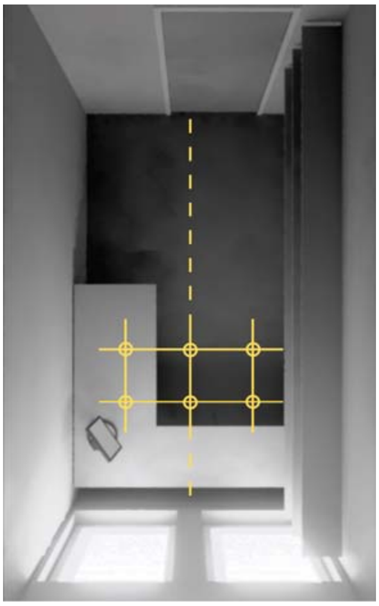


Figure 4.9 *Plan of the room indicating sensor points that were used to estimate electric lighting energy savings and the line (dotted) for which the illuminance, daylight factor and daylight autonomy is calculated. All points are placed 0.8 metres above floor level.*

4.7 Reference case with daylight re-directing blinds

Traditional blinds can be replaced with a daylight re-directing blind of a simple construction where two different slat angles are used and manoeuvred together: one more open at the top and one more closed at the bottom. This can easily be achieved by shortening the inner strings of the “ladder” that hold the slats in place, see Figure 4.10. The benefit of such a blind is that the blind will allow more daylight to penetrate, since it is more open at the top than a traditional blind, hopefully without creating more glare.

Figure 4.10 *A daylight re-directing blind can be made with a simple clip that shortens the inner string of the blind ladder. Here, a difference in slat angles of approx 45 degrees is achieved. (Photo: Thore Sonesson).*

The division line between the two parts should not be too low so that disturbing glare is introduced in the upper part of the field of view. If the cut-off angle should be reached at all times of the year, the difference in slat angle should not be too great. Further, a small difference in slat angles does not disturb the degree of freedom of movement as much as a larger difference in slat angle does. (Bülow-Hübe, 2007).

An automated blind with a control system that seeks to position the blind according to the cut-off angle might create to much glare in the summertime. In this case, the cut-off angle could be defined as that for the upper part of the blind instead of the lower part. This would then automatically lead to that the bottom part is more closed, and therefore darker and less disturbing for the observer.

To study the potential benefit of such a blind, the effect on the illuminance for some possible slat angle differences and positions of the break-point was made for the reference case 30%. In this case, the upper part of the window is at 2.1 m above floor, thus the glass area reaches up to approx 2.0 m. The break-point was therefore put both at 1.8 and 1.6 m above the floor. The upper part will thus represent an area of approx. 20 % and 40 % respectively. The division line at 1.6 m might be a bit low, since eye level is approx at 1.2 m for a seated person. Two different slat angle differences where studied: 20 and 45 degrees, Since the slat angle 0° might create too much glare, a conservative slat angle of 60 degrees for the bottom part was studied. The top part was thus studied at 40° and 15° respectively, see Figure 4.11. For June 21st, this means that the cut-off angle is reached in all parts of the blind. The blind was modelled with the same white colour as before.

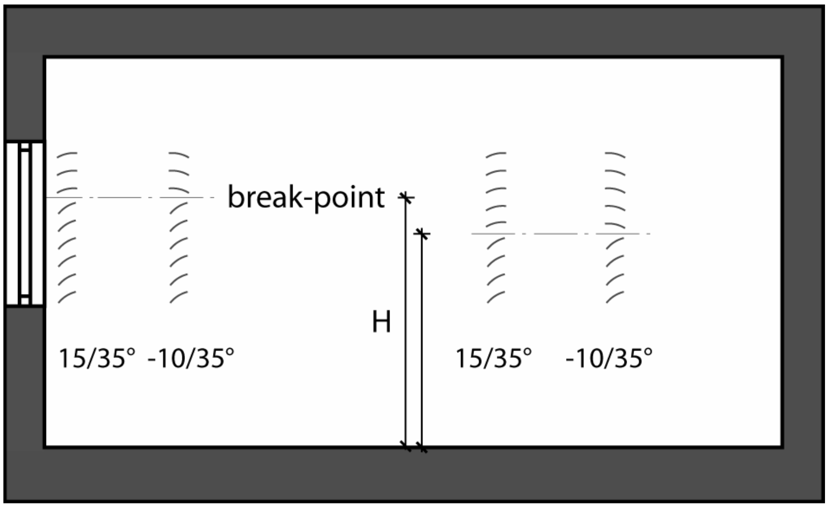


Figure 4.11 *The height (H) of the break-point between the upper and lower part of the daylight re-directing blind can influence the risk of glare. The slat angles used for the upper and lower parts are also shown.*

4.8 Parametric studies for case 60% and 100%

Some parametric studies were performed for the cases with 60 % and 100 % window area. First some alternative shading systems were studied, then a different orientation.

4.8.1 Alternative shading devices

Some alternative shading devices where also studied since the luminance of the window was considered too high with the selected louvre system. It also permitted direct sunlight to penetrate during the winter season.

First, a translucent curtain was added on the inside of the window from the top of the view window at approx 2.1 metre down to desk level, leaving the upper part of the window without curtain (and the lowest part for case 100%). Second, an exterior daylight re-directing venetian blind was investigated with slats at 45° at the bottom part and

15° for the top part. The break-point between the two slats angles was also put at 2.1 meters above floor, i.e. just above the view window. The transmittance of the translucent curtain was selected to 22 % according to Dubois (2001a) who recommends a transmittance between 10 and 25 %. The exterior venetian blind was 80 mm wide with aluminium coloured slats (*R*=63 %), i.e. the same reflectance as for the louvre system.

4.8.2 Orientation towards west

If the office was to face other orientations than south, the effective solar angles towards the window plane will be different, and generally lower solar heights will be experienced. A louvre system will thus perform worse than towards the southerly orientation. This effect is not studied extensively in this report, but a few renderings are performed to show the resulting luminous environment for sunny conditions. The study is thus limited to the case 60% turned towards the west, and for the afternoon hours when the sun hits the façade.

5 Results

5.1 Cell-type office

5.1.1 Luminance distribution, observers field of view

The luminance for the selected observer's field of view for the cases 30%, 60% and 100% was calculated for sunny conditions both with and without shading devices. All rendered images of these simulations are found in Appendix 1. The results show that shading devices are absolutely necessary to reduce the luminance of the sky seen through the window. An example for the case 30% is displayed in Figure 5.1. Here the luminance of the window itself exceeds the recommended maximum value of 2000 cd/m² both without any blinds and with blinds at 0°, which is well above the cut-off angle at approx -30°. At a slat angle of 60° the window luminance is decreased below 2000 cd/m², but so is also the general light level in the room. This also results in the fact that the screen appears brighter, but this is only due to another exposure for this picture. In the simulation, the screen always glows with a luminance slightly higher than 100 cd/m². Therefore, pictures where the screen appears black can be interpreted as the view having to much contrast to be tolerable for working in.

For the highly glazed cases 60% and 100% with fixed louvres, direct sunlight can penetrate the façade at effective solar heights approx. below 42°, see examples in Figure 5.2. This corresponds to solar heights at noon at the end of August and in mid April. It would not be sufficient to tilt the slats much more, since this would only slightly extend the time during the year at which the cut-off angle is reached. This is due to the extremely low solar heights experienced in the winter season in Sweden. Here, the louvre system should be changed to a more suitable one, or an internal shading device should be added for glare protection. Some alternative solutions will be studied in Section 5.6.

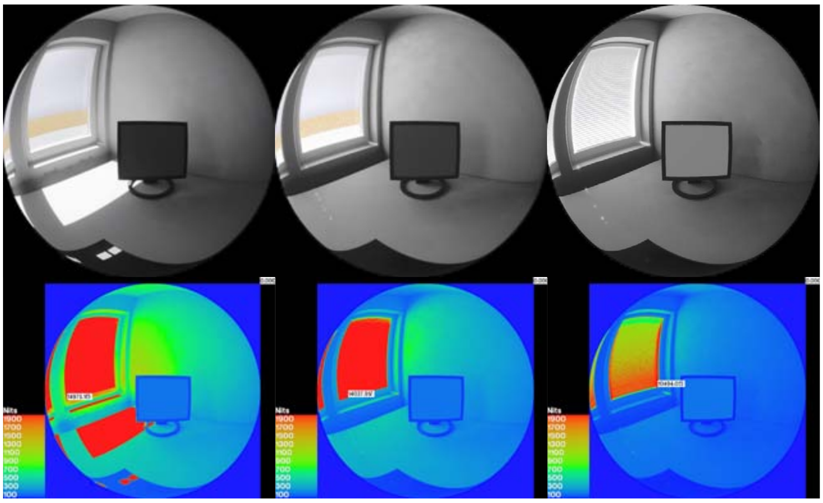


Figure 5.1 *Luminance distributions for the observer's field of view for WWAR 30% without blinds (left), with blinds 0° (middle) and blinds 60° (right) for June at 12.00 solar time. Filtered image above, false colour image below.*

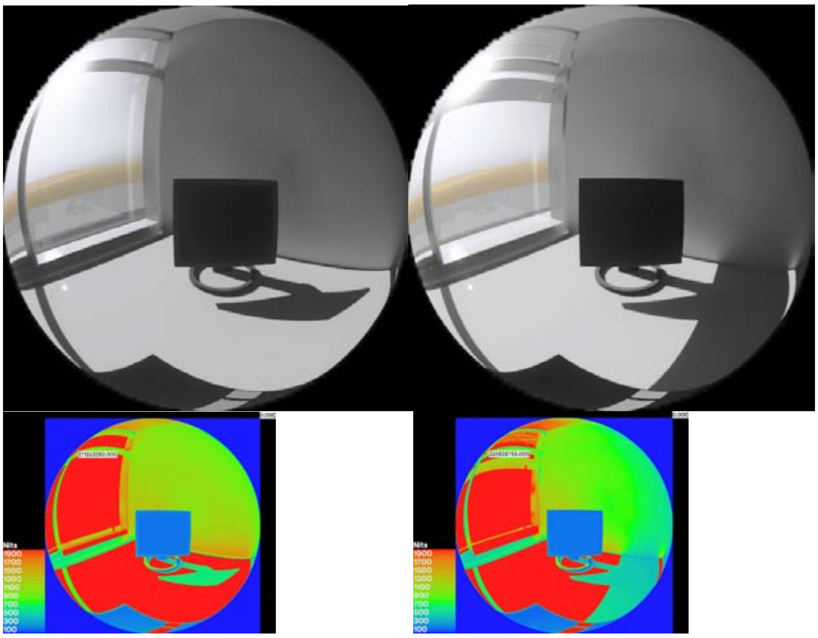


Figure 5.2 *Luminance distributions for the observer's field of view for WWAR 60% without and with louvres 0° for March at 12.00 solar time. Filtered image above, false colour image below.*

5.1.2 Effect of window size on illuminance

The illuminance at a plane 0.8 m above the floor was calculated for June 21st at 12.00 solar time. The results are displayed in Figure 5.3. The outdoor global illuminance at the same time was calculated to 72 klux. The illuminance in the sunpatch on the table is approximately the same for all cases (about 42 klux), but the size of the sunpatch increases with increased window area. The illuminance at the back of the room is about 550 lux for the 30% case, 1150 lux for the 60 % case and 1750 lux for 100% case without shading devices. All shading devices manage to eliminate the sunpatch for June 21st.

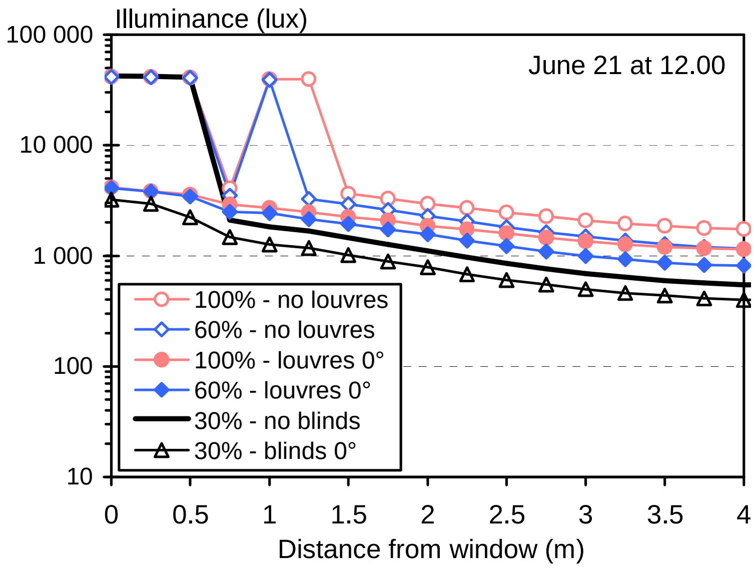


Figure 5.3 *Illuminance at summer solstice for all six cases. June 21st at 12.00 at 0.8 m above the floor and at the centre-line behind a window, 0.8 m from side wall. CIE Clear sky with sun. Note the logarithmic scale.*

If the illuminance values behind the sunpatch (at 2 m) are compared to the 30% reference case, it can be seen that horizontal blinds reduce the illuminance by about 30 %. The illuminance in the cases 60% and 100% with louvres, is about 40 % and 67% higher respectively, see Figure 5.4.

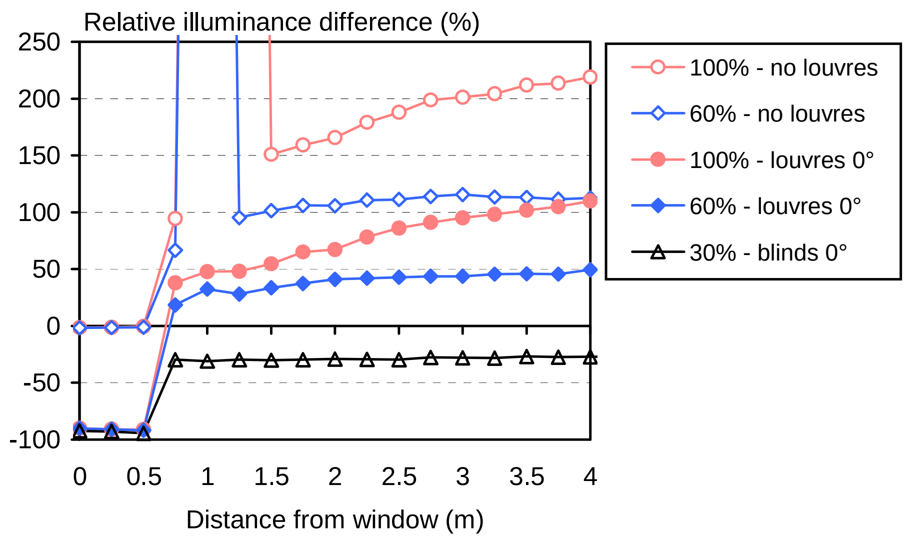


Figure 5.4 *Difference in illuminance level compared to the reference case WWAR 30%, at a line 0.8 m from side wall, June 21st at 12.00. CIE clear sky with sun.*

The illuminance was also calculated for Dec 21st at 12.00 solar time, Figure 5.5. The outdoor global illuminance was here calculated to only 7 klux. Since the solar height is very low, the back wall is strongly lit even with shading devices (expect for the case 30% with blinds 60°, just above the cut-off angle), and the back wall reflects light back down towards the measuring plane. This is why the illuminance is higher at the back-half of the room.

For the sunny condition at equinox the outdoor illuminance was calculated to 44 klux. The indoor illuminance is shown in Figure 5.6. The maximum illuminance in the sunpatch is about 30 klux. It is clear that the sunpatch reaches much further into the room when the window is larger and especially taller. With louvres, the average illuminance across the room in cases 60% and 100% is only 7-12 % higher than the reference case without blinds. Blinds at 30° reduce the average illuminance by over 80 %, and by almost 60 % at 2 m from the window.

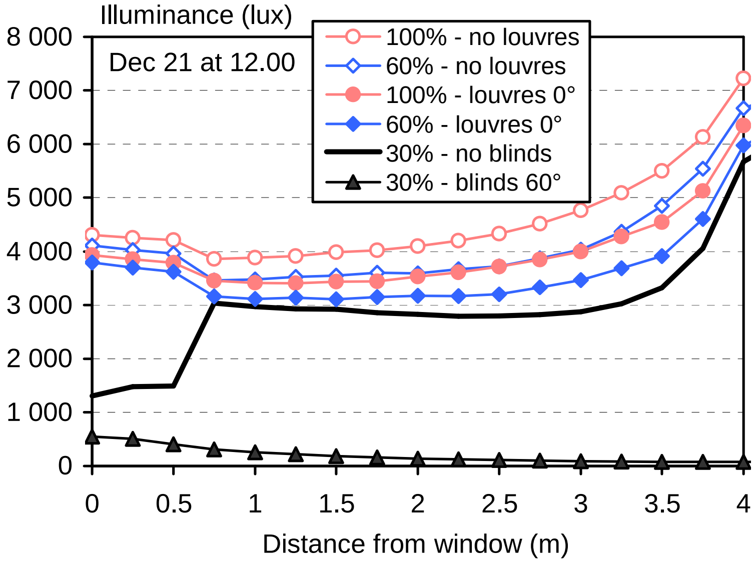


Figure 5.5 *Illuminance at winter solstice for all six cases. Dec 21st at 12.00 at 0.8 m from side wall. CIE clear sky with sun.*

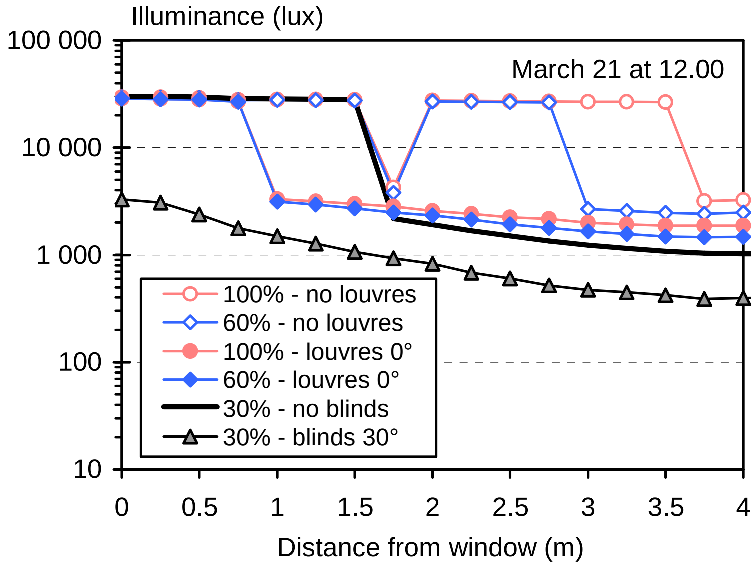


Figure 5.6 *Illuminance at equinox for all six cases. March 21st at 12.00 at 0.8 m from side wall. CIE clear sky with sun.*

The overcast condition was calculated for a CIE overcast sky in March, and corrected to correspond to a sky that gives a global outdoor illuminance of 10 klux. The results are shown in Figure 5.7. If divided by 100, the values can be interpreted as the daylight factor. One interesting result is that the average illuminance across the room is actually 3 % lower for the case 60% with louvres and only 7 % higher in the case 100% with louvres compared to the reference case 30% without blinds. This clearly shows the flexibility of a retractable shading system!

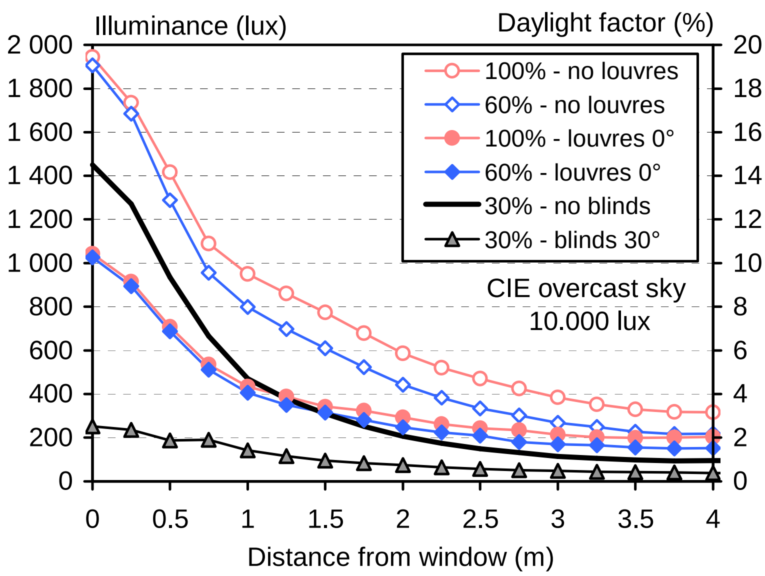


Figure 5.7 *Illuminance at equinox for all six cases for a CIE overcast sky of 10.000 lux. Centre-line behind window, 0.8 m from side wall.*

The relative difference in illuminance compared to the case 30% without blinds is shown in Figure 5.8. It can be interesting to compare the illuminance for the 60% and 100 % cases without shading to the relative transmittance of those systems as stated in Table 4.1. The glass area times the somewhat lower visual transmittance of theses systems where 186 % and 277 % higher than the 30% case. However, the illuminance is only up to at most 136 % and 240 % higher respectively. The larger glass areas are therefore not fully reflected by an equally higher illuminance. One reason is probably that the light which is transmitted through the glazed area below desk level mostly becomes absorbed by the floor and does not contribute much to the illuminance at desk level.

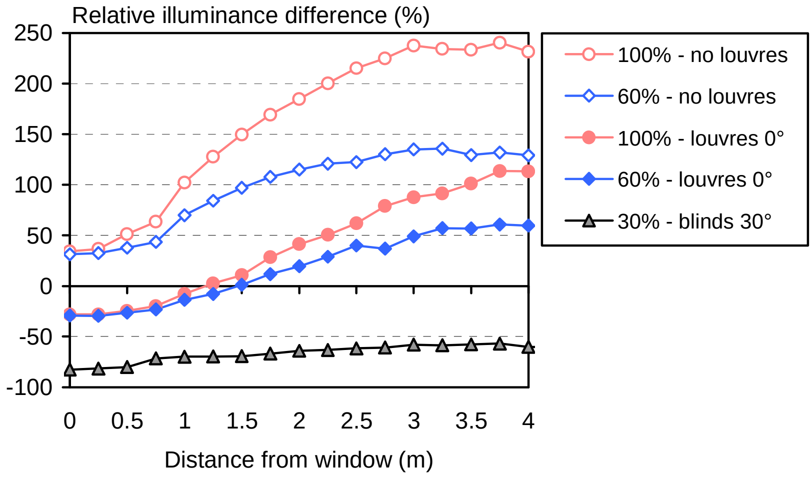


Figure 5.8 *Difference in illuminance level compared to the reference case WWAR 30%, at a line 0.8 m from side wall, CIE overcast sky.*

5.1.3 Daylight autonomy and electric lighting use

The daylight factor was calculated for the Perez all weather sky model in Daysim, and the results are displayed in Figure 5.9. The slightly different results compared to the curves in Figure 5.7 depend on the different sky models used to calculate the light distribution, see Section 4.6.

If no shading devices are used, the daylight factor is of course much higher for larger window areas, up to 15 % close to the window for case 100%. Blinds and louvers significantly reduce the daylight factor, especially close to the window. Interesting to note is that the daylight factor at 1,5 metres is approximately the same for 30% without blinds, as for both 60% and 100% with louvres. The resulting daylight autonomy (assuming fixed blinds and louvres) for a desired illuminance of 500 lux in the centre-line of the room is shown in Figure 5.10. Fixed shading devices mean that they are assumed to be on at all times. For the case 30% with blinds rather closed, this simulation thus underestimates the 'true' daylight autonomy since the users may open the blinds or retract them fully, depending on weather conditions.

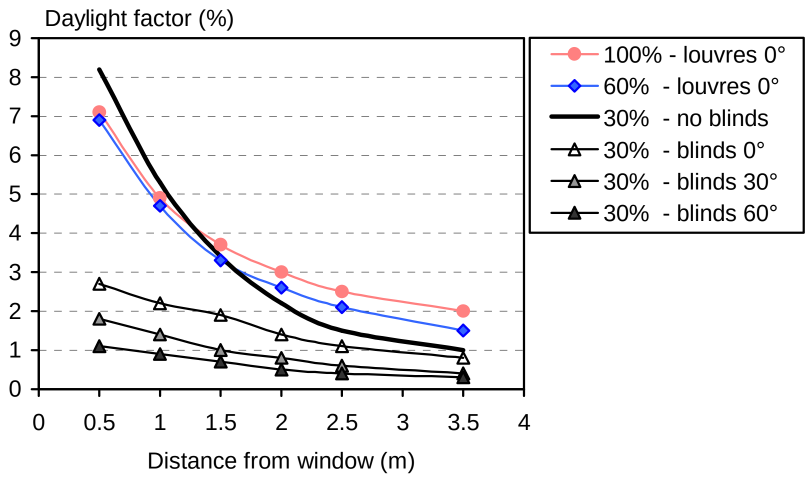


Figure 5.9 *Daylight factors calculated in Daysim using the Perez all weather sky model.*

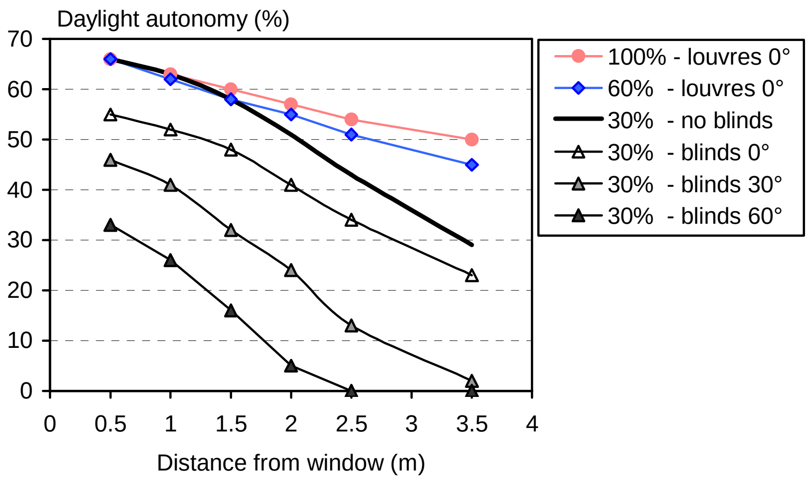


Figure 5.10 *Daylight autonomy (percent of working hours with >500 lux from daylight on work plane sensors) for Gothenburg, lat 57.7°N.*

The annual electric lighting energy use was also calculated. Assuming a light installation of 12 W/m², the use of electricity would amount to 28 kWh/m² and year if the lights are switched on 9 hours per day, 5 days per week. Assuming manual light switching, with a mix of active and passive users, the electricity use is between 20–23 kWh/m²a, see case

'Manual' in Figure 5.11. With installation of presence detectors (case 'Occup'), lighting electricity use is estimated to 23 kWh/m²a and equal for all glazing areas. This is because this control only acts on presence and the users are not assumed to interact with the lighting system in any other way. The presence is equal in all cases, and perhaps also estimated rather high: users only leave the office for lunch and two other short breaks. With a photo sensor controlled dimming system, and mixed users, lighting electricity use varies between 11 and 18 kWh/m²a, see case 'Photo' in Figure 5.11.

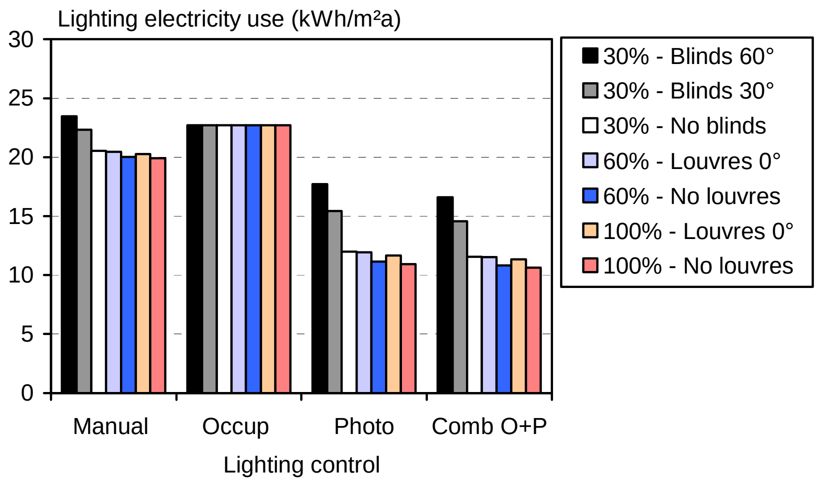


Figure 5.11 *Calculated lighting electricity use (kWh/m²a) for 4 light control strategies: Manual on/off, Switch on/off occupancy sensor, Photo-sensor controlled dimming system and Combined on/off occupancy and dimming system. Mix of active and passive users. Installed lighting power density 12 W/m², 500 lux.*

The last case, 'Comb O+P', represents a combined system with presence detectors and dimming system. There is no difference between different user types for this strategy. Here, lighting electricity use varies between 11 and 17 kWh/m²a. Interesting to note is that there is a surprisingly small difference between cases with and without louvres, and among case 30% without blinds, and cases 60% and 100%. This is due to the placement of the sensors, rather close to the window, where the daylight factor is similar for these 5 cases. However, the electricity use for fixed blinds at both 30° and 60° is significantly higher, see also Figure 5.12. Since users tend to change their blinds during the year, this is probably an overestimation of electricity use. Therefore, an estimation of electricity use with controlled blinds (not only controlled lighting) is introduced in a simple manner by mixing the results from these previous 4 cases, together with information about global solar irradiation. This was possible since Daysim also provides output with hourly values of electricity use. First, the case 'cut-off' is introduced, where the slat angle is assumed to be changed every month to correspond to the cut-off angle for solar radiation (i.e. direct solar transmittance is avoided) for that month. Then, a control strategy called sun-tracking is introduced. This represents a more advanced strategy where the blind is either on (down) or off (up) in every time-step depending on the global irradiation level for the time step. When the blind is down, the cut-off angle is used. The calculation was performed for two thresholds of outdoor global irradiation: 200 and 100 W/m² respectively. Over the year, the electricity use is then similar to the case with blinds at 0°, or about 12-13 kWh/m² which is then less than half of 28 which was the estimate for having the lights fully on during all working hours!

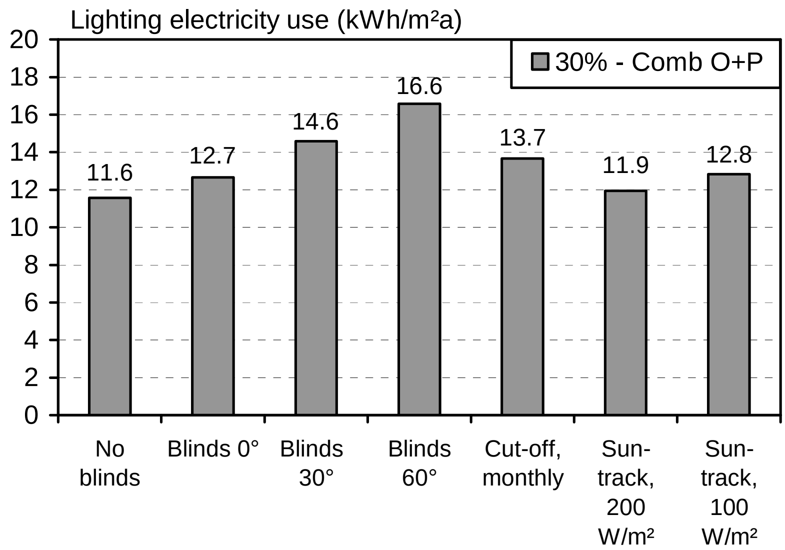


Figure 5.12 *Calculated lighting electricity use (kWh/m²a) for case 30% without shading and with fixed and controlled blinds. Cut-off is a fixed blind which is tilted monthly to its cut-off angle, while sun-tracking also pulls it up above a set value of the global irradiation. Combined on/off occupancy and dimming system.*

5.1.4 Effect of venetian blind slat angle

A special study was made for the case 30% with venetian blinds to study the relationship between slat angles and window luminance and room illuminance. This parametric study was performed for sunny conditions and for summer solstice only. The illuminance was calculated for various blind positions: at least every 15 degree between –45° to +75° was studied. As can be seen in Figure 5.13, the illuminance is always higher without blinds. At 2 m from the window, the illuminance varies between 1100 lux for no blinds to 130 lux for blinds 75°.

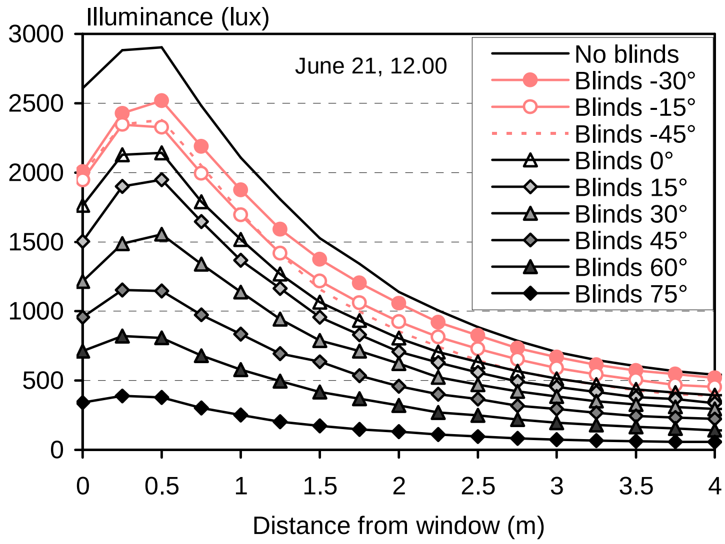


Figure 5.13 *Illuminance at summer solstice for the case WWAR 30% for various slat angles. Middle of the room. Note that this line lies in the shade, thus the illuminance is not displayed for the sunpatch.*

The illuminance in a certain point varies almost linearly with slat angle in the range between the cut-off angle -30° to fully closed at 75° (due to the strings holding the slats, the blinds cannot in practice be tilted more than 75-80°). A closer look at the resulting average illuminance in the room compared to the room with no blinds reveals that the visual transmittance of the blind system is almost linear for slat angles above cut-off, but a polynomial fit is even better, see Figure 5.14. Renderings for the observer's field of view are shown in Appendix 2.

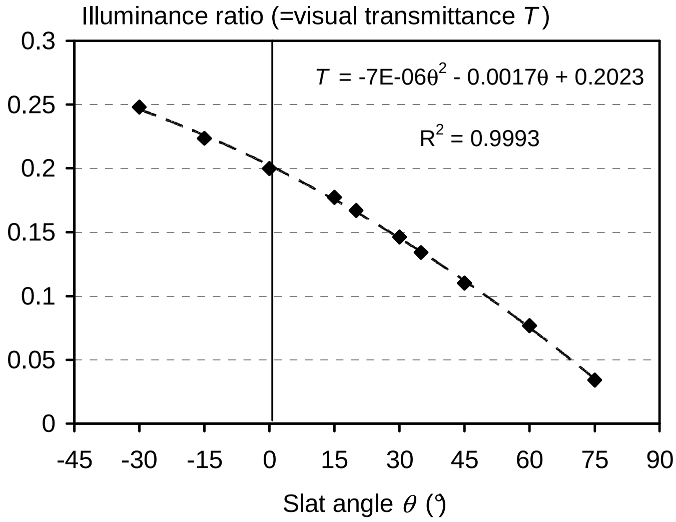


Figure 5.14 *Ratio between average illuminance for the room with and without blinds for various slat angles. Calculated for sunny conditions at summer solstice for the case WWAR 30%.*

5.1.5 Effect of daylight-redirecting blinds

The effect of introducing a so called daylight-redirecting blind was studied. A rendering from March is shown in Figure 5.15. The illuminance for the sunny summer case is shown in Figure 5.16, and the relative illuminance difference compared to blinds 60° is shown in Figure 5.17. As mentioned earlier a conservative slat angle of 60 degrees was studied for the bottom part of the blind. The top part was studied at 40° and 15° respectively and compared to the results of a traditional undivided blind. If the slat angle difference between the lower and upper part is too high, sunlight might penetrate the upper part of the blind at times when this is not wanted. A small difference may therefore be a better solution, especially for northern latitudes with low solar angles. However, less light will of course penetrate such a blind, and it is therefore less useful. This problem is discussed more deeply in (Bülow-Hübe, 2007).

The average illuminance in the room is only 8-17 % higher for re-directing blinds where the break-point is put at 1.8 m above the floor, and 20-43 % higher for re-directing blinds which open more above 1.6 m. For the summer case the slat angle difference is thus of less importance than the height at which the break-point is put. However, a simpler solution that in most cases will give just as much or more light is just to open the blinds 15 degrees more, see results for Blinds 45°.

The sunny winter case is shown in Figure 5.18. With blinds at 60° the illuminance 2 m from the window is about 140 lux. The effect of opening the blind with 20 degrees at the top only has a small effect. At two meters, the illuminance is about 15-25% higher or 20-40 lux more in absolute terms. The average illuminance in the room is increased by 15-30 %. For a larger slat angle difference (45°), more sunlight will penetrate the blind system and illuminate the back of the room. For the blind 15/60°_1.6 m, the illuminance is about 80 lux higher 2 m from the window, or 65 % more than the blind at 60° would give.

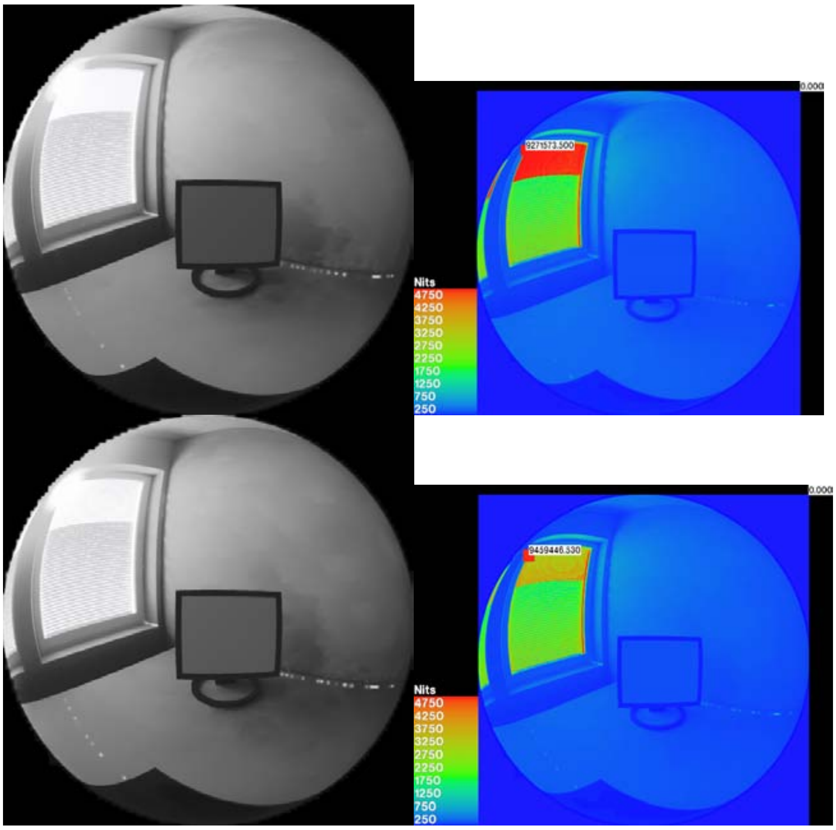


Figure 5.15 *Observer´s view for the case WWAR 30% with a re-directing blind 15/60°_1.6 m(top), 40/60°_1.6 m (bottom). 21 March at 12.*

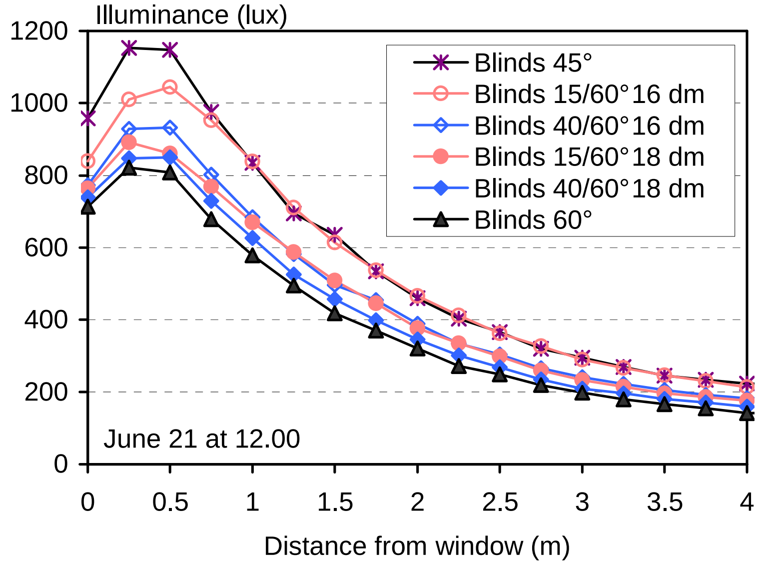


Figure 5.16 *Illuminance at summer solstice for the case WWAR 30% with regular blinds at 45° and 60° and 4 re-directing blinds. Centre-line in room, 0.8 m above floor.*

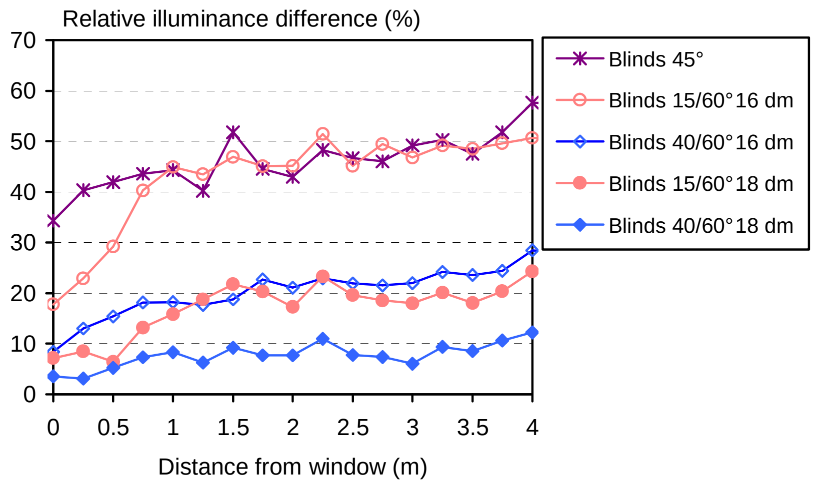


Figure 5.17 *Relative illuminance at summer solstice for the case WWAR 30% with one ordinary blind at 45° and 4 re-directing blinds compared to a regular blind at 60°. Centre-line in room, 0.8 m above floor.*

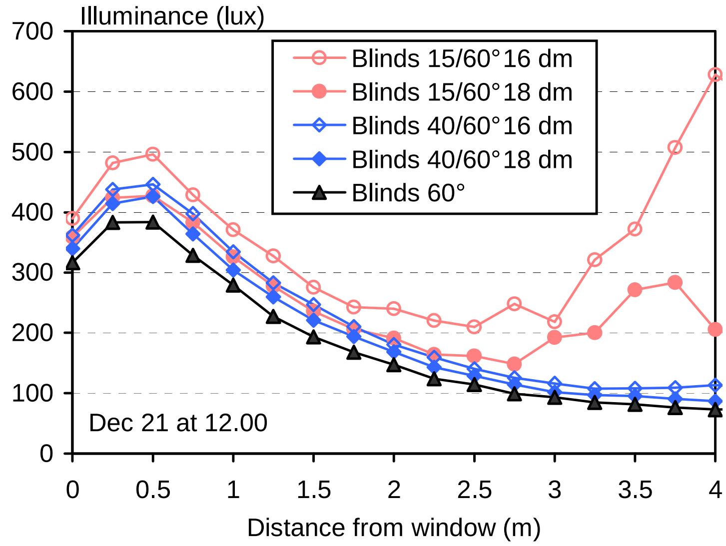


Figure 5.18 *Illuminance at winter solstice for the case WWAR 30% with a regular blind at the cut-off angle 60° and four re-directing blinds. Centre-line in room, 0.8 m above floor.*

All re-directing blinds studied will let some sunlight through in the morning and afternoon, see Figure 5.19. This might create a glare problem if the sunlight patch on the wall is too low (depending on where the division line is put in the window), if more than one person is sitting in the room, or if the floor plan is designed as open-plan. The blind 40/60 degrees could however be accepted if it is slightly more closed: If tilted to 60/80°, the cut-off angle is approximately reached for 10 o'clock. Other renderings from March and December at 12.00 are shown in Appendix 3.

A further improvement could be to use a mirror-like slat for the upper part, but this has not been evaluated since this cannot be simulated well in the backward ray-tracing algorithm that is used here. Potential risk of disturbing reflections to neighbours should also be investigated, plus the extra maintenance required to keeping the slats clean.

Figure 5.19 *View of room from the top illustrating the light distribution with re-directing blinds 15/60°_16dm (left) and 40/60°_16dm (middle), and regular blinds at 60° (right) for the winter case at 10 o'clock. The vertical light stripe on the wall is an artefact due to poorly mounted blinds (slightly too narrow).*

5.1.6 Alternative shading devices for case 60% and 100%

The selected louvre system for the cases 60% and 100% does not eliminate sunlight when the solar height is below 42 degrees. Thus, sunlight can penetrate the shading system between the end of August until mid April for a south facing room. Therefore, some alternative solutions were investigated. First, a translucent curtain was added on the inside of the window from the top of the view window at approx 2.1 metre down to desk level. As an alternative, the louvers were replaced by an exterior daylight re-directing venetian blind with slats at 45° at the bottom part and 15° for the top part. The break-point between the two slats angles was also put at 2.1 meters above floor. The transmittance of the translucent curtain was selected to 22 %. The exterior venetian blind was 80 mm wide with the same colour and reflectance as for the louvre system.

The resulting renderings for the observer's field of view for March 21 at 12.00 are shown in Figure 5.20 for case 60% and compared to the original case with louvres. Both the curtain and the exterior venetian blind effectively reduce the luminance on the table around the computer screen, and the window luminance is also reduced. In Figure 5.21 a view from the back illustrates clearly the position of the curtain and the view out. In Figure 5.22 a view from the top is shown for the same cases. Since the curtain was not mounted all the way up to the ceiling, there is still some sunlight that can penetrate deep into the room. This can be avoided by a larger curtain, but at the expense of a lower light level in the room.

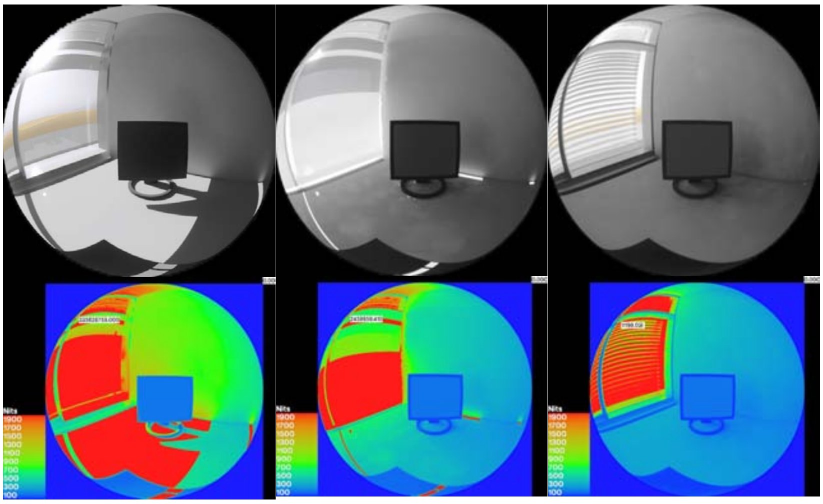


Figure 5.20 *Luminance distributions for the observer's field of view for WWAR 60% with louvres (left), with added interior curtain (middle), and with the louvres replaced by a venetian re-directing blind 15/45° (right) for March 21 at 12.00. Filtered image above, false colour image below.*

Figure 5.21 *View of room from the back for WWAR 60% illustrating the light distribution with louvres (left), with added interior curtain (middle), and with re-directing exterior blinds 15/45° (right) for 21st March at 15.00.*

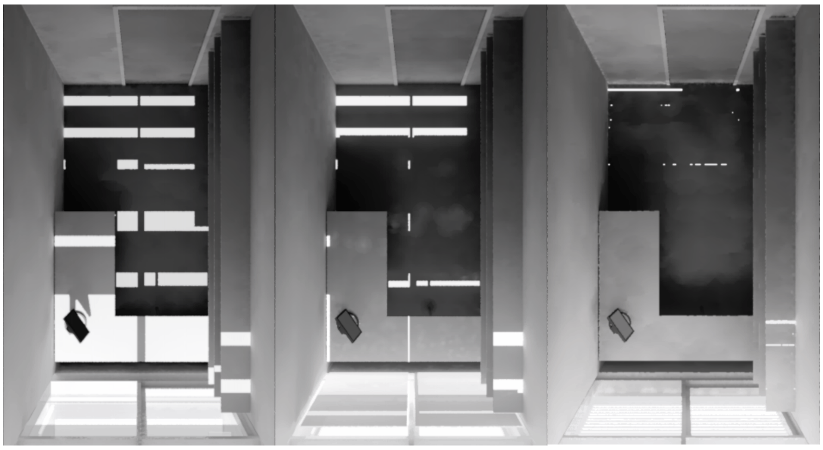


Figure 5.22 View of room from the top for WWAR 60% illustrating the light distribution with louvres (left), with added interior curtain (middle), and with re-directing exterior blinds 15/45° (right) for 21st March at 12.00. The vertical light stripe on the wall is an artefact due to poorly mounted blinds (slightly too narrow).

The daylight factor and daylight autonomy was calculated in Daysim and the results are shown in Figures 5.23-24. The cases 30% with intermediate blinds at 0° and 30° respectively are included as a reference. It is interesting to see that the much larger window surface does not generate significantly higher daylight factors when effective shading is applied. In fact, both the daylight factor and the daylight autonomy falls between the two cases with 30 % window area! At one metre from the window, the daylight autonomy is the same for the two cases 30% with blinds 30° and 60% with exterior blinds 15/45°.

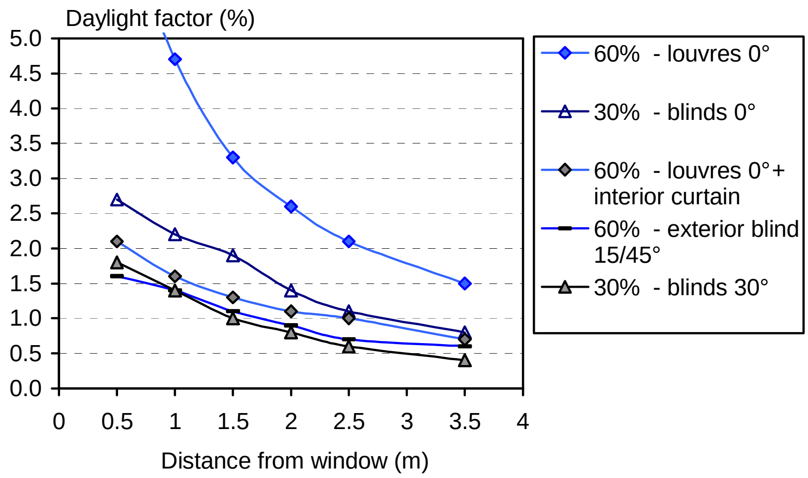


Figure 5.23 *Daylight factors for WWAR 60% for the original case with horizontal louvres without and with an added interior curtain, and for re-directing exterior blinds 15/45°. The cases 30% with intermediate blinds at 0° and 30° are also shown for comparison.*

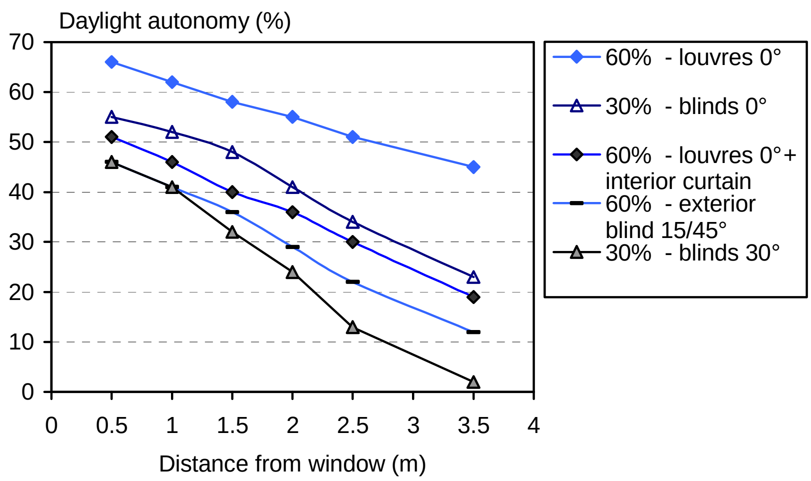


Figure 5.24 *Daylight autonomy for WWAR 60% for the original case with horizontal louvres without and with an added interior curtain, and for re-directing exterior blinds 15/45°. The cases 30% with intermediate blinds at 0° and 30° are also shown for comparison.*

The resulting electricity use for mixed users and case 60% with the added curtain is 21.7 kWh/m²a with manual light switching, 14.2 for the dimming system and 13.5 kWh/m²a for the combined switch on/off + dimming. With external blinds 15/45° the numbers are instead 22.1; 15.0 and 14.1 kWh/m²a. The latter numbers are very similar to the case 30% with blinds at 30°!

For the case 100%, the view for the observer for June 21st at 12 is shown in Figure 5.25, and the view from the back in March at 15.00 is shown in Figure 5.26. It is clear that the curtain as well as the exterior blind reduces the illuminance and the risk of glare much better than just the louvre system itself.

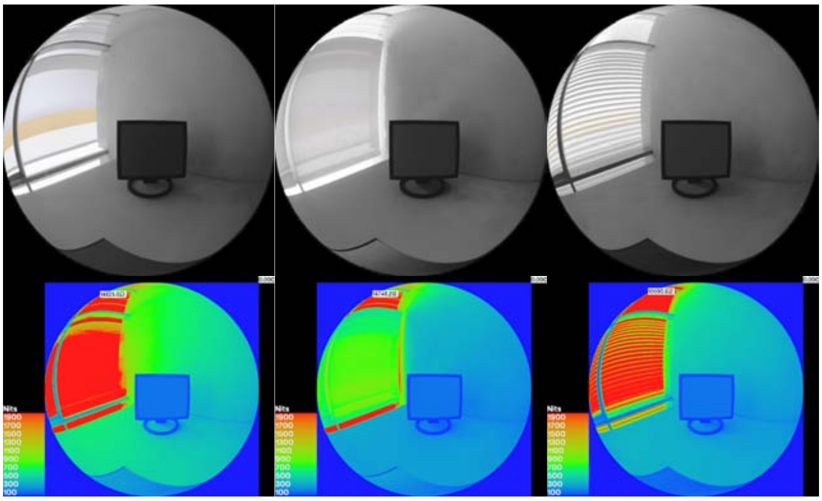


Figure 5.25 *Luminance distributions for the observer's field of view for WWAR 100% with louvres (left), with added interior curtain (middle), and with the louvres replaced by an exterior venetian re-directing blind 15/45° (right) for June 21 at 12.00.*

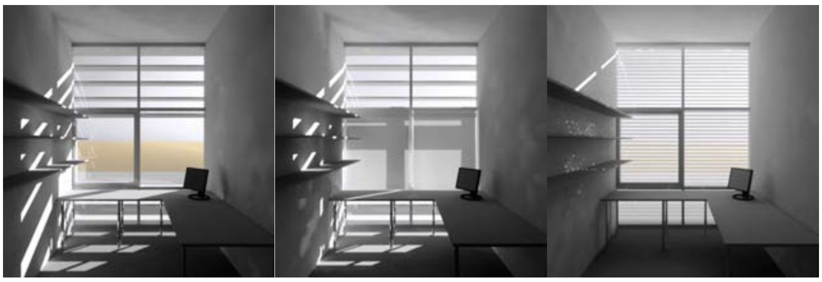


Figure 5.26 *View of room from the back for WWAR 100% illustrating the light distribution for 21st March at 15.00. Shading devices as in Figure 5.23.*

5.1.7 Case 60 % - Effect of westerly orientation

So far, only offices orientated towards the south have been studied. This should be the easiest case to shade, since the solar angle is higher than for east and west facing offices. The effect of turning the office towards west will be used as an illustration of potential difficulties with lower solar heights. In Figure 5.27, the case 60% is shown with the original louvre system for June, March and December for the afternoon hours when the sun hits the façade at an oblique angle.

Figure 5.27 *View from the back for a west facing office with 60 % window area and external louvres. June (left) and March (middle) for 15 hrs, and Dec at 14 hours (right).*

5.2 Open plan office

In this section the situation with an open floor plan is studied. A side-lit room is created that is 4 room modules wide, and where 8 offices are created. An interior wall divides the space, so that no corner rooms are studied. Behind this wall, the open plan office continues with 3 more room modules. These only appear at the very back of the overview pictures that are created. In the cases where blinds and curtains are added, these are not added in this section of the room.

The selection of pictures to be generated was not as complete as for the cell type office. The pictures were selected to provide a general idea of the possibilities and problems with the open plan space. For the most part, an overview picture was generated from the back of the room. For some cases two observer views where generated, one for the person sitting closest to the window, and one for the second row. See Figure 4.4.

5.2.1 Comparison of glazed area without shading

A comparison between the three studied window areas without shading devices for a sunny day at noon during equinox is shown in Figure 5.28.

To the left is shown an overview of the room and to the right the luminance is displayed as a false-colour image.

As the glazed area increases, a larger portion of the bright sky is visible, and the glare situation is more difficult. The ceiling is also rather bright in the cases 60 % and 100%.

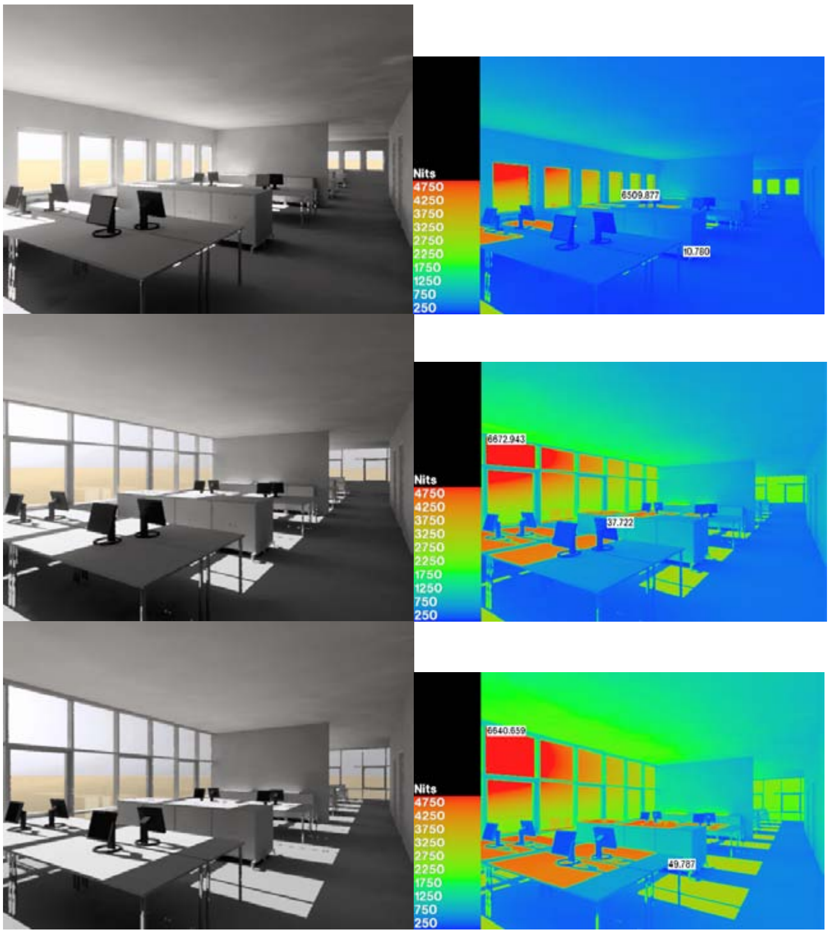


Figure 5.28 *Open plan office, WWAR 30% without blinds, WWAR 60% and 100% without louvres. Perspective from the back corner for March 21st 12 hrs, pcond image (left), and false colour picture (right).*

5.2.2 Comparison of glazed area with shading devices

A comparison between the three studied window areas with shading devices for a sunny day at noon during equinox is shown in Figure 5.29. To the left is shown an overview of the room and to the right the luminance is displayed as a false-colour image. As we can see, the case with 30 % window area and blinds at 30° manage to avoid direct sunlight penetration, while still allowing for some view to the outside. The light level in the room is however lower, but the glare situation is probably the best among these three.

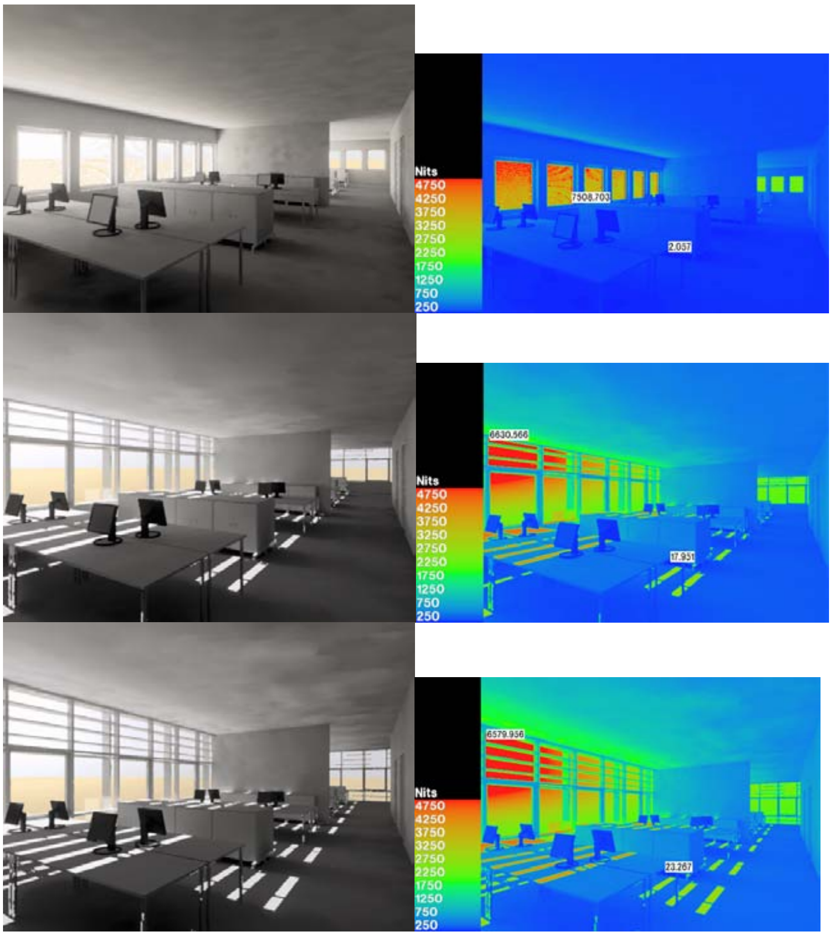


Figure 5.29 *Open plan office, WWAR 30% with blinds 30°, WWAR 60% and 100% with louvres. Perspective from the back for 12 hrs March 21st (left), and false colour picture (right).*

5.2.3 WWAR 60% with shading devices at various solar heights

The situation in the room with 60 % glazing with louvers on sunny days in June, March and December is shown in Figure 5.30. The left pictures show the situation at noon, and the right picture is from the afternoon. As was already shown for the cell office, the louvers are not sufficient to shade from direct solar radiation in March or December. Either extra glare protection is needed, or another shading system should be used. The effect on an interior curtain in front of the lower window is shown in the next section. Pictures from the position of Observer 1 and 2 are shown in Figure 5.31 for the afternoon hours.

Figure 5.30 *Open plan office, WWAR 60% with louvres. Perspective from the back for 12 hrs (left column) and 15 hrs (14 for Dec) hrs (right)., June 21st (top row), March 21st (middle), Dec 21st (bottom row).*

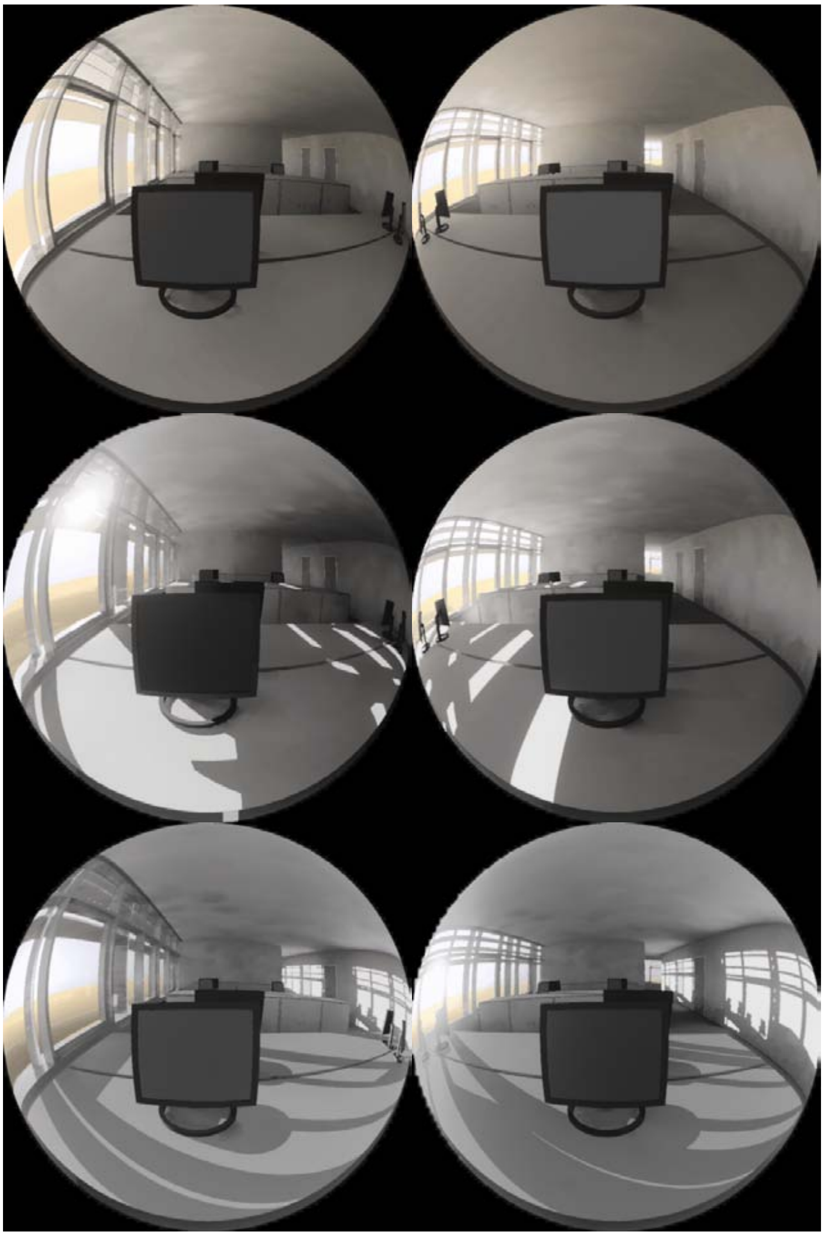


Figure 5.31 Open plan office, WWAR 60% with louvres. Observer's view from seating position 1 (left) and 2 (right), June 21st (top row) at 15, March 21st at 15 (middle), Dec 21st at 14 (bottom row)

5.2.4 WWAR 60% with improved shading

The case 60% with louvers is shown again for the sunny condition in June at noon, Figure 5.32. Since the luminance of the sky seen through the window is above 3000 cd/m², there is a risk of glare. Therefore, some alternatives with improved shading are investigated. The sunny condition in June at noon is again shown in the next images, Figure 5.33. First, an interior curtain is added in front of the view windows, identical to the one used for the cell-type office. Secondly, the exterior louvers are replaced by an 80 mm wide exterior aluminium blind. In the blind case, different slat angles are also investigated. First, horizontal slats are studied (0°), then a blind with slat angle 45°. Finally, a blind is studied that has a slat angle of 15° in front of the top windows, and 45 degrees in front of the view windows, as so called daylight re-directing blind. This is then called 15°/45°. The reason for choosing a rather small slat angle difference stems from the very low solar angles experienced during the winter time in Sweden, see Sec 4.7 and also (Bülow-Hübe, 2007).

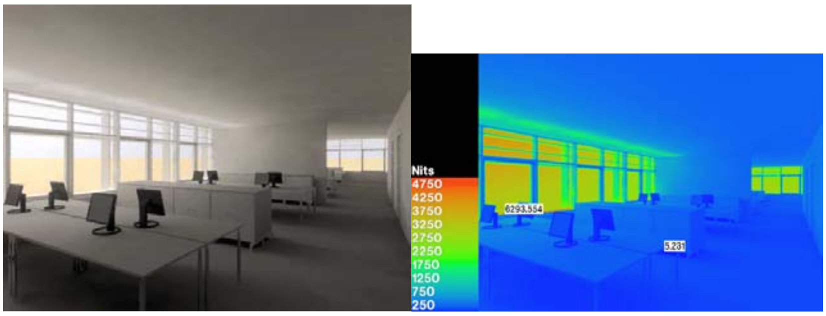
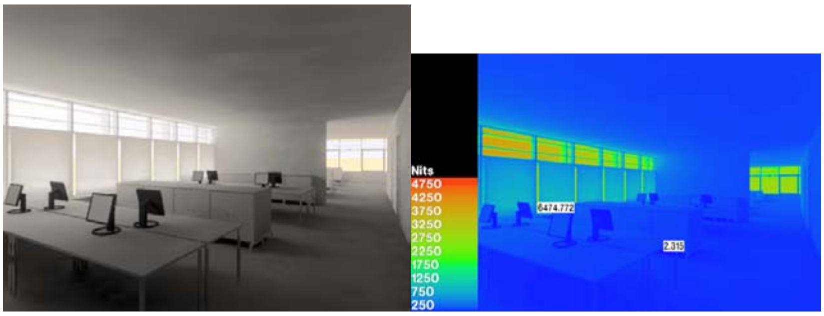
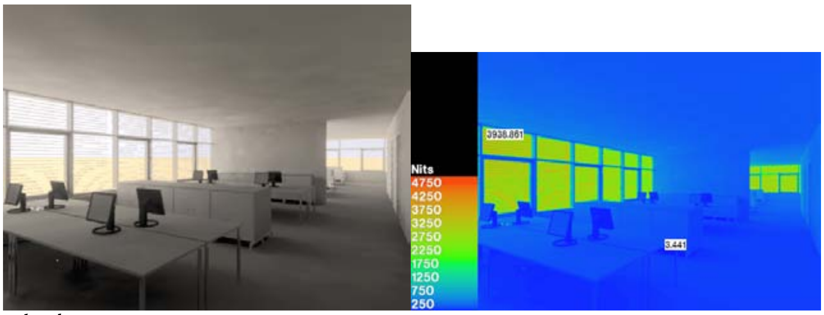


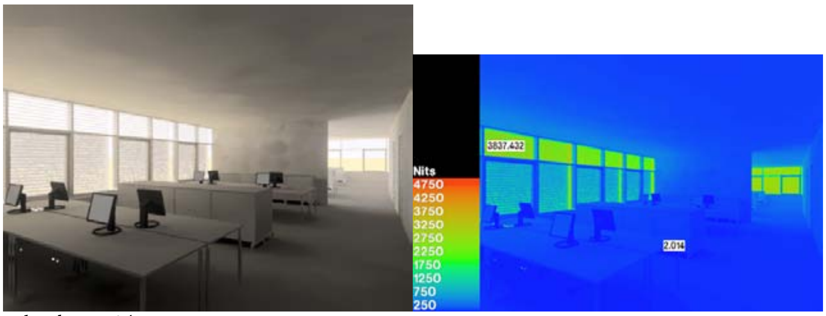
Figure 5.32 Open plan office, WWAR 60% with louvers. Perspective from the back corner for June 21 at noon.



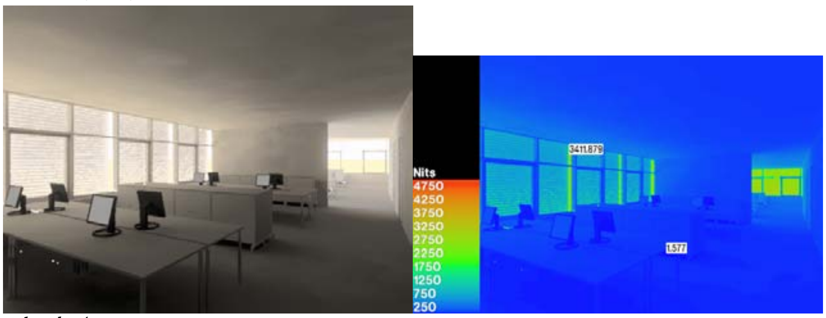
Louvres+curtain



Blinds 0°



Blinds 15°/45°



Blinds 45°

Figure 5.33 *Open plan office WWAR 60% with various shading devices. Perspective from the back corner for June 21 at noon. Pcond image left, false colour image right.*

Views for observer 1 and 2 where also generated, and these are shown in Figure 5.34 for the case with an interior curtain. Please note the different scale in the false colour image. It appears as if the innermost sitting position provides a better contrast on the screen.

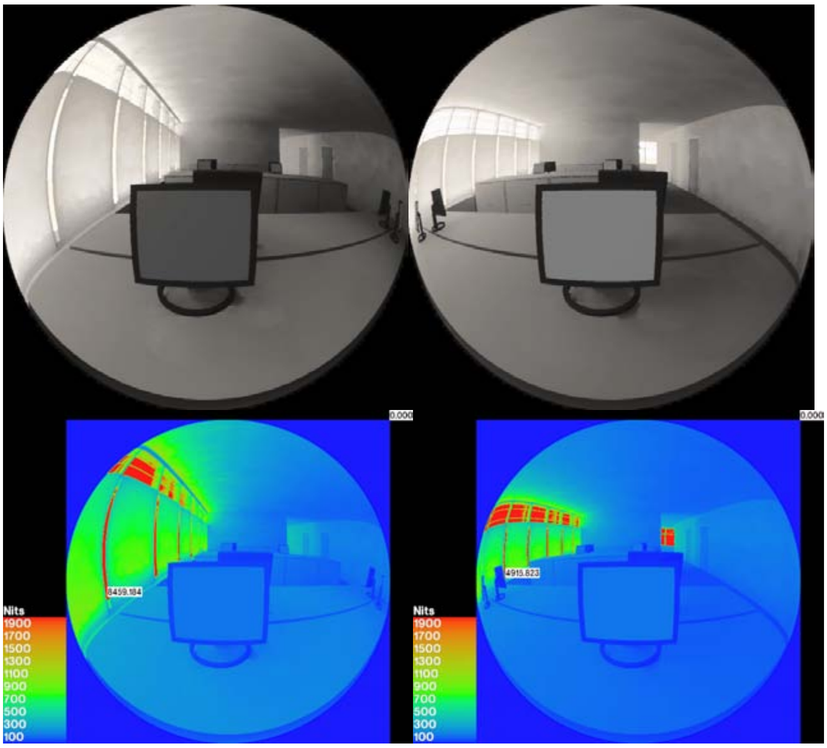


Figure 5.34 *Open plan office, WWAR 60% with louvers and interior curtain. Observer's view from seating position 1 (left) and 2 (right), June 21st at 12 hrs, pcond image (top row) and false colour image (bottom row).*

5.2.5 Daylight factor (CIE overcast sky)

The daylight factor was calculated in Rayfront with the CIE overcast sky for two cases with the 30% window-to-wall area ratio and 5 cases with the 60% WWAR. For the 30% case, interior blinds were investigated with slat angles 0° and 30° respectively. For the 60% case, the daylight factor was calculated for the case with exterior louvres, with louvres and interior curtain in front of the view window, and for three variations of exterior 80 mm blinds: 0° slat angle, 45° slat angle, and 15° at the top and 45° at the view window (called 15/45°).

The highest daylight factor among these 5 cases is achieved in the 60% case with louvers followed by the 60% case with blinds 0°. The lowest daylight factor was given for the 60% case with blinds 45°, Figure 5.35.

The daylight factor for the case 30% case with blinds 0° yields almost the same daylight factor at one meter from the window as the 60% case with blinds 0°, but when moving away from the window wall, the daylight factors decreases more rapidly in the 30% case.

It is also interesting to compare the cases 60% + blinds 45° and 60% + blinds 15°/45°. The second case with the daylight blind 15°/45° gives about 20% more illuminance at one meter from the window, and around 30% more at 5 metres from the window for a CIE overcast sky.

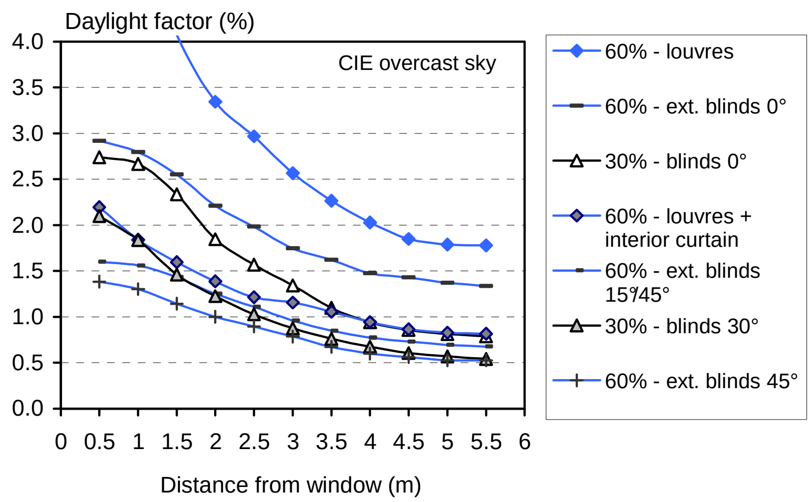


Figure 5.35 *Calculated daylight factor for the CIE overcast sky for the cases 30% and 60% window area together with some different shading devices.*

6 Discussion and conclusions

This study shows that it is difficult to find one shading system that performs well all through the year. I think it is safe to say that fixed systems in general perform more poorly than movable systems. With a fixed exterior shading system such as louvres, it is likely that additional shading devices such as interior curtains or blinds are required to avoid sunlight penetration during the winter season, and to reduce glare.

A first criterion for a shading system is that it should ensure that direct sunlight penetration can be avoided. However, this study shows that it is probably not sufficient to just avoid direct sunlight penetration in order to avoid glare. Many of the performed simulations show that the remaining view of the sky or of the shading system itself might still be too bright and will create glare. Therefore, shading devices with variable light transmittance such as blinds are preferable. Other studies show that if mounted on the outside, blinds can also provide the necessary solar protection to avoid overheating. If mounted on the inside the solar protection performance is poor and additional exterior shading or solar control glass is needed to address the overheating problem. (Wall & Bülow-Hübe, 2001)

In order to avoid the glare problem, the luminance of the window surface must be drastically decreased on sunny days and on days with bright skies. This can be achieved by effective shading systems, which however will automatically also reduce the interior daylight level, so that the full benefit of large windows cannot be exploited. Therefore, this study shows that increasing the window area does not automatically lead to much lower use of lighting electricity even if a dimmable daylight responsive lighting system is installed.

In some cases the calculated daylight autonomy may be underestimated, since the shading is assumed fixed in Daysim. If the user actively controls the shading manually, and pulls it up on cloudy days, or if the shading is motorised an attached to a control system, the actual daylight autonomy will increase. However, the Swedish winter is often very dark with extremely short days and low outdoor light levels even at midday.

For this period the daylight will never be enough no matter the glazing size and electric lighting will be required.

Radiance is a good tool for accurately estimating daylight distribution for selected climate conditions. It is however very time consuming to get an overall picture for the whole year, since this requires many simulations. Further, Radiance requires an expert user since it takes a lot of time to learn and master. Daysim is a promising tool to estimate the yearly daylight distribution, and since it builds on a Radiance simulation at the bottom, the results can be very accurate. However, the menu shell still needs improvement, both regarding user-friendliness and freedom of bugs. It is also recommended that the user has some previous experience of Radiance.

Although many light control strategies can be simulated in Daysim, there are still some options that would need further development, for example that fully dimmed luminaries should automatically turn off after some delay time to avoid ballast losses. The many options available between users of different kinds and their interactions with the light system are also a bit confusing and hard to understand. Further, it would be very interesting to extend the possible control strategies to more advanced control of the shading system itself, for example a sun-tracking control which adjusts the slat angle for the blinds depending on the solar angle. Today, there is just one rather crude option for control of shading systems.

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Photosphere: http://www.anyhere.com/

Radiance: http://radsite.lbl.gov/radiance/HOME.html

Rayfront: http://www.schorsch.com

Appendix 1 Renderings for cell offices

1.1 Observer view for WWAR 30%

1.1.1 WWAR 30% without blinds

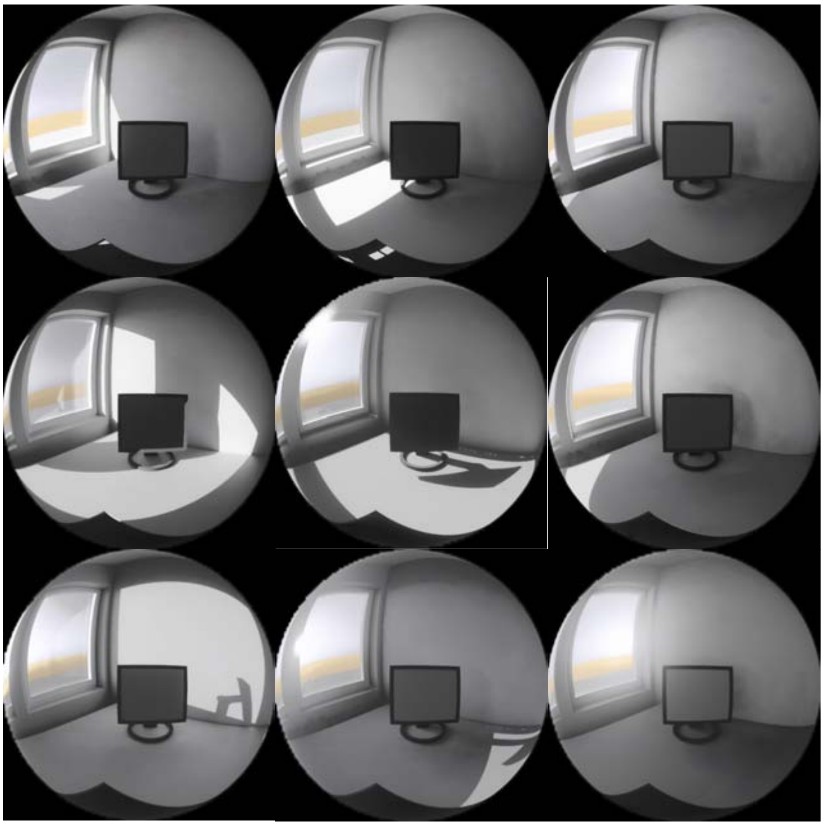


Figure A.1a *Interior views of a south facing office room at different hours (sunny conditions). Top row: June 21st at 9, 12 and 15 hrs. Middle row: March or Sept 21st at 9, 12 and 15 hrs. Bottom row: Dec 21st at 10, 12 and 14 hrs.*

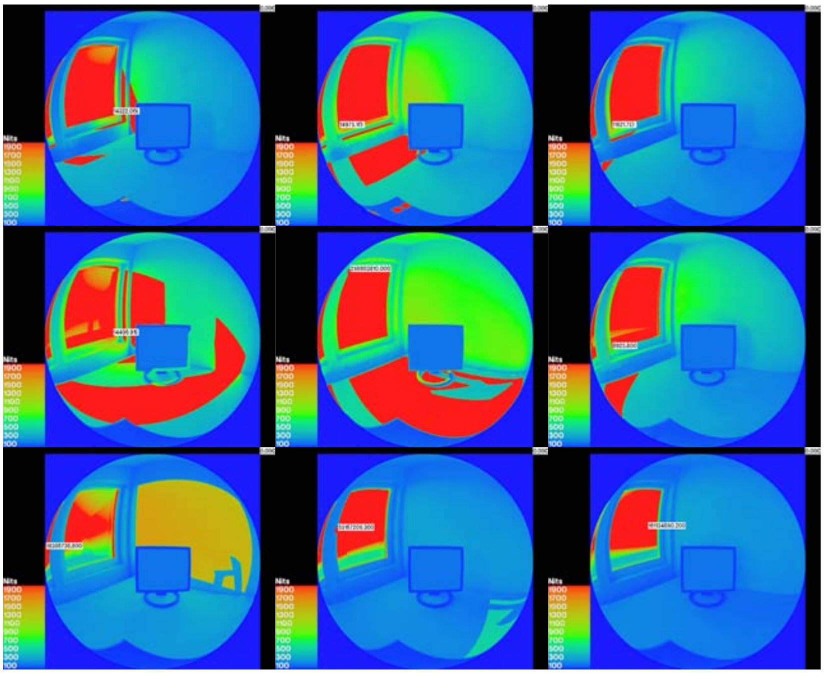


Figure A.1b *False colour images of the interior views in Figure A.1a.*

1.1.2 WWAR 30% with blinds

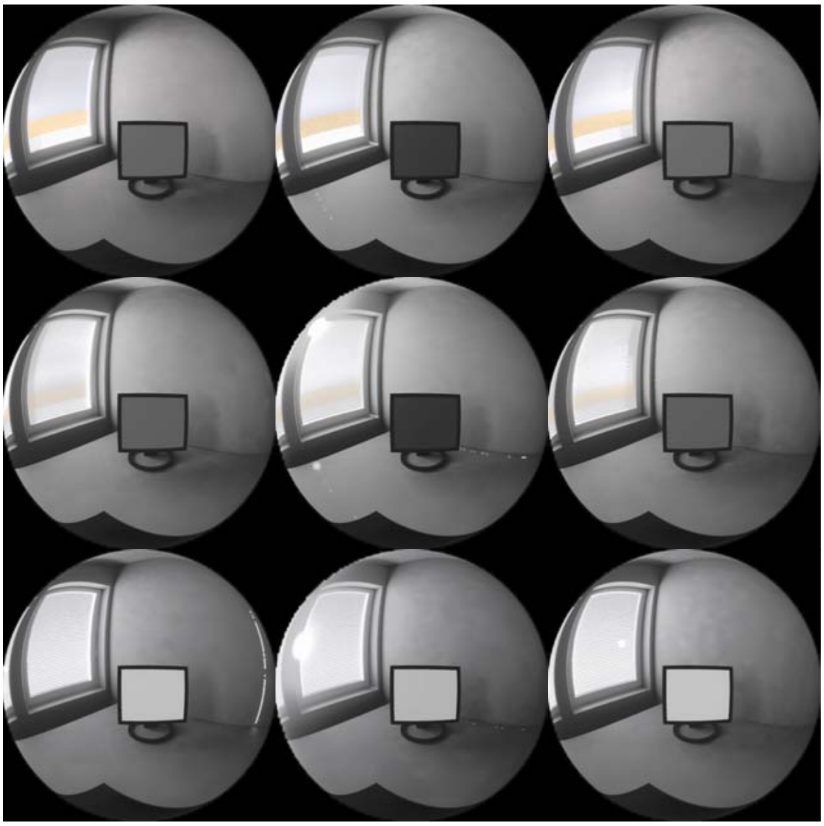


Figure A.2a *Interior views of a south facing office room at different hours (sunny conditions). Top row: June 21st at 9, 12 and 15 hrs with blinds 0°. Middle row: March or Sept 21st at 9, 12 and 15 hrs with blinds 30°. Bottom row: Dec 21st at 10, 12 and 14 hrs with blinds at 60°.*

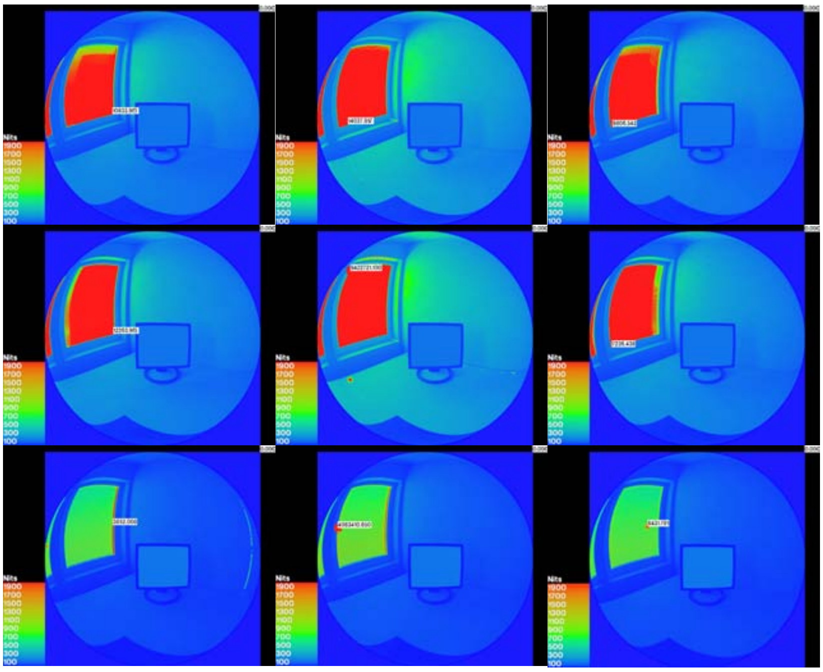


Figure A.2b *False colour images of the interior views in Figure A.2a.*

1.2 Observer view for WWAR 60%

1.2.1 WWAR 60% without louvres

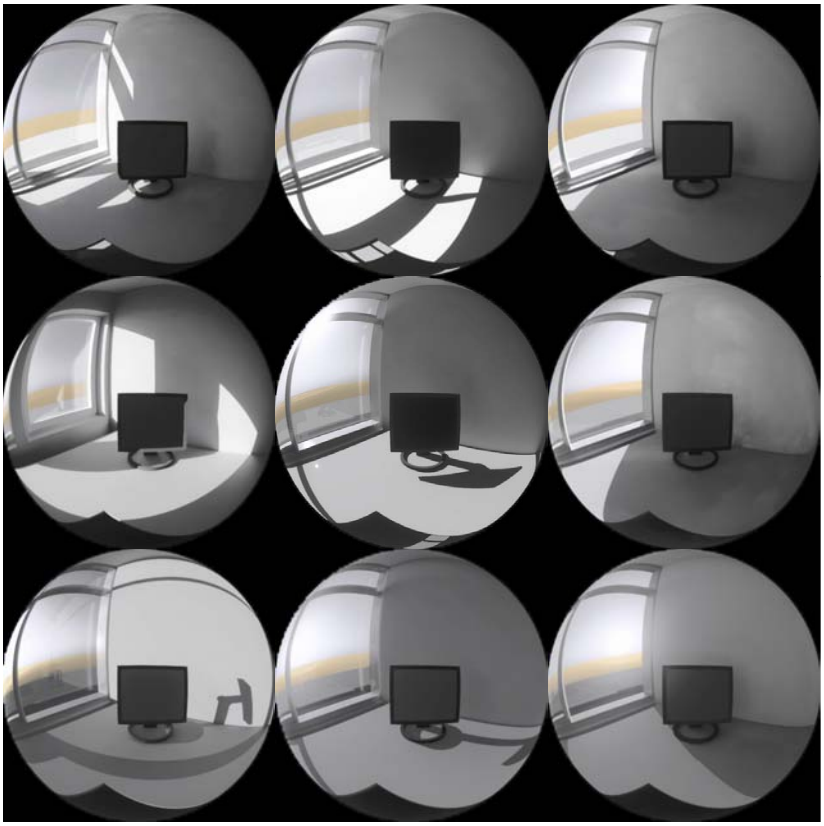


Figure A.3a Interior views of a south facing office room at different hours (sunny conditions). Top row: June 21st at 9, 12 and 15 hrs. Middle row: March or Sept 21st at 9, 12 and 15 hrs. Bottom row: Dec 21st at 10, 12 and 14 hrs.

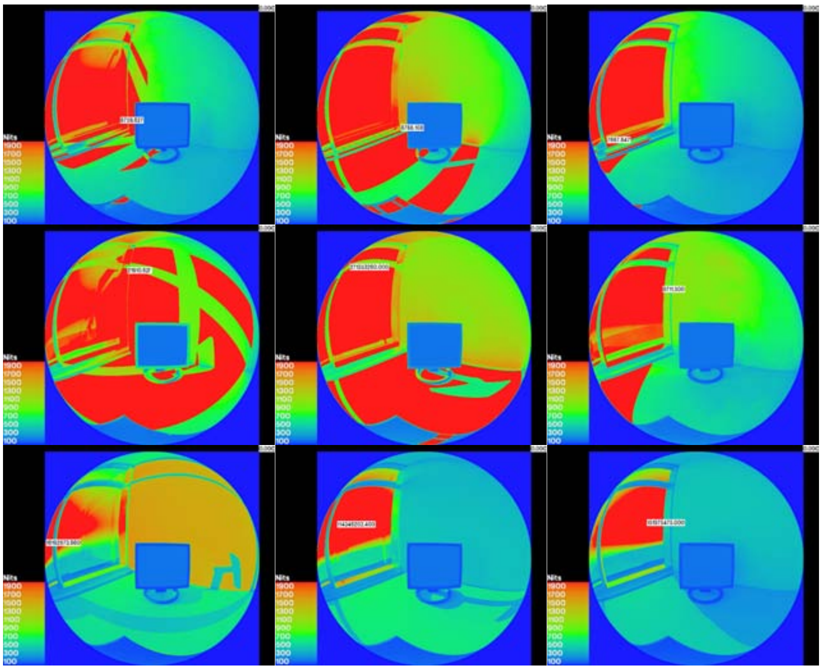


Figure A.3b False colour images of the interior views in Figure A.3a.

1.2.2 WWAR 60% with louvres

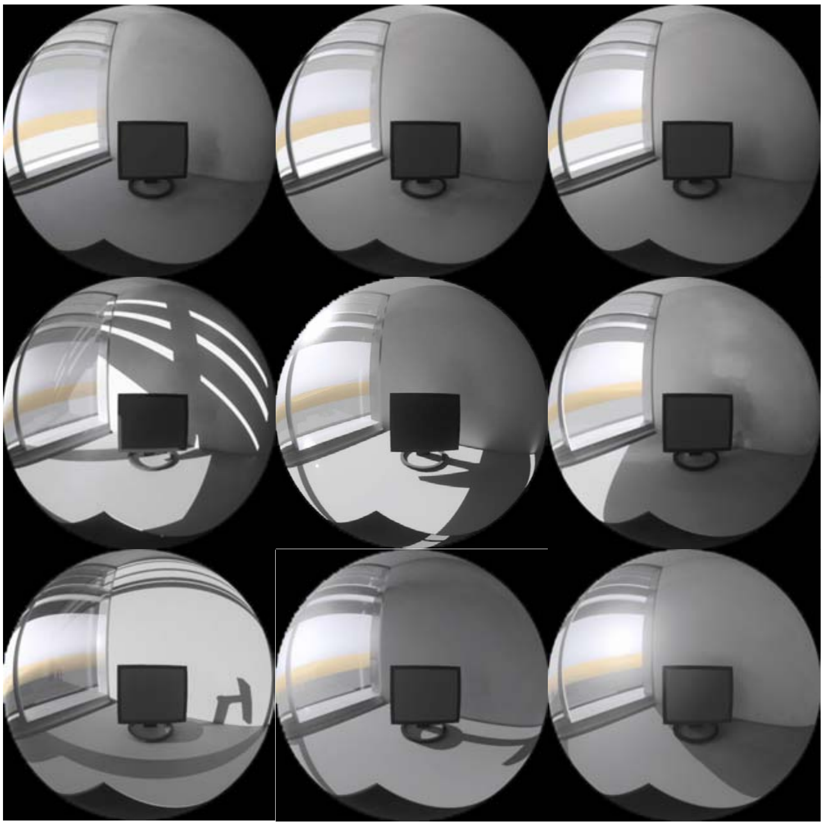


Figure A.4a *Interior views of a south facing office room at different hours (sunny conditions). Top row: June 21st at 9, 12 and 15 hrs. Middle row: March or Sept 21st at 9, 12 and 15 hrs. Bottom row: Dec 21st at 10, 12 and 14 hrs.*

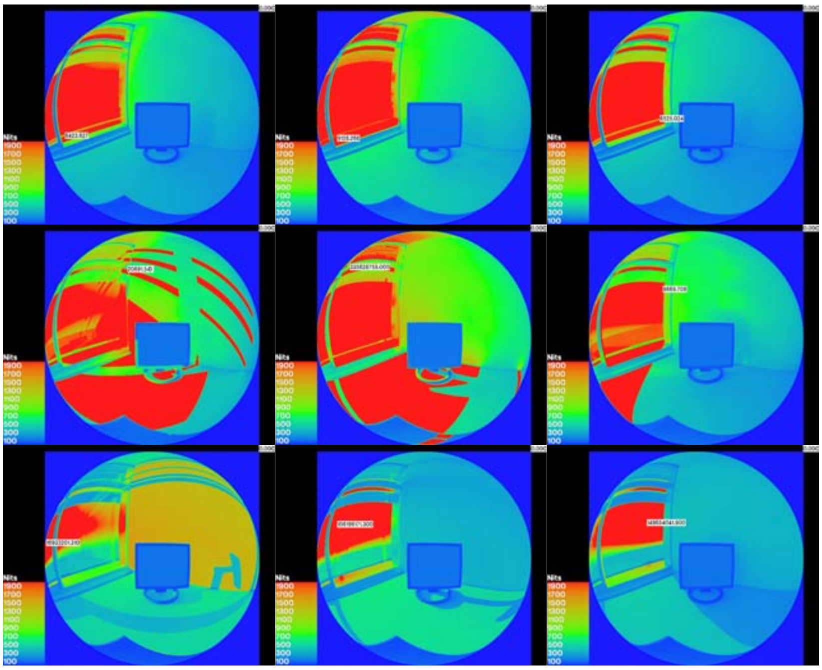


Figure A.4b False colour images of the interior views in Figure A.4a.

1.3 Observer view for WWAR 100%

1.3.1 WWAR 100% without louvres

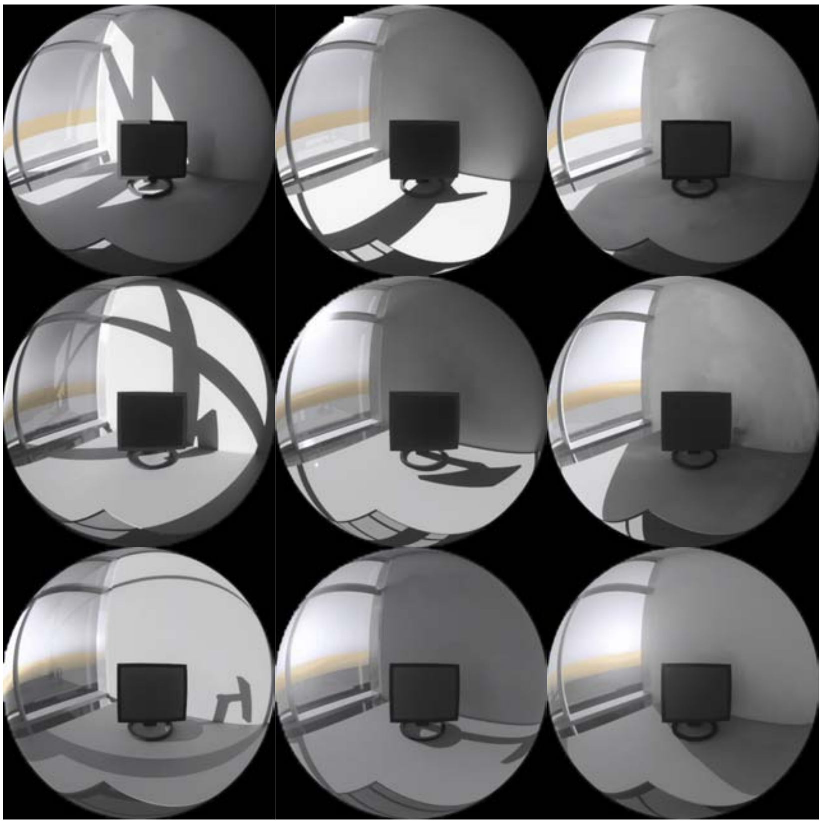


Figure A.5a *Interior views of a south facing office room at different hours (sunny conditions). Top row: June 21st at 9, 12 and 15 hrs. Middle row: March or Sept 21st at 9, 12 and 15 hrs. Bottom row: Dec 21st at 10, 12 and 14 hrs.*

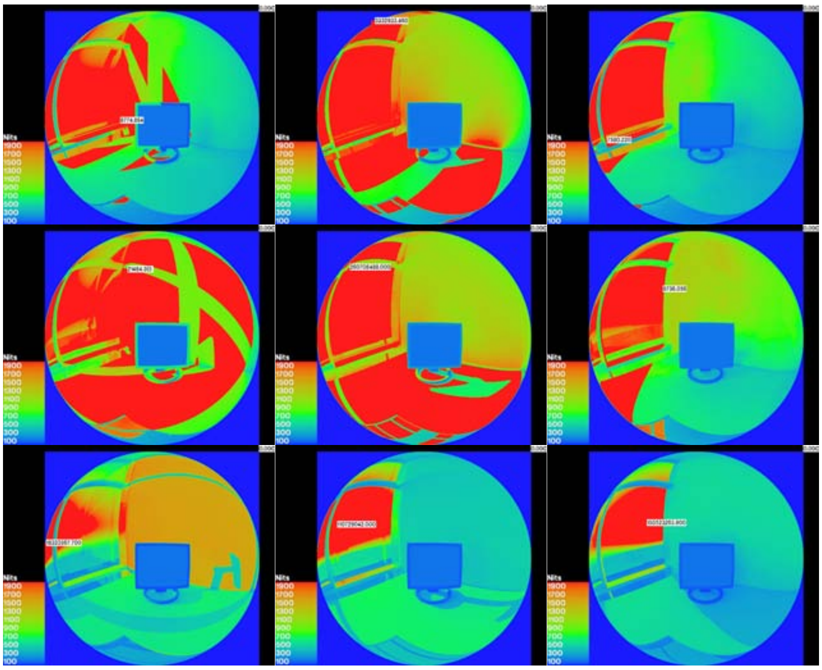


Figure A.5b False colour images of the interior views in Figure A.5a.

1.3.2 WWAR 100% with louvres

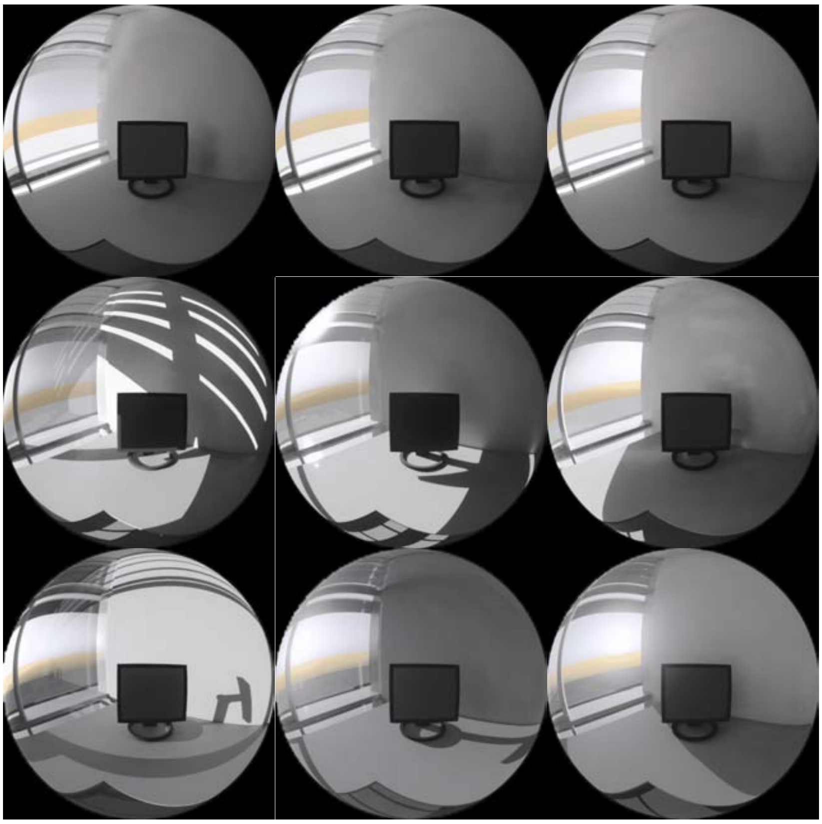


Figure A.6a *Interior views of a south facing office room at different hours (sunny conditions). Top row: June 21st at 9, 12 and 15 hrs. Middle row: March or Sept 21st at 9, 12 and 15 hrs. Bottom row: Dec 21st at 10, 12 and 14 hrs.*

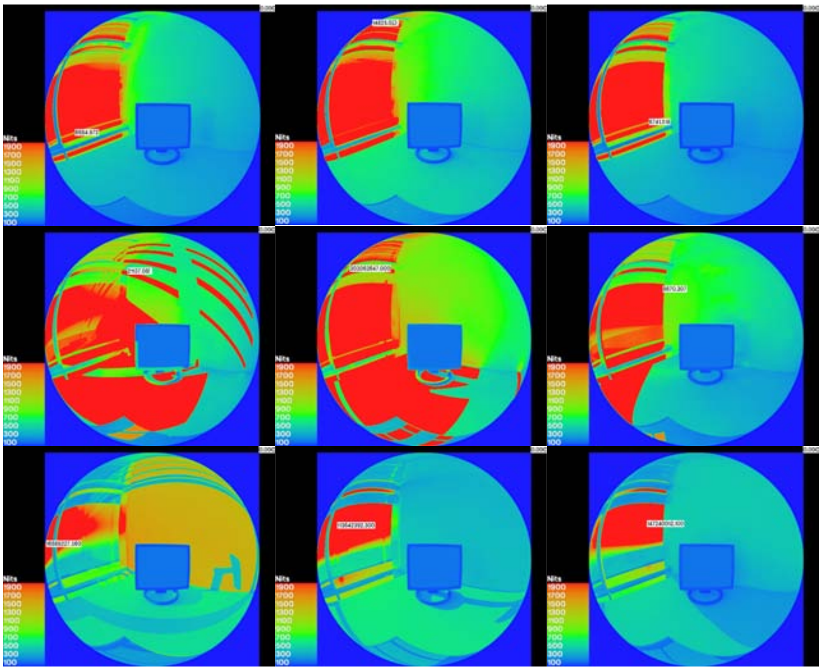


Figure A.6b False colour images of the interior views in Figure A.6a.

1.4 Other views

WWAR 30%	WWAR 60%	WWAR 100%
Blinds 30°	Louvres	Louvres

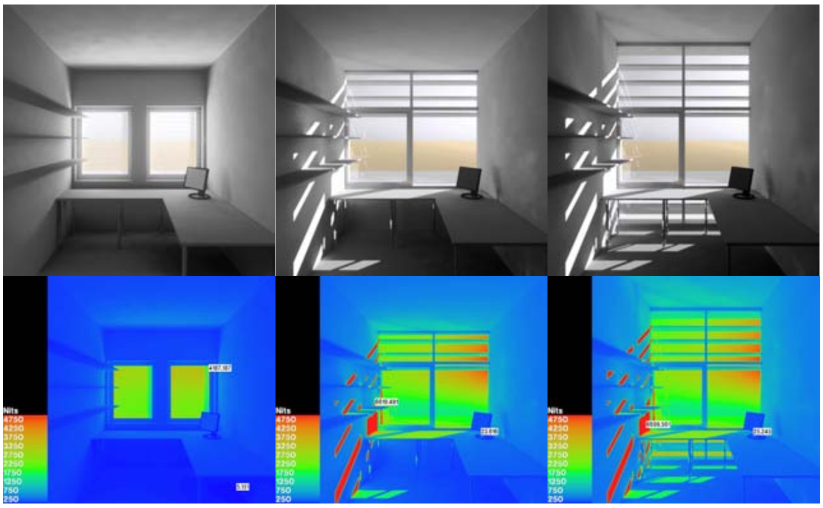


Figure A.7 *Interior views from the back of a south facing office room with different glass areas. Top row: March 21st 15 hrs. Bottom row: False colour image, note the different scale.*

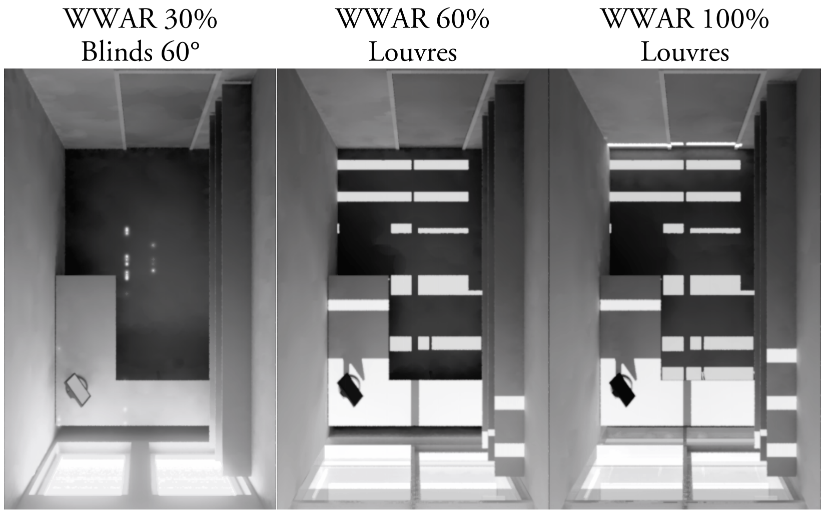


Figure A.8 *Views from the top of a south facing office room with different glass areas. March 21st 12 hrs.*

Appendix 2 Effect of slat angle on window luminance

A special study was made on the luminance on the window for various slat angles for the reference case WWAR 30%. The study was performed for sunny conditions, June 21st at 12 hrs. Please note that the cut-off angle is approximately -30 degrees for this case, therefore some negative angles were also included. The luminance of the whole window does not start to decrease until the blinds are rather closed, see the results for 60° and 75°.

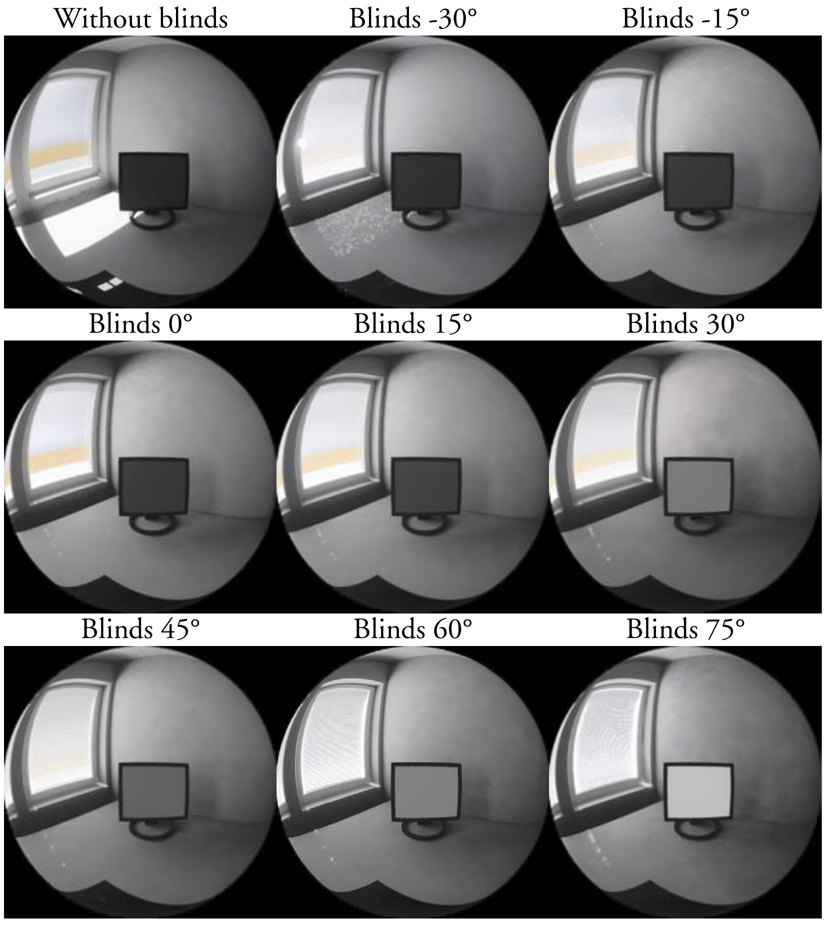


Figure A.9a *Interior views for various slat angles compared to no blinds. June 21st at 12 hrs, sunny sky. WWAR 30%.*

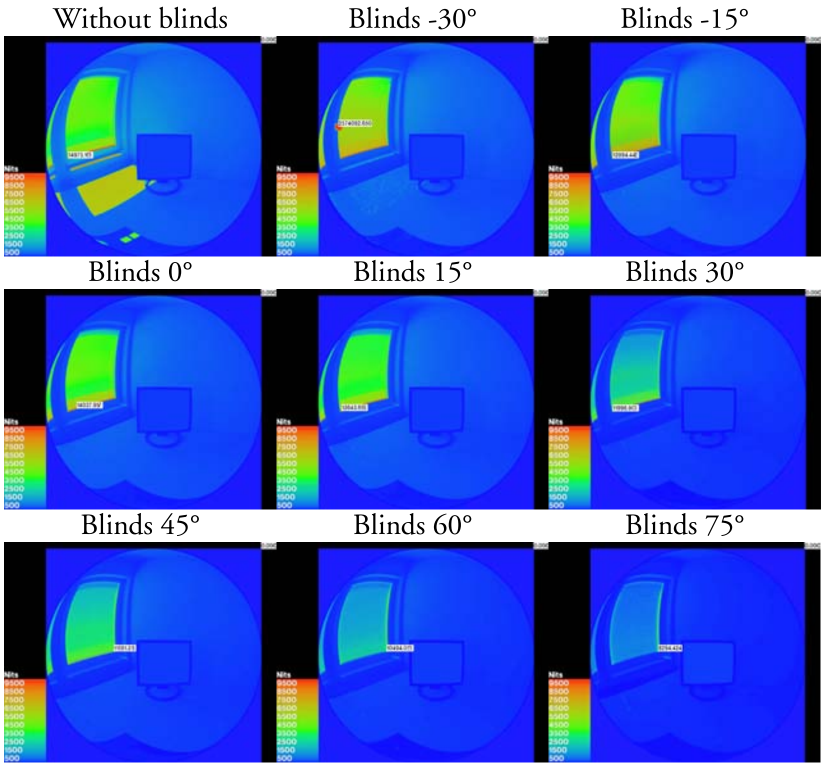
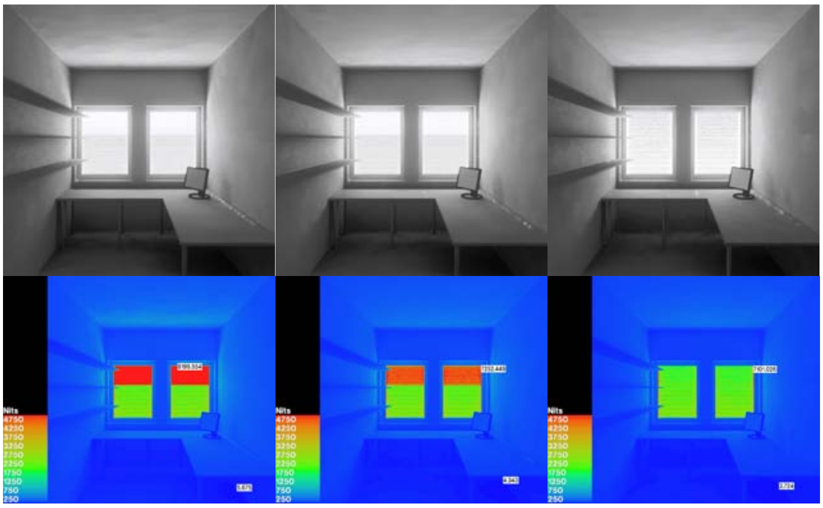


Figure A.9b *False colour images for interior views in Figure A.9a. Note that the luminance scale is different than from pictures 1-6.*

Appendix 3 Effect of daylight re-directing blinds

Blinds 15/60°_16dm Blinds 40/60°_16dm Blinds 60°

March 21st at 12.00



Dec 21st at 12.00

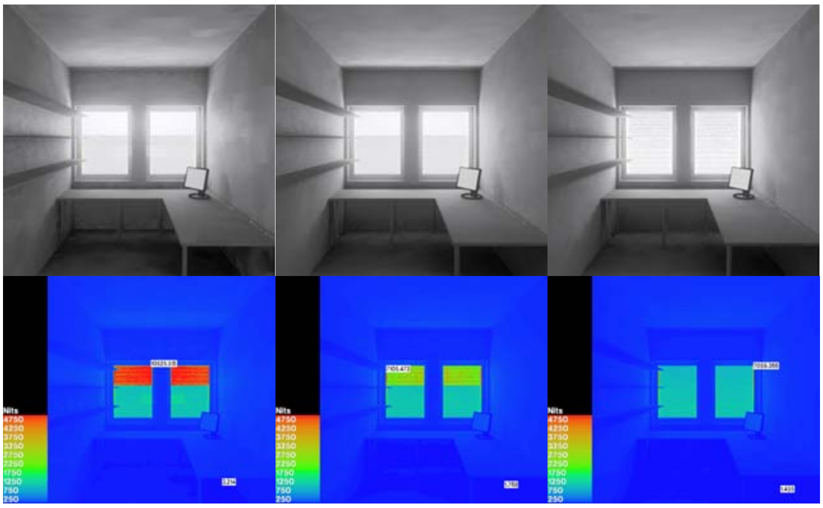
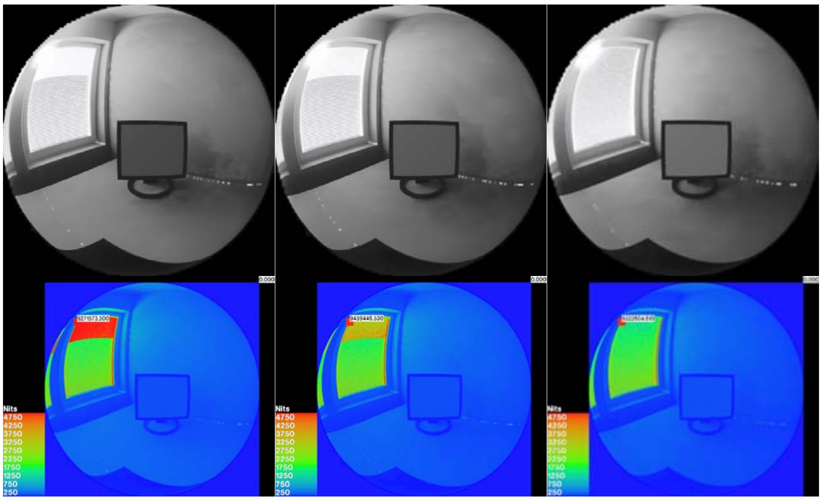


Figure A.10 *View from the back of the room displaying the apperance (top) and false colour image (below) with blinds 15/60°_16dm (left), blinds 40/60°_16dm, and blinds 60° for March 21st at 12.00 solar time. Top two rows: March 21st 12.00, bottom two rows: Dec 21st at 12.00.*

Blinds 15/60°_16dm Blinds 40/60°_16dm Blinds 60°

March 21st at 12.00



Dec 21st at 12.00

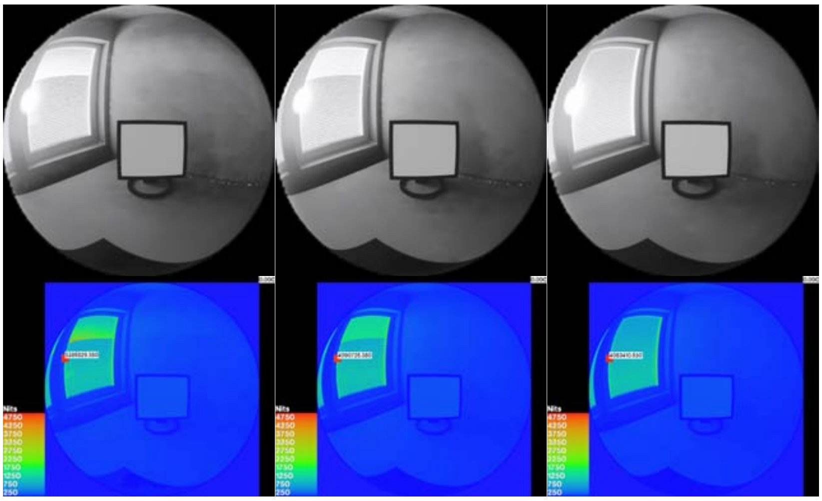


Figure A.11 *Observer view displaying the appearance (top) and false colour image (below) with blinds 15/60°_16dm (left), blinds 40/60°_16dm (middle), and blinds 60° (right) for March 21st and Dec 21st respectively at 12.00 solar time.*

Blinds 15/60°_16dm Blinds 40/60°_16dm Blinds 60°

March 21st at 12.00

Dec 21st at 12.00

Figure A.12 *Top view displaying the appearance with blinds 15/60°_16dm (left), blinds 40/60°_16dm (middle), and blinds 60° (right) for March 21st and Dec 21st respectively at 12.00 solar time.*

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